Effects of drip and flood irrigation on carbon dioxide exchange and crop growth in the maize ecosystem in the Hetao Irrigation District, China (Postprint)

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Abstract

Drip irrigation and flood irrigation are major irrigation methods for maize crops in the Hetao Irrigation District, Inner Mongolia Autonomous Region, China. This research delves into the effects of these irrigation methods on carbon dioxide (CO2) exchange and crop growth in this region. The experimental site was divided into drip and flood irrigation zones. The irrigation schedules of this study aligned with the local commonly used irrigation schedule. We employed a developed chamber system to measure the diurnal CO2 exchange of maize plants during various growth stages under both drip and flood irrigation methods. From May to September in 2020 and 2021, two sets of repeated experiments were conducted. In each experiment, a total of nine measurements of CO2 exchange were performed to obtain carbon exchange data at different growth stages of maize crop. During each CO2 exchange measurement event, CO2 flux data were collected every two hours over a day-long period to capture the diurnal variations in CO2 exchange. During each CO2 exchange measurement event, the biological parameters (aboveground biomass and crop growth rate) of maize and environmental parameters (including air humidity, air temperature, precipitation, soil water content, and photosynthetically active radiation) were measured. The results indicated a V-shaped trend in net ecosystem CO2 exchange in daytime, reducing slowly at night, while the net assimilation rate (net primary productivity) exhibited a contrasting trend. Notably, compared with flood irrigation, drip irrigation demonstrated significantly higher average daily soil CO2 emission and greater average daily CO2 absorption by maize plants. Consequently, within the maize ecosystem, drip irrigation appeared more conducive to absorbing atmospheric CO2. Furthermore, drip irrigation demonstrated a faster crop growth rate and increased aboveground biomass compared with flood irrigation. A strong linear relationship existed between leaf area index and light utilization efficiency, irrespective of the irrigation method. Notably, drip irrigation displayed superior light use efficiency compared with flood irrigation. The final yield results corroborated these findings, indicating that drip irrigation yielded higher harvest index and overall yield than flood irrigation. The results of this study provide a basis for the selection of optimal irrigation methods commonly used in the Hetao Irrigation District. This research also serves as a reference for future irrigation studies that consider measurements of both carbon emissions and yield simultaneously.

Full Text

Effects of Drip and Flood Irrigation on Carbon Dioxide Exchange and Crop Growth in the Maize Ecosystem in the Hetao Irrigation District, China

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Abstract: Drip irrigation and flood irrigation represent the two major irrigation methods for maize cultivation in the Hetao Irrigation District of Inner Mongolia Autonomous Region, China. This research investigates the effects of these irrigation methods on carbon dioxide (CO) exchange and crop growth in this region. The experimental site was divided into drip and flood irrigation zones, with irrigation schedules aligned with local common practices. We employed a custom-built chamber system to measure diurnal CO exchange of maize plants during various growth stages under both irrigation methods. From May to September in 2020 and 2021, two sets of repeated experiments were conducted, with nine CO exchange measurements performed in each experiment to obtain carbon exchange data at different maize growth stages. During each measurement event, CO flux data were collected every two hours over a 24-hour period to capture diurnal variations in CO exchange. Concurrently, biological parameters (aboveground biomass and crop growth rate) of maize and environmental parameters (including air humidity, air temperature, precipitation, soil water content, and photosynthetically active radiation) were measured. The results revealed a V-shaped trend in net ecosystem CO exchange during daytime, decreasing slowly at night, while the net assimilation rate (net primary productivity) exhibited a contrasting pattern. Notably, compared with flood irrigation, drip irrigation demonstrated significantly higher average daily soil CO emission and greater average daily CO absorption by maize plants. Consequently, within the maize ecosystem, drip irrigation appeared more conducive to absorbing atmospheric CO . Furthermore, drip irrigation exhibited a faster crop growth rate and increased aboveground biomass compared with flood irrigation. A strong linear relationship existed between leaf area index and light utilization efficiency, irrespective of irrigation method, with drip irrigation displaying superior light use efficiency compared with flood irrigation. Final yield results corroborated these findings, indicating that drip irrigation produced higher harvest index and overall yield than flood irrigation. These results provide a basis for selecting optimal irrigation methods in the Hetao Irrigation District and serve as a reference for future irrigation studies that simultaneously consider carbon emissions and yield measurements.

Keywords: carbon dioxide exchange; maize growth; drip irrigation; harvest index; net primary productivity; Hetao Irrigation District

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1 Introduction

The Hetao Irrigation District, situated in Northwest China, experiences a continental climate characterized by abundant sunlight and high evaporation. With average annual rainfall of approximately 130 mm and average annual evaporation of approximately 2300 mm [?], meeting crop growth requirements poses a significant challenge. The district benefits from the Yellow River, China' s second longest river, which flows through the region, making both groundwater and river water resources abundantly available [?, ?]. Drip irrigation and flood irrigation represent the main methods for utilizing these water resources [?].

The effects of drip and flood irrigation on maize growth and CO exchange between maize plants—the major food crop in the Hetao Irrigation District, constituting approximately 35% of the total planting area—and the atmosphere vary significantly [?, ?]. Therefore, thoroughly investigating the effects of these two irrigation methods on carbon emissions and their implications for maize biomass and yield is crucial. Key parameters such as net ecosystem CO exchange (NEE), crop net primary productivity (NPP), and soil respiration (Rs) play pivotal roles in demonstrating CO exchange between ecosystem and atmosphere [?, ?]. Two primary methods—eddy covariance and chamber-based approaches—are currently employed for measuring CO exchange. Eddy covariance, a large-scale and fixed-point observation technique, is suitable for assessing overall emissions within an entire ecosystem [?]. However, it cannot differentiate carbon emissions originating from the crop itself versus other sources such as soil, microorganisms, and animals, making it unsuitable for studying carbon flux in small-scale agricultural fields. In contrast, chamber-based approaches allow examination of carbon flux in small-scale agricultural fields [?], enabling separate measurements of CO emissions from both crops and soil and facilitating more comprehensive analysis of carbon emissions in agricultural fields.

Currently, most studies on carbon emission measurement using the chamber method have employed manual measurement, which is labor-intensive [?, ?], and most have measured carbon emissions only once from 09:00 to 13:00 (Beijing time), representing the average emission rate of the day [?]. However, environmental factors such as temperature and soil humidity greatly influence carbon emission from agroecosystems, leading to large daily variation in CO emission [?, ?, ?]. Thus, average CO emission cannot accurately reflect daily variation in CO emission. Additionally, light utilization efficiency cannot be calculated by measuring carbon emission only once. Many researchers have begun employing the chamber method to measure crop carbon exchange multiple times daily to obtain comprehensive data on daily variation of carbon exchange at canopy scale. Lindner et al. [?] studied diurnal NEE variation in rice cropland and manually conducted measurements between 06:00 and 18:00 (Beijing time); however, the labor-intensive nature of the chamber method limits measurement of nighttime CO exchange data. While most studies have used model estimation methods to determine nighttime average emission values [?], these values cannot capture specific variation patterns of nighttime emissions [?], hindering accurate reflection of nighttime emission trends.

As maize plants grow very tall, measuring CO exchange requires substantial labor. Currently, most studies have focused only on soil carbon emission in the maize ecosystem. For example, Guo et al. [?] studied the influences of drip and flood irrigation on soil CO emission and soil carbon sequestration in maize cropland. However, studying soil carbon emission alone cannot provide a comprehensive understanding of the effects of different irrigation methods on crop growth and CO exchange in maize ecosystems. To comprehensively investigate the influence of drip and flood irrigation on carbon emissions in maize fields and explore the correlation among carbon emission, crop biomass, and yield, gathering substantial data regarding diurnal variations in carbon emission is essential.

In this research, nighttime CO exchange was measured using an automated gas sampling chamber developed by our research team [?, ?], and daytime CO exchange was measured with a dynamic chamber. The objectives of this study are: (1) to quantify and compare diurnal NPP, NEE, and Rs of maize plants at various growth stages under drip and flood irrigation conditions; (2) to analyze the correlation between biological factors and light response parameters under the two irrigation conditions; and (3) to compare the advantages and disadvantages of the two irrigation methods by considering CO emission, crop growth, and yield.

2 Materials and Methods

2.1 Site Description

The experiment was conducted at the Science and Technology Experimental Station in Xingongzhong Town (41°05 16 N, 108°03 50 E), Wuyuan County, Bayannur City, Inner Mongolia Autonomous Region, China (Fig. 1), at an elevation of 1102 m. The experimental site is part of the Hetao Irrigation District and has a continental climate characterized by low average annual rainfall [?], which is insufficient to meet crop growth requirements [?]. Soil analysis (including soil physical and chemical parameters) at the experimental site revealed that the topsoil layer (0.00–30.00 cm) consisted of slightly alkaline irrigation-silted soil with a pH value of 8.3. The organic matter, nitrogen, and carbon concentrations were 17.82, 0.80, and 27.15 g/kg, respectively. The soil bulk density and water capacity were 1.4 g/cm^3 and 28%, respectively.

2.2 Experimental Design

2.2.1 Local Corn Cultivation Requirements The research object of this study was the local conventional spring maize ('Xianyu 1225'). The agronomic requirements for plant spacing of corn in the area are illustrated in Figure 2. The plant spacing of maize is 0.20 m, with wide and narrow rows alternately set, where the wide row spacing is 0.80 m and the narrow row spacing is 0.40 m. To reduce evaporation and increase temperature, local cultivation requirements also involve the use of plastic mulch in narrow rows, with a plastic film width of 0.50 m. By conducting surveys on local irrigation practices and aligning with literature data on commonly used irrigation schedules in this region [?, ?, ?], we established an irrigation schedule for this study (Fig. 3). For flood irrigation, three irrigation events were conducted during the entire growth period: the seedling stage (approximately 7 d after sowing, lasting for 25 d and covering the period from emergence to 5-leaf stage), the jointing stage (lasting approximately 25 d, occurring from mid-July to early August and covering the 5-9 leaf stage), and the tasseling stage (approximately two months after sowing, lasting approximately 20 d). For drip irrigation, groundwater was used as the water source, and six irrigations (approximately once every two weeks) were performed throughout the growth period. Base fertilizer was applied before sowing (3 May) and was top-dressed once during the reproductive growth period.

2.2.2 Requirements for Maize Planting and Management at the Experimental Site A schematic diagram of the experimental design is outlined in Figure 3, covering an area of 1.00 hm^2. Flood irrigation was provided to one half of the experimental site, and drip irrigation was provided to the other half. An isolation belt was set between flood irrigation and drip irrigation zones to prevent interaction between the two irrigation methods. For drip irrigation, one drip irrigation pipe supplied water for two rows of maize, and this pipe was placed in the middle of the narrow row (Fig. 2a). Flood irrigation provided water directly from the Yellow River through canal valves. Both irrigation methods employed at the experimental site adhered to local agricultural irrigation practices. The precise irrigation schedule and quantities are shown in Figure 3. The basal fertilizer applied included urea, diammonium phosphate, and potassium sulfate, with application amounts of 375, 375, and 225 kg/hm^2, respectively. In June, top-dressing with urea (150 kg/hm^2) was carried out. In 2020, sowing occurred on 7 May (day of year (DOY) 128) and harvest on 25 September (DOY 269), with a total growth length of 141 d. In 2021, sowing occurred on 9 May (DOY 129) and harvest on 28 September (DOY 271), with a growth length of 142 d.

2.3 Measurements

2.3.1 Microclimate The main climatic changes, including air temperature, air humidity (HOBO U23-001, Onset Computer Corp, Massachusetts, USA), and photosynthetically active radiation (PAR) (HOBO S-LIA-M003, Onset Computer Corp, Massachusetts, USA), were measured at a meteorological station located near the experimental site. These data were recorded by a recorder (HOBO H21-USB, Onset Computer Corp, Massachusetts, USA) every minute. Additionally, soil temperature and volumetric soil water content (TDR-315L, Acclima, Meridian, Idaho, USA) at the topsoil (10.00 cm) were measured. The volumetric soil water content was measured every 5 min and averaged and logged every 30 min using a data logger (CR3000, Campbell, Logan, Utah, USA). Five TDR-315L sensors were deployed in each irrigation zone to calculate the average soil temperature and volumetric soil water content of the corresponding area. Additionally, a rain gauge was used to measure rainfall each time.

2.3.2 Measurement of Soil and Maize CO Flux During Nighttime At night, the closed static chamber method was used to measure the CO flux of soil and maize ecosystem. Figure 4a shows the static chamber used for measuring CO flux in maize plants. The length and width of the static chamber are both 0.54 m. The chamber has two different heights of 0.54 m and 1.10 m, with total height increased by superimposing one chamber over another to accommodate maize plants of different heights. During nighttime, the chamber can accurately control the opening and closing of the lid. When the static chamber is closed, the temperature- and humidity-adjusting device works automatically to adjust the temperature and humidity in the chamber. After the chamber is closed, the gas sampling device automatically collects gas samples at 0, 5, 10, and 15 min. Subsequently, the chamber automatically opens following collection of the four gas samples. This cyclic gas collection process repeats every 2 h. CO flux measurements were conducted between 22:00 and 04:00 (Beijing time). The working principle and mode of chamber have already been described by Wachiye et al. [**?**] and Yang et al. [**?**]. The collected gas was assessed in laboratory using gas chromatography (GC-2010PLUS, Shimadzu, Kyoto, Japan). The static chamber method was also adopted for measuring soil CO flux during nighttime, with gas collection and measurement methods similar to those for maize CO flux. The chamber' s length, width, and height for soil CO_2 flux measurement are 0.36, 0.36, and 0.36 m, respectively.

2.3.3 Measurement of Soil and Maize CO_2 Flux During Daytime The chamber used to measure maize CO_2 flux during daytime was similar to that used during nighttime; however, the dynamic chamber method was employed (Fig. 4b). An infrared CO_2 gas analyzer (TD600-SH-B; Beijing Tiandi Shouhe Tech Development Co., Ltd., Beijing, China) extracted gas directly from the chamber to measure changes in gas concentration, after which the measured gas returned to the chamber. In the dynamic chamber method, a set of CO_2 flux data could be measured after the chamber was closed for 3–5 min, reducing physiological effects on crops due to chamber sealing. To avoid excessive temperature increase in the chamber, ice was placed on the outside of the chamber to cool it during measurements [?]. Daytime measurements were recorded from 06:00 to 20:00 at 2 h intervals. Compared with maize, the soil was much less sensitive to temperature, and as maize blocked sunlight, the chamber had minimal effect on soil temperature. Therefore, the daytime measurement method for soil CO_2 flux was the same as the nighttime measurement method.

2.3.4 Temporal and Spatial Arrangement of Gas Collection Experiments for Measuring CO_2 Flux The gas collection experiments for measuring CO_2 flux commenced during the vegetative stages of maize growth, specifically at the 7-leaf stage. Experiments were conducted on sunny days, with gas sampling performed every ten days, and a total of nine gas sampling events conducted throughout the entire experiment. In each gas sampling event, samples were collected from six different sampling plots in both flood irrigation and drip irrigation zones. Maize plants selected for measurements during gas sampling were chosen randomly after germination, resulting in a total of 54 gas sampling points for both flood irrigation and drip irrigation. During each gas sampling event, samples were collected once every 2 h throughout the day. Before gas sampling, a frame or collar was installed around each maize sample plot a month in advance. Additionally, a soil CO_2 flux measurement plot, employing the same frame-setting mode and CO_2 flux measurement timing as those of its corresponding maize sample, was set up near each maize sample plot' s location.

2.3.5 Measurements of Growth Parameters and Yield of Maize Crops Following gas measurement, the aboveground biomass (AGB) of maize in each gas sampling plot was harvested and measured. This involved drying the maize to a constant weight at 85°C in an oven and then recording the dry matter weight. Simultaneously, the leaf area index (LAI) of maize in each gas sampling event was measured using a plant canopy analyzer (LAI-2200C, LI-COR, Lincoln, Nebraska, USA). The LAI was calculated by averaging measurements recorded from four points around the gas sampling plot. For yield measurement, six areas were randomly selected in both drip and flood irrigation zones, with each measurement point covering 9.00 m^2 area. To prevent inaccuracies, particular attention was paid to avoid selecting areas that had been part of gas measurement plots during yield measurement area selection, as biomass from these gas measurement plots had already been harvested and could potentially introduce inaccuracies in yield measurements. The maize yield in both drip and flood irrigation zones was evaluated by measuring AGB and yield in the yield measurement areas. The grain was weighed after drying the grains in an oven to a constant weight at 85°C. The harvest index (HI) was determined as the ratio of dry grain weight to total plant dry weight.

2.4 Calculations

2.4.1 CO Flux and Net Primary Productivity (NPP) Calculation The NEE and Rs were measured using the chamber method and calculated using established formulas [**?**, **?**]:

$$F_{CO_2} = k_{CO_2} \times \frac{V}{A} \times \frac{\Delta c}{\Delta t} \times \frac{273.15}{T}$$

where F_{CO_2} is the CO flux (mg CO /(m^2·h)); k_{CO_2} is the gas constant at 273.15 K (equivalent to 0.536 g C/ L); T is the air temperature (K); V is the chamber volume (L); A is the chamber surface area (m^2); and $\Delta c/\Delta t$ is the altered CO concentration in the chamber (mL/(L · h)).

The NPP was obtained using established formulas [**?**]:

$$NPP = NEE - Rs$$

where NPP is the net primary productivity (mol CO /(m^2 · s)); NEE is the net ecosystem CO exchange (mol CO /(m^2 · s)); and Rs is the soil respiration (mol CO /(m^2 · s)). NEE and Rs are calculated using Equation 1, where NEE or Rs replaces F_{CO_2} in Equation 1.

2.4.2 Calculation of Net Ecosystem CO Exchange (NEE) and NPP of Maize Ecosystem In this experiment, the average area occupied by each maize plant was 0.12 m^2, determined by the average row spacing of 0.60 m and plant spacing of 0.20 m (plant density in Fig. 2). When measuring CO flux using the chamber method, the average area occupied by each maize plant within the chamber differs from the average area occupied by each maize plant in its natural state. Therefore, net CO exchange in the chamber ($F_{chamber}$) differs from NEE; it is necessary to convert $F_{chamber}$ to NEE. When measuring CO flux using the chamber method, the total amount of CO exchange per second in the chamber ($T_{chamber}$) was calculated as follows:

$$T_{chamber} = F_{chamber} \times A_{chamber}$$

where $F_{chamber}$ is the net CO exchange in the chamber (mol CO /(m^2 • s)) and $A_{chamber}$ (the region labeled as "maize chamber" in Fig. 2) is the area of the chamber (m^2).

The area occupied by the maize in the chamber under the specified planting density was different from the actual area of the chamber. The difference in the total amount of CO exchange per second under two different areas was T_{soil} (mol CO /s), which is calculated as follows:

$$T_{soil} = F_{chamber} \times (A - A_{chamber})$$

where A is the bare soil area occupied by two maize plants at the specified density (m^2).

Finally, NEE was calculated as follows:

$$NEE = \frac{T_{chamber} - T_{soil}}{2 \times L_{plant} \times L_{row}}$$

where L_{plant} is the plant spacing (0.20 m); L_{row} is the row spacing (0.60 m); $L_{plant} \times L_{row}$ represents the area occupied by a corn plant ("plant density" as shown in Fig. 2); and $2 \times L_{plant} \times L_{row}$ represents the area occupied by two corn plants. After calculating NEE, the NPP was determined using Equation 2.

2.5 Empirical Description of Canopy Responses

After measurement of NEE changes in the maize ecosystem during daytime, the leading light-related parameters of maize at the canopy scale were calculated using the Michaelis-Menten model [**?**]. The formula used in the model is:

$$NEE = \frac{\alpha \times \beta \times PAR}{\alpha \times PAR + \beta} - \gamma$$

where PAR is the photosynthetically active radiation (mol photon/(m^2 • s)); α is an approximation of the canopy light use efficiency ((mol CO /(m^2 • s))/(mol photon/(m^2 • s))); β is the maximum NEE of ecosystem (mol CO /(m^2 • s)); and γ is the average ecosystem respiration during the observation period (mol CO /(m^2 • s)). By utilizing the daytime measurements of NEE and PAR parameters, the values of parameters α, β, and γ in Equation 6 can be estimated. These parameters reflect the carbon exchange capacity of maize ecosystem. Additionally, $\alpha \times \beta \times PAR/(\alpha \times PAR + \beta)$ for high PAR ($PAR = 2000$ mol photon/(m^2 • s) in this study) can be thought of as the average maximum canopy uptake capacity (often noted as $(\beta + \gamma)_{2000}$ (mol CO /(m^2 • s))).

3 Results

3.1 Microclimate

The primary meteorological data during the main growth period of maize (experimental period, DOY160–260) are presented in Figure 5. Data on daily average air humidity and air temperature variations in the two years (Fig. 5a) revealed minimal divergence between the daily average temperature lines for the two years, suggesting a small average temperature difference. The daily average temperature remained stable in the early stages of maize growth and later showed a downward trend. Like average air humidity, the average air temperature for the two years showed minimal divergence. The daily average air humidity showed a gradual increase throughout the maize growth period. Precipitation and soil water content (represented by the parameter of soil water content at a depth of 10.00 cm (VWC10)) data indicated that VWC10 rapidly increased after precipitation, followed by slow reduction (Fig. 5b). In the PAR variation diagram, average PAR during daytime was around 900 mol photon/($m^2 \cdot s$), but during rainy weather PAR reduced rapidly (Fig. 5b and c).

3.2 Daily Patterns of CO Flux Under Drip and Flood Irrigation

The gas sample data collected over nine days at each maize growth stage are shown in Figures 6 and 7. Figure 6 presents data for 2020, while Figure 7 presents data for 2021. Daily data included variations in NPP, NEE, and Rs. Regarding NPP, the daily variation range shifted from small to large and then decreased during the entire growth period. Notably, peak NPP changes occurred on DOY217 and DOY219 in 2020 and 2021, respectively, aligning with the maize 14-leaf stage. Daily NPP variations showed initial increments followed by declines during daytime, but all values were positive, indicating that maize absorbed carbon and synthesized organic matter during daytime. At nighttime, daily NPP variations showed negative values and tended to reduce gradually, implying that maize respiration at nighttime consumed organic matter and exhaled CO . Like NPP, the daily NEE variation range during the whole growth period showed the trend of initial increase and then reduction, with the date of maximum variation range matching that for NPP (peak NEE changes occurred on DOY217 and DOY219 in 2020 and 2021, respectively). However, unlike NPP, a negative value of daily NEE variation during daytime suggested that the whole ecosystem was a carbon sink, while a positive value at nighttime indicated that the entire ecosystem was a carbon source. Rs, throughout the growth period, displayed an initial increase followed by reduction. Daily Rs variation also initially increased and then reduced; particularly, Rs initially increased and then decreased during daytime and decreased at nighttime.

As shown in Figures 6 and 7, the NEE variation curves within the drip irrigation zone during daytime predominantly fall below those of the flood irrigation zone (a smaller negative value of NEE indicates higher carbon absorption capacity). Additionally, the NPP variation curves in the drip irrigation zone generally showed a trend above those in the flood irrigation zone (a larger positive value of NPP indicates greater carbon absorption capacity). These findings imply that, compared with the flood irrigation zone, the maize ecosystem in the drip irrigation zone exhibits increased CO absorption during daytime. Conversely, during nighttime, the NEE variation curves in the drip irrigation zone were mostly positioned above those of the flood irrigation zone (a larger positive value of NEE indicates higher carbon emissions). Additionally, the NPP variation curves in most of the drip irrigation zone tended to be below those in the flood irrigation zone (a smaller negative value of NPP indicates greater carbon emissions). This indicates that, in contrast to the flood irrigation zone, the maize ecosystem in the drip irrigation zone emits more CO during nighttime. Regarding Rs, the daily variation curves of Rs in the drip irrigation zone during both daytime and nighttime consistently exceeded those in the flood irrigation zone, signifying higher carbon emissions in the drip irrigation zone than in the flood irrigation zone.

3.3 Relationships Between Light Response Parameters and Biological Factors

The light response parameters for each experimental day, α and $(\beta+\gamma)_{2000}$, were calculated using Equation 6 based on daily data from Figures 6 and 7. The variations in α and $(\beta+\gamma)_{2000}$ for each experimental day are illustrated in Figure 8. The α and $(\beta+\gamma)_{2000}$ values tended to increase initially, followed by subsequent decrease. In 2020, peak values for flood irrigation and drip irrigation were observed on DOY211, coinciding with the 14-leaf stage of maize growth period. At this stage, flood irrigation displayed α value of 0.106 (mol CO /($m^2 \cdot$ s))/(mol photon/($m^2 \cdot$ s)), while drip irrigation had slightly elevated values, with α at 0.113 (mol CO /($m^2 \cdot$ s))/(mol photon/($m^2 \cdot$ s)) and $(\beta+\gamma)_{2000}$ at 52.743 mol CO /($m^2 \cdot$ s). Similarly, in 2021, both flood irrigation and drip irrigation reached their peak values on DOY213, aligning with the 14-leaf stage of maize growth period. At this point, flood irrigation exhibited α value of 0.112 (mol CO /($m^2 \cdot$ s))/(mol photon/($m^2 \cdot$ s)) and $(\beta+\gamma)_{2000}$ value of 50.852 mol CO /($m^2 \cdot$ s), while drip irrigation showed slightly higher values, with α at 0.116 (mol CO /($m^2 \cdot$ s))/(mol photon/($m^2 \cdot$ s)) and $(\beta+\gamma)_{2000}$ at 52.451 mol CO /($m^2 \cdot$ s). Furthermore, as shown in Figure 8, where a consistent trend was observed, for most dates the α and $(\beta+\gamma)_{2000}$ values in the drip irrigation zone surpassed those in the flood irrigation zone. This trend suggests higher efficiency in light utilization and carbon absorption within the maize canopy in the drip irrigation zone.

Figure 9 illustrates the relationship between main light response parameters and crop biological parameters. As shown in Figure 9a, there is a strong linear relationship between α and LAI. The slope of drip irrigation (0.043) was greater than that of flood irrigation (0.039), indicating that with crop growth, the α parameter of maize under drip irrigation increased more rapidly, thus favoring crop growth. The parameters of $(\beta+\gamma)_{2000}$ and AGB demonstrated a clear polynomial relationship (Fig. 9b). Comparing the polynomial curves of maize under drip irrigation and flood irrigation, it is apparent that the maximum value of the polynomial curve under drip irrigation surpassed that under flood irrigation. During the late growth stage of maize, compared with flood irrigation, the $(\beta + \gamma)_{2000}$ value of maize under drip irrigation was higher at the same AGB. Therefore, with increasing AGB, drip irrigation progressively played a more significant role in promoting crop growth.

3.4 Effects of Drip and Flood Irrigation on Maize Yield

The data in Table 1 illustrate AGB, crop growth rate (CGR), HI, yield, and average daily NEE ($NEE_{average}$) during the maize growth stage under drip and flood irrigation conditions across the two-year experiment. Figure 10 demonstrates the variations of AGB and CGR during different maize growth periods in 2020 and 2021. Notably, the AGB of maize maintained an increasing trend during the whole growth period in both 2020 and 2021, while CGR exhibited an initial increase followed by a decrease throughout the maize growth cycle in both years. Comparing the values in 2020 and 2021, maize AGB and maize CGR were greater under drip irrigation condition than under flood irrigation condition. The yield from drip irrigation was higher than that from flood irrigation. Specifically, in 2021, the yields from drip and flood irrigation were 887.5 and 753.2 g/m^2, respectively. In the preceding year, 2020, the yields from drip and flood irrigation stood at 917.7 and 745.3 g/m^2, respectively. Evidently, the yield in the drip irrigation zone consistently exceeded that in the flood irrigation zone. Additionally, the HI in the drip irrigation system was higher than that in the flood irrigation system. In 2021, the HI values under drip irrigation and flood irrigation were 0.51 and 0.49, respectively. Similarly, in 2020, the HI values for drip irrigation and flood irrigation conditions were 0.52 and 0.48, respectively. In 2021, the $NEE_{average}$ values under drip irrigation and flood irrigation conditions were -10.34 and -7.10 g C/(m$^2 \cdot$ d), respectively; in 2020, the $NEE_{average}$ under drip irrigation and flood irrigation conditions were -10.37 and -6.38 g C/(m$^2 \cdot$ d), respectively. Therefore, the maize plants cultivated under drip irrigation absorbed more CO from the atmosphere than those under flood irrigation.

4 Discussion

4.1 Daily Variations in NPP, NEE, and Soil Respiration (Rs) Under Drip and Flood Irrigation Conditions

Upon comparing the NPP, NEE, and Rs values of maize under both drip and flood irrigation conditions (Figs. 6 and 7), certain commonalities emerged in these parameters. Notably, for both irrigation techniques, the total soil CO emission displayed an initial increase followed by subsequent reduction during maize growth. This trend aligns with that reported in a previous study [**?**], which suggested that as maize develops, its root system develops, thereby escalating carbon emissions. The roots of crops are the major factors contributing to Rs [?, ?]. The observed changes in CO emission were evaluated. Moreover, the range of variation in daily NPP or NEE showed a pattern of initial increase and subsequent decrease, mirroring the daily fluctuations of maize carbon emission monitored through the eddy covariance technique [?]. This pattern likely emerged from the growth phase wherein leaf area and biomass begin to increase, and the extent of photosynthesis or respiration increases [?]. However, as maize approaches maturation, a senescence phase ensues, leading to reduction in photosynthesis and respiration rates [?].

The NPP, NEE, and Rs of maize under both irrigation conditions exhibit notable differences. Notably, soil CO emissions are higher under drip irrigation compared to flood irrigation (Figs. 6 and 7), which is consistent with findings by Zhang et al. [?] and Wei et al. [?]. Despite causing less soil disturbance, drip irrigation paradoxically results in higher CO emissions than flood irrigation. Pu et al. [?] suggest that the frequent alternation between dry and wet soil conditions under drip irrigation fosters microbial respiration and activity, thereby intensifying soil CO flux. In terms of CO absorption by the maize ecosystem, crops absorb a relatively higher amount of CO ($\text{NEE}_{average}$) under drip irrigation, indicating that within the entire maize ecosystem, drip irrigation promotes greater atmospheric CO fixation. Drip irrigation, known for its potential to significantly enhance the photosynthesis rate [?], inevitably leads to increased CO fixation. Additionally, by preserving soil aeration, drip irrigation fosters plant root growth, enhancing AGB and leaf area [?]. Leaf area plays a crucial role in NEE as it determines the photosynthetic surface area [?], which likely explains why drip irrigation fixes more CO than flood irrigation.

4.2 Maize Growth Variables and Light Response Parameters Under Drip and Flood Irrigation

Parameter α is a crucial factor that reflects light utilization and is closely associated with crop growth [?]. A higher α value signifies conditions more conducive to crop growth [?]. Multiple studies have established a strong correlation between crop α and LAI (Fig. 9a). For instance, Lindner et al. [?] identified a linear relationship of 0.91 between α and rice LAI. In this investigation, a similarly high correlation between α and LAI was observed ($R^2 = 0.85$ for drip irrigation and $R^2 = 0.83$ for flood irrigation). Comparing α and LAI relationships under flood irrigation and drip irrigation, it is evident that maize α under drip irrigation is higher at the same LAI level. This finding aligns with previous research [?], indicating that drip irrigation has the potential to significantly enhance photosynthesis rates.

The parameter $(\beta + \gamma)_{2000}$ is a significant indicator reflecting the maximum production capacity of crops. Peng et al. [?] revealed a polynomial relationship between the parameter $(\beta + \gamma)_{2000}$ and AGB. This study also demonstrated a polynomial relationship between this parameter and AGB (Fig. 9b). In the early growth stages, predominant growth occurred in stems and leaves, with leaves being the primary factor promoting photosynthesis [?]. Consequently,

$(\beta + \gamma)_{2000}$ exhibited an increasing trend. However, during the late growing season, both crop respiration and photosynthesis rates declined [?], leading to a reduction in $(\beta+\gamma)_{2000}$. Notably, during the late growing season, the $(\beta+\gamma)_{2000}$ parameter for maize under drip irrigation surpassed that under flood irrigation. This study further supports the notion that drip irrigation can significantly enhance photosynthesis rates [?].

4.3 Effect of Drip and Flood Irrigation on NEE, Aboveground Biomass (AGB), and Yield of Maize

Table 1 depicts the AGB and yield for flood and drip irrigation, and it is evident that under drip irrigation condition, the AGB during each growth period is higher. This outcome is consistent with the research of Umair et al. [?], which discovered that drip irrigation enhances the photosynthesis rate and stimulates plant root growth. Additionally, these results align with the findings of higher NPP under drip irrigation. NPP, denoting the net CO uptake by canopy, significantly influences CO flux into terrestrial biosphere [?, ?]. The yield under drip irrigation surpasses that under flood irrigation, consistent with the study of Tian et al. [?], which exhibited a significant increase in maize yield (by 28%) with drip irrigation compared to flood irrigation treatments. Fu et al. [?] and Leghari et al. [?] similarly found that drip irrigation improves water conservation and grain yield. This higher yield corresponds with the observed larger CGR (Fig. 10) and α (Fig. 8) under drip irrigation in this study.

5 Conclusions

This study delves into the carbon exchange and crop growth of maize under drip and flood irrigation conditions in the Hetao Irrigation District to investigate their effects. The findings suggest that drip irrigation accelerates crop growth and development while increasing yield more effectively than flood irrigation. Soil emissions are higher under drip irrigation, yet the ecosystem is more conducive to carbon fixation than under flood irrigation. Consequently, drip irrigation in this region appears more effective in reducing CO emissions and enhancing production. This research offers valuable insights for decision-making regarding maize irrigation methods in the Hetao Irrigation District in the future. However, it is important to note that this study has yet to consider the potentially significant effects of various trace elements present in the water sources used for these irrigation methods on carbon emissions and crop growth. Investigating the influence of waterborne trace elements on carbon emissions and crop growth represents a crucial avenue for future research.

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

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Note: Figure translations are in progress. See original paper for figures.