Carbon Dioxide Exchange in an Irrigated Agricultural Field within an Oasis, Northwest China

XI-BIN JI, WEN-ZHI ZHAO, ER-SI KANG, ZHI-HUI ZHANG, BO-WEN JIN, AND LI-WEN ZHAO

Linze Inland River Basin Comprehensive Research Station, Heihe Key Laboratory of Ecohydrology and Integrated River Basin Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science, Lanzhou, China

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ABSTRACT

Continuous eddy covariance measurements of CO₂, water vapor, and heat fluxes were obtained from a maize field within an oasis in northwest China from 1 May 2008 to 30 April 2009. The experimental setup used was shown to provide reliable flux estimates on the basis of cross-checks made using various quality tests of the flux data. Results show that the highest half-hourly CO₂ fluxes \( F_c \) were 255.7 and 6.9 \( \mu \text{mol m}^{-2} \text{s}^{-1} \) during the growing and nongrowing seasons, respectively. The daily net ecosystem exchange of carbon (NEE) ranged from −14.7 to 2.2 g C m\(^{-2}\) day\(^{-1}\) during the growing season; however, the daily NEE fell to between 0.2 and 2.1 g C m\(^{-2}\) day\(^{-1}\) during the nongrowing season. The annual NEE calculated by integrating flux measurements and filling in missing and spurious data was about −487.9 g C m\(^{-2}\). The total NEE during the growing season (−692.9 g C m\(^{-2}\)) and the annual NEE were in the middle of the range, when compared with results obtained for maize fields in different studies and regions, whereas the differences between the off-season NEE from this study (205.0 g C m\(^{-2}\)) and those defined in previous studies were very small. In addition, the seasonal variations in energy balance and evapotranspiration over the maize field were also addressed.

1. Introduction

Micrometeorological measurements of the net exchange of carbon dioxide (CO₂), water vapor, and energy between terrestrial ecosystems and the atmosphere are now being made routinely at sites worldwide (e.g., the AmeriFlux, EuroFlux, and AsiaFlux networks) to determine the role of terrestrial ecosystems in the global carbon cycle (Baldocchi et al. 2001; Anthoni et al. 2004). Cropoland represents about 12% of the earth’s surface (Wood et al. 2000; Verma et al. 2005) and, in general, can have equal or greater net ecosystem production (NEP) than the natural ecosystems that were converted for crop production (Law et al. 2002; Barford et al. 2001; Hollinger et al. 2004). The eddy covariance method has become the predominant means of measuring carbon dioxide, water vapor, and heat exchange at these flux sites all over the world (Baldocchi et al. 2001; Law and Verma 2004; Foken 2008, 105–161). However, studies of some ecosystem types are still underrepresented in the literature. Most of the agricultural eddy covariance sites studies are in humid and subhumid temperate climate zones (Anthoni et al. 2004; Hollinger et al. 2005; Verma et al. 2005; Yu et al. 2006). To date, the year-round net ecosystem exchange (NEE) of carbon dioxide flux in the agroecosystems of northwest China's arid inland area has not been investigated.

The arid inland area of northwest China consists of various relatively independent inland river basins (Kang et al. 1999, 2007). The Heihe River basin is the second largest inland river basin in northwest China, covering an area of \( 13 \times 10^4 \) km\(^2\). The limited water resources from the mountains in the upper-stream area are collectively utilized in the artificial oases in the middle-stream plain area, where irrigation agriculture is very well developed, forming a farmland vegetation ecosystem. Although the irrigated agricultural ecosystem represents only 17% of the Heihe River basin, it plays a dominant role in the carbon cycle of the entire basin. For example, the irrigated ecosystem, which functions as an artificial oasis, represents about 75% of the total net primary productivity, or

Corresponding author address: Xibin Ji, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Science, No. 320 Donggang West Road, Lanzhou, 730000, China.

E-mail: xuanzhij@ns.lzb.ac.cn

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approximately 13.6 Tg C yr\(^{-1}\) (Kang et al. 2007). This productivity is a result of the flat topography, good photothermal conditions, and widespread irrigation systems. The agricultural ecosystem of the Heihe River basin oasis area is dominated by maize and is relatively homogenous; consequently, it is a model ecosystem for estimating the carbon dioxide exchange between the agricultural ecosystems and the atmosphere. Even so, there are no published long-term studies that address the annual carbon dioxide exchange for the agricultural ecosystem within the oasis in the middle stream of Heihe River basin.

The general aims of this study are 1) to assess and control the quality of the flux data, 2) to determine the diurnal and seasonal variation in the NEE of the irrigated agricultural field in the arid region, and 3) to compare the NEE measured values (eddy covariance method) with values obtained by other researchers working in maize agroecosystems in different regions.

2. Methods

a. Site description

This work was conducted over maize fields at an agricultural experimental water-saving plot (1 km \(\times\) 1 km) of the Linze Inland River Basin Comprehensive Research Station (39°19′38″N, 100°08′27″E, elevation 1365 m). The research station is part of the Chinese Ecosystem Research Network, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. The site is located in the middle portion of the Zhangye irrigated oases in the middle stream of the Heihe River basin, northwest China. The terrain and field site are ideal for micrometeorological flux measurements because the terrain is relatively flat (the mean slope ranged between 2.1% and 4.5%) and the maize canopy extends over approximately 0.5 km in all directions.

The site has a typical continental arid climate: dry and hot in summer, cold in winter. The water vapor originates mainly from the southeast summer monsoon that comes from the Pacific Ocean and the southwest summer monsoon that comes from the Indian Ocean, as well as from westerly air flows (Kang et al. 2007). The mean annual air temperature is about 7.6°C, with an absolute maximum of 39.1°C and an absolute minimum of \(-27.3°C\). Mean annual precipitation is 117 mm, nearly 70% of which falls between July and September. Average annual pan evaporation is 2390 mm. The mean annual wind velocity is 3.2 m s\(^{-1}\), and the prevailing wind direction is northwest. The soil is a sandy loam. Soil organic matter and pH value are 0.72% and 8.86, respectively.

The surface irrigation districts account for 95% of the total irrigation area, and border irrigation is the primary surface irrigation method. During the 1-yr period from 1 May 2008 to 30 April 2009, nine irrigation events applied 1050 mm of water to the area. Fertilizer was applied at a rate of 326 kg N ha\(^{-1}\), 27 kg P\(_2\)O\(_5\) ha\(^{-1}\), and 17 kg K ha\(^{-1}\), respectively, during the 2008 growing season. The maize was sown on 29 April 2008 and harvested on 7 October 2008. During the growing season, the maximum maize height and value of the leaf area index were 1.8 m and 4.85, respectively.

b. Field measurements

Continuous measurements were made at the study site beginning around maize planting time in 2008 (26 April 2008). The eddy covariance technique was used to measure fluctuations in wind speed, temperature, carbon dioxide and water vapor above the canopy. A three-dimensional (3D) sonic anemometer (HS-50, Gill Solent Instruments, Lymington, Hampshire, United Kingdom) and an open-path infrared gas analyzer (LI-7500, Li-Cor, Inc., Lincoln, Nebraska) were used for the measurements. Vertical fluxes of momentum, sensible heat, carbon dioxide, and water vapor were determined using the 3D sonic anemometer to sample the three components of wind speed \((u, v, w)\) and virtual acoustic temperature. The measurement of water vapor and carbon dioxide mole densities above the crop field were made using the open-path infrared gas analyzer.

Fast response sensors of the sonic anemometer and the open-path infrared gas analyzer mounted at a height of 4.5 m above the ground. The open sides of the asymmetric sonic anemometer were exposed to the northwest at the experimental plot. Data were recorded on a personal computer inside a small hut, 50 m from the eddy covariance tower. The sampling frequency was 20 Hz. Estimates of the flux footprint indicated that under average conditions 90% of the flux came from within 360 m of the eddy covariance tower. The energy balance closure deficit was likely to be small as the annual value of energy balance ratio \([\Sigma(\lambda E + H)/\Sigma(R_n - G - S)]\) was 92.6%, where \(R_n\) is net radiation; \(\lambda E\), \(H\), and \(G\) are latent, sensible, soil heat fluxes; and \(S\) is the rate of change of heat storage (air and biomass) between the soil surface and the level of the eddy covariance instrumentation.

An ENVIS Environmental Monitoring System (IMKO GmbH, Ettlingen, Germany) was mounted at a distance of about 60 m from the eddy covariance tower. Net radiation and photosynthetically active radiation (PAR) were measured by a CNR-1 net radiometer (Kipp and Zonen, Delft, The Netherlands) and an LI-190 quantum sensor (Li-Cor, Inc.) above the canopy at a height of 2 m, respectively. Measurements of air temperature, relative humidity, air pressure, and wind speed and direction were made at the top of the canopy and 2 m above the canopy.
using an HMP45D temperature probe and relative humidity probe (Vaisala, Helsinki, Finland), a PTB100 barometer probe (Vaisala), LISA cup anemometer (Sigelkow GmbH, Hamburg, Germany), and a wind indicator Young 8100 (Sigelkow), respectively. Mean wind speed and direction can also be derived from the sonic anemometer output: the agreement between the cup and ultrasonic anemometers was found to be excellent most of the time. Canopy temperature was measured with a PS12AF1 surface pyrometer (Keller HCM GmbH, Ibbenbüren-Laggenbeck, Germany) at a height of 2 m above the canopy. Soil temperature and volumetric soil water content were measured with a Pt100 sensor (IMKO) and a time domain reflectometer TRIME-IT (IMKO), respectively. Soil temperature was measured at depths of 5, 10, 20, 40, 80 and 120 cm within the soil. Soil moisture was measured at depths of 10, 20, 50, 100, 200, 300 cm within the soil. Soil heat fluxes were measured using an HFP01 plane probe (Hukseflux Thermal Sensors, Delft, the Netherlands) and three replicate heat flux plates at 0.05 m. Precipitation was measured with RG 50 tipping-bucket rainfall gauges (SEBA Hydrometrie GmbH, Gewerbestr, Germany). All abovementioned data were measured every 10 min, averaged every 30 min, and recorded on a TRIME logger (IMKO).

c. Data processing and gap filling

All raw data were saved to the hard disk of a personal computer using the EDDYMEAS software package (Kolle and Rebmann 2007) with postprocessing software EDDYSOFT (Kolle and Rebmann 2007). Mean half-hourly eddy fluxes over the crop field were calculated as the covariance between the vertical wind speed and the scalar signals using a block averaging method. A two-dimensional (2D) coordinate rotation was applied to force the average vertical wind speed \( w \) to zero and to align the horizontal wind \( u \) to mean wind direction. The instrument effects that damp the high-frequency fluctuations including the dynamic frequency response of the sonic anemometer and infrared gas analyzer, the scalar path averaging, and the sensor separation were corrected in accordance with the method described by Moore (1986). Both the \( CO_2 \) flux and latent heat flux were corrected for density effects using the method described by Webb et al. (1980). On the basis of Burba et al. (2008), correction was also made for the influence of instrument surface heat exchange from the LI-7500 open-path gas analyzer on the \( CO_2 \) flux measurements.

NEE was the sum of the turbulent \( CO_2 \) flux and an estimate of the flux from \( CO_2 \) storage between the ground surface and the eddy covariance measurement height at 4.5 m above the ground. This storage term was computed from the difference in \( CO_2 \) mole mixing ratio for the 30-min periods before and after the flux measurements using only the measurement height. To minimize problems associated with insufficient turbulent mixing at night, the effect of low friction velocity \( u_* \) on nighttime NEE was examined as described by Reichstein et al. (2005). When the value of \( u_* \) was below 0.15 m s\(^{-1}\) (the maximum \( u_* \) threshold), the observed nighttime NEE values (solar radiation less than 10 W m\(^{-2}\)) were discarded. Positive fluxes indicate mass and energy transfer from the surface to the atmosphere; negative flux densities represent the reverse.

The eddy covariance technique is limited by when measurements are missing or rejected as a result of system failures, maintenance and calibration, and weather conditions. In total, 16% of the NEE data were rejected, with 60% of the missing values occurring at night. Gaps in data were filled using several approaches. Short data gaps of 2 h or less were populated by means of linear interpolation. Large daytime gaps during the growing season were filled using a nonlinear exponential regression, referred to as the Misterlich function, and described in Falge et al. (2001); the missing nighttime NEE were estimated as a function of soil temperature and soil moisture (Reichstein et al. 2002).

3. Results

a. Quality test of the flux data

Two different tests were performed to check the overall system reliability of the flux measurements: integral turbulence characteristics and spectral analysis. Foken and Wichura (1996) proposed to use the Monin-Obukhov (MO) similarity relations as a quality test for eddy covariance measurements. In particular, the similarity relations for the vertical velocity and temperature standard deviations are considered. According to Kaimal and Finnigan (1994), for unstable and near-neutral conditions, these are given as

\[
\frac{\sigma_w}{u_*} = a_1 [1 + 3(z_m - d)/L]^{1/3} \quad \text{and} \quad \frac{\sigma_T}{T_w} = a_2 [1 + 9.5(z_m - d)/L]^{5/3},
\]

where \( \sigma_w \) and \( \sigma_T \) are the standard deviation of vertical wind velocity and air temperature fluctuations, respectively; \( u_* \) is the friction velocity; \( T_w = -wTr'/u_* \); \( z_m \) is the measurement height; \( d \) is the displacement height; \( L \) is the Obukhov stability length; and \( a_1, b_1, a_2, \) and \( b_2 \) are empirical coefficients. The nonlinear least squares determined values for the coefficients \( a_1 (a_1 = 1.22), b_1 (b_1 = 0.31 \approx 1/3), a_2 (a_2 = 2.5), \) and \( b_2 (b_2 = -0.34 \approx -1/3) \) that were close to the most frequently
reported values (1.25, 1/3, 2, and −1/3, respectively) for flat terrain (Kaimal and Finnigan 1994).

This MO test characterizes whether turbulence is well developed according to the similarity theory of turbulent fluctuations. Essentially, it gives information on the site and setup. This test cannot, however, be used for scalar fluxes in neutral conditions because the ratio $\sigma_f/T_u$ is affected by excessive relative errors. To remove $\sigma_f/T_u$ data measured under neutral conditions, the data for the sensible heat flux density with values larger than 100 W m$^{-2}$ were selected (Aubinet et al. 2001). All daily measurements between May 2008 and April 2009 were considered for $\sigma_w/u_u$. The standard deviation of $\sigma_f/T_u$ and $\sigma_w/u_u$ according to the atmospheric stability, $(z_m - d)/L$, can be seen in Fig. 1. In all cases, the agreement between the measured values and the theoretical prediction is satisfying ($R^2 \geq 0.91$). The agreement of vertical velocity standard deviation with theoretical predictions suggests that the measurements were not affected by additional mechanical turbulence due to obstacles or instrumental distortion. The agreement of measurement temperature standard deviation with the theoretical values also suggests that heterogeneous surface temperature conditions have little impact on the data. This suggests that our measurements are valid and representative of the site.

Spectral analyses of measured turbulent fluctuations provide a useful tool for assessing the reliability of our flux measurements. We generated power spectra $[S_x(f)]$ and cospectra $[C_{wx}(f)]$ of measured fluctuations in the fluctuating wind velocity components along the longitudinal ($x$), lateral ($y$), and vertical directions ($w$), and CO2, H2O, and temperature $T$ by averaging the spectral coefficients from 8 half-hourly data segments on a sunny day (1 July 2008), each with 36,000 data points. The power spectra of $u$, $v$, $w$, and $T$, CO2, and H2O exhibited an inertial subrange with the expected slope of $−2/3$ (Fig. 2). The results suggested that the instrument
effects, including the dynamic frequency response of the sonic anemometer and of the infrared gas analyzer, and the scalar path averaging did not obviously damp the high-frequency fluctuations. The cospectrum of vertical wind speed with $T$ decreases at an inertial subrange following the expected slope of $-4/3$ (Fig. 3). The good agreement of the heat cospectrum behavior also confirms the good quality of the measurements. On the other hand, the steeper decrease with frequency of the cospectra of vertical wind speed $w$ with the CO$_2$ and H$_2$O at inertial subrange reveals that the sensor response mismatch and sensor separation did dampen the high-frequency fluctuations somewhat (Fig. 3). Consequently, we corrected the fluxes for this systematic error using the Moore (1986) method.

b. Meteorological information, soil water, and leaf area index

Air and soil temperatures ($T_a$ at 6 m height; $T_s$ at 0.1 m depth), PAR, precipitation $P$, irrigation $I$, soil water (top 1.0 m), and leaf area index (LAI) are included in Table 1. During the 2008 maize growing season, after the maize was sown (on 29 April; the maize ripened beginning in early October and was harvested on 7 October), the climate conditions in the study area were sunny and warm, giving favorable conditions for good plant development. Sufficient water was maintained: the monthly mean volumetric soil water content averaged between 0.28 and 0.30 m$^3$ m$^{-3}$ throughout the growing seasons. In winter, freezing occurred in the topsoil from the end of November 2008 to mid-March. Although the soil moisture during the winter was less than that observed during other periods, note that the time domain reflectometer (TDR) probe measures liquid water in soil, not for solid water. Thus, the observed soil moisture increased when the weather became warmer at the end of March 2009 and the soil began to thaw because of the thawing of the frozen water in the soil. The peak green LAI was 5.1 during the 2008 growing season.

c. Energy flux and evapotranspiration

The monthly ensemble mean values of the diurnal patterns of the net radiation $R_n$, soil heat flux $G$, sensible heat flux $H$, and latent heat flux $\lambda E$ throughout the year are shown in Fig. 4. These fluxes exhibited a similar diurnal pattern (a roughly parabolic pattern) reaching

![Fig. 3. Mean cospectra ($C_{wx}$) of vertical wind speed $w$ and variable $x$ where $x$ is the sonic air temperature $T$, CO$_2$, and H$_2$O above the canopy for 8 half-hour periods from 0830 to 1230 (local time) 1 Jul 2008. The $C_{wx}$ were multiplied by frequency $f$ and normalized by the covariance between $w$ and $x$. The solid line is the $-4/3$ slope expected in the surface layer inertial subrange.](http://journals.ametsoc.org/jamc/article-pdf/50/11/2298/3558574/2011jamc2614_1.pdf)

<table>
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<tr>
<th>Year</th>
<th>Month</th>
<th>$T_a$ ($^\circ$C)$^a$</th>
<th>$T_s$ ($^\circ$C)$^b$</th>
<th>PAR (µmol m$^{-2}$ s$^{-1}$)</th>
<th>$P$ (mm)</th>
<th>$I$ (mm)</th>
<th>$\theta$ (m$^3$ m$^{-3}$)$^c$</th>
<th>LAI (m$^2$ m$^{-2}$)</th>
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<td>18.8</td>
<td>20.6</td>
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<td>3.6</td>
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<td>21.7</td>
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<td>16.8</td>
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<td>25.4</td>
<td>105</td>
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<td>10.7</td>
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$^a$ Air temperature $T_a$ at 6-m depth.

$^b$ Soil temperature $T_s$ at 0.1-m depth.

$^c$ Soil volumetric water content $\theta$ in top 1 m.
Fig. 4. Monthly ensemble mean values in half-hourly energy balance showing the diurnal variation throughout the year (May 2009 to April 2009).
the maximum values around noon, with the half-hour values also being quite similar during the maize growing (from May through September 2008) and nongrowing season (from October 2008 through April 2009). The daytime (defined as that period for which the incident solar radiation exceeded 100 W m\(^{-2}\)) mean \(R_n\) over the growing season varied from 354.3 (May) to 445.2 W m\(^{-2}\) (June), for a mean of 405.0 W m\(^{-2}\). In contrast, the daytime mean \(R_n\) over the nongrowing season were less than that over the growing season, and varied from 206.3 (December) to 333.3 W m\(^{-2}\) (October), for a mean of 273.0 W m\(^{-2}\).

Note that the proportions of \(R_n\), partitioned into \(H\), \(\lambda E\), and \(G\) demonstrated a significant seasonal difference for various months as a result of variation in solar radiation, soil moisture and crop development. For example, the daytime mean \(G\) were 104.8 W m\(^{-2}\) or 29.5% of \(R_n\) during the maize early growing season (May) and 72.4 W m\(^{-2}\) or 25.9% of \(R_n\) during the nongrowing season (varied from 31.1 W m\(^{-2}\), 11.1% of \(R_n\), in November 2008 to 124.1 W m\(^{-2}\), 38.5% of \(R_n\), in April 2009), respectively. The daytime mean \(G\) during the middle (from June through August) and late growing season (September) was 68.5 W m\(^{-2}\) or 16.4% of \(R_n\) and varied from 46.4 W m\(^{-2}\) (11.6% of \(R_n\); July) to 78.8 W m\(^{-2}\) (18.5% of \(R_n\); June). This is greatly due to crop development—the denser canopy with larger LAI reduces the solar radiation that reaches the soil surface during the middle and late growing season. The sensible heat flux represented the major energy term during the nongrowing and the early growing season (Fig. 4). The daytime mean \(H\) were about 145.3 W m\(^{-2}\) or 41.0% of \(R_n\) in May 2008 and 123.9 W m\(^{-2}\) or 45.6% of \(R_n\) (varied from 97.3 W m\(^{-2}\), 47.2% of \(R_n\), in December to 151.1 W m\(^{-2}\), 45.3% of \(R_n\), in October). In contrast, the daytime mean \(H\) was 80.5 W m\(^{-2}\) or 19.4% of \(R_n\) during the middle and late growing season and varied from 53.3 W m\(^{-2}\) (13.3% of \(R_n\); July) to 124.2 W m\(^{-2}\) (31.1% of \(R_n\); September). The portion of \(R_n\) partitioned into \(H\) (daytime means) was lower during the middle and late growing season than during the other periods of the year, indicative of the lower vertical air temperature gradients. The latent heat fluxes (daytime means) were substantially greater during the growing season (from May through September 2008) than during the nongrowing season (from October 2008 through April 2009). The daytime mean \(\lambda E\) were 221.0 W m\(^{-2}\) or 53.8% of \(R_n\) (varied from 104.6 W m\(^{-2}\), 29.5% of \(R_n\), in May to 300.7 W m\(^{-2}\), 75.0% of \(R_n\), in July) during the growing season and 32.6 W m\(^{-2}\) or 11.5% of \(R_n\) (varied from 13.2 W m\(^{-2}\), 6.1% of \(R_n\), in January to 68.2 W m\(^{-2}\), 20.5% of \(R_n\), in October) during the nongrowing season, respectively. This indicates that evapotranspiration was relatively stronger during the growing season, owing to the higher potential atmospheric forcing factors (i.e., higher solar radiation and air temperature) and well-watered conditions (pertinent environmental, plant, and soil data are provided in Table 1) with nine irrigation events supplying 1050 mm of water.

The half-hourly water vapor fluxes have been summed to daily (24 h) evapotranspiration (ET) estimates, and its units were converted from millimoles per meter squared per second to millimeters per day (expressed as millimeters of evapotranspiration). The seasonal variation in ET over the maize field is shown in Fig. 5a, and it was expected to increase at an exponential rate with increasing net radiation (Fig. 5b). The daily mean ET were 3.51 mm day\(^{-1}\) (ranged from 0.43 to 7.08 mm day\(^{-1}\)) during the growing season and 0.46 mm day\(^{-1}\) (ranged from 0.02 to 1.47 mm day\(^{-1}\)), respectively. The cumulative ET were 561.62 mm during the growing season and 94.38 mm during the nongrowing season, respectively, and the ratio ET to the sum of irrigation \(I\) and precipitation \(P\) were about 0.58 and 0.57. This implied that the magnitude of the deep seepage loss, on average, was a relatively large portion of water budget in the maize field and that waste of water in the agricultural
system should be minimized by adopting effective water-saving irrigation techniques instead of the surface irrigation in use currently.

d. **Net ecosystem exchange during the growing season**

The diurnal variation in NEE was analyzed by calculating half-hourly ensemble mean values for the carbon dioxide exchange of the agroecosystem (between the maize field and the atmosphere). The dataset presented during the maize growing season was divided into five parts, one for each of the months from May through September. Figure 6 shows the diurnal course of CO$_2$ flux for each month. During the daytime, the leaf assimilation onset induces CO$_2$ flux to become negative and the maize field behaves as a large CO$_2$ sink. The maize field becomes a CO$_2$ source during the nocturnal period (because of respiration from plant, soil, and roots). The monthly ensemble mean value of the net CO$_2$ uptake in July (the peak growing season) were by far the highest throughout the growing season and reached up to 8.6 µmol m$^{-2}$ s$^{-1}$ with the maximum values of 35.4 µmol m$^{-2}$ s$^{-1}$ in the daytime (peak half-hourly CO$_2$ flux was $-55.7$ µmol m$^{-2}$ s$^{-1}$). In May, the ecosystem behaved as a small CO$_2$ source with a mean CO$_2$ flux of 0.8 µmol m$^{-2}$ s$^{-1}$ and a peak CO$_2$ uptake of 2.8 µmol m$^{-2}$ s$^{-1}$; these values are a result of the small LAI for the young maize plants. Later in the growing season (e.g., September) the net CO$_2$ uptake decreased sharply; this may be due to the decrease in PAR and LAI. In a few cases, the release of stored CO$_2$ in the morning hours was observed following nights with very stable conditions.

Figure 7 shows the NEE of the agroecosystem (between the maize field and the atmosphere) during the growing season; half-hourly fluxes have been summed to daily (24 h) NEE estimates. The seasonally NEE ranged from 2.2 to $-14.7$ g C m$^{-2}$ day$^{-1}$ and was controlled, to a certain extent, by green LAI. For example, during the initial maize growing season (May 2008), the LAI was only 0.13 m$^2$ m$^{-2}$ (Table 1), much lower than later growing season (September 2008), when it was 2.29 m$^2$ m$^{-2}$. The mean daily NEE of 1.0 g C m$^{-2}$ day$^{-1}$ was much higher than the mean daily NEE in the late stage (September 2008) of the maize growing season.
(−1.9 g C m⁻² day⁻¹), despite the fact that the air temperature and PAR in May were higher than those in September. The maize field was a source of carbon, with a maximal rate of emission of about 2.2 g C m⁻² day⁻¹, during the early growing season. The positive NEE values, which indicate the respiration rate was higher than the assimilation rate, were observed for a few days. Except for the initial and end stages of the maize growing season, the maize field absorbed CO₂ and acted as carbon sink; the maximal rate of net carbon uptake by the canopy was 14.7 g C m⁻² day⁻¹ in mid-July. Over the entire growing season (160 days), the net carbon NEE of the irrigated maize ecosystem in this study region was −692.9 g C m⁻².

e. Net ecosystem exchange during the nongrowing season

The monthly ensemble mean values of the diurnal variation in NEE during the nongrowing season are shown in Fig. 8. The results indicate that the maize field was a weak source of CO₂ during the nongrowing season, and that emissions were primarily controlled by soil temperature. The diurnal variation in NEE exhibited an approximately reverse parabolic pattern, reaching the maximum value near midday, with lower values in the morning, afternoon, and night, depending on solar radiation. The highest soil CO₂ efflux rates were observed in October 2008, probably because of warm temperatures in October combined with the residual crop biomass. The maximum monthly ensemble mean value for the NEE was about 3.1 µmol m⁻² s⁻¹ with a maximum peak half-hourly NEE of 6.9 µmol m⁻² s⁻¹. However, during the winter (December 2008, January and February 2009), after the soil had frozen, the diurnal variation in NEE showed no significant patterns that could be related to soil or air temperature, and the agroecosystem displayed weak emission rates.

Figure 9 shows the seasonal variation in NEE of the agroecosystem during the nongrowing season. In general, the agroecosystem was a weak source of carbon, and the soil CO₂ efflux depended on the soil temperature. The values of the daily NEE during the nongrowing season ranged from 0.2 to 2.4 g C m⁻² day⁻¹; here, we estimated that the accumulated NEE nongrowing season (205 days) in the agroecosystem was 205.0 g C m⁻². During the winter when the soil was frozen,
the mean NEE was 0.6 g C m⁻² day⁻¹, obviously lower than the mean NEE in autumn (1.5 g C m⁻² day⁻¹; October and November 2008) and in spring (1.0 g C m⁻² day⁻¹; February–April 2009).

f. Carbon dioxide flux response to canopy conductance

The canopy conductance $g_c$ was calculated using an inverted Penman–Monteith big leaf model (Monteith and Unsworth 1990). Figure 10 shows the relationship between $F_c$ and $g_c$ (the daytime data were selected for period of the growing season). Data suggest that the increase in absolute values of $F_c$ with increasing $g_c$ is clear, which indicates that the variation in $F_c$ was partly due to stomatal closure.

g. Comparison of NEE with other maize studies

The annual NEE in our study, $-487.9$ g C m⁻², and the nongrowing-season NEE, 205.0 g C m⁻², were both in the middle of the ranges of results observed for maize in different studies and regions (Table 2). Nevertheless, the integrated NEE for growing season from our results was 187.5 g C m⁻² less than a maize field in Illinois ($-880.4$ g C m⁻²): this is probably due to differences in cropping systems, climatic condition and field management.

However, the integrated apparent net ecosystem uptake for the growing season from our studied results was substantially larger than that obtained by Li et al. (2006) for the maize/wheat rotation ecosystem of the North China Plain. This difference is explained by the much shorter growing season of the summer maize (102 days) and the lower photosynthetic capacity of the fields in the Li et al. (2006) study (maximum daily NEE were $-10.2$ and $-12.5$ g C m⁻² day⁻¹ in the years 2002/03 and 2003/04, respectively). However, during the nongrowing season, the differences between our NEE results and those from other studies were small because of the smaller amount of agroecosystem respiration, as compared with net ecosystem uptake for the growing season.

4. Conclusions

The eddy covariance system provides reliable CO₂ exchange estimates for the maize agroecosystem within the artificial oases of northwest China, as shown by cross-checks of data using integral turbulence characteristics and spectral analysis. The results from this study show that the annual NEE in our study, $-487.9$ g C m⁻², was in the middle of the range when compared with results obtained for maize fields in different studies and regions. In addition, the observations of energy balance indicate that the latent heat flux (221.0 W m⁻² or 53.8% of $R_n$), on average, was substantially more than sensible heat flux (daytime means; 93.4 W m⁻² or 23.7% of $R_n$) during the growing season and sensible heat flux (daytime means, 123.9 W m⁻² or 45.6% of $R_n$) represented the major energy term during the nongrowing season. The cumulative annual ET were 656.0 mm, constituted of a nearly

<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Crop</th>
<th>Net carbon uptake (g C m⁻² day⁻¹)</th>
<th>Growing-season NEE (g C m⁻²)</th>
<th>Nongrowing-season NEE (g C m⁻²)</th>
<th>Annual NEE (g C m⁻²)</th>
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<td>$-692.9$</td>
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equal proportion of the sum of irrigation (1050.0 mm) and precipitation (90.7 mm) at 57.5%. This implied that the magnitude of the deep seepage loss was a relatively large portion of water budget in the maize field.

Further refinements are necessary to estimate the NEE uncertainty, including improving the friction velocity correction, gap filling technique, Webb–Pearman–Leuning correction, energy balance closure, and so on. This could improve the performance of the eddy covariance technique to measure CO2, water and energy fluxes with better accuracy in the irrigated maize agroecosystem in the arid region of northwest China. Furthermore, future studies are also needed to partition the measured canopy mass and energy fluxes into plant and soil components using eco-physiological, micrometeorological, and biogeochemical approaches to examine environmental control and feedback on mass and energy exchange in this region.

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REFERENCES


