Agricultural Water Management 281 (2023) 108235

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Eddy covariance quantification of carbon and water dynamics in twin-row vs. single-row planted corn

Saseendran S. Anapalli [a,*], Srinivasa N. Pinnamaneni [b], Daryl R. Chastain [a], Krishna N. Reddy [b], Clyde Douglas Simmons, III [c]

[a] Sustainable Water Management Research Unit, USDA ARS, Stoneville, MS 38776, USA
[b] Crop Production Systems Research Unit, USDA-ARS, Stoneville, MS 38776, USA
[c] Research Chairman, Delta Council, 3215 Tribbet Road, Leland, MS 38776, USA

ARTICLE INFO

Handling Editor - Dr. B.E. Clothier

Keywords:
Water productivity
Aquifers
Groundwater
Irrigated agriculture
Evapotranspiration
Consumptive water use

ABSTRACT

For sustainable irrigated crop production, enhancing the productivity of pumped water from aquifers, which are fast declining, is critical. In this investigation, the yield and water use efficiency (WUE) of corn planted in a single-row (SR) on a raised-bed ridge-furrow system was compared with corn planted in a twin-row (TR) pattern. The crop's consumptive water use (evapotranspiration, ET) was quantified using the eddy covariance (EC) technology. The crops for the investigation were raised on large-scale farmer's fields (above 100 ha). In the EC system, CO_2 and water vapor fluxes over corn plant canopies were monitored using an infrared gas analyzer, and wind turbulence was quantified using an omnidirectional 3D sonic anemometer. The LAI, grain yield, ET, net ecosystem exchange of CO_2 (NEE), and gross primary productivity (GPP) measured under TR were higher than SR by 18%, 19%, 22%, 90%, and 41%, respectively. Also, WUE in NEE (WUE_{NE}, ratio of NEE to ET) was higher under TR than SR by 40%, rendering TR the best choice for corn planting in the region. WUE for grain yield (WUE_{GY}, ratio of grain yield to ET) and net ecosystem respiration did not differ appreciably across TR and SR systems. The measured ET in TR was 518 mm, while SR was 426 mm during the crop season (emergence to physiological maturity). The study conducted in large-scale farm fields gives better confidence than results obtained based on conventional small-plot studies recommending the TR over SR planting in the region for grain yield and WUE_{NE} in corn production systems.

1. Introduction

For optimizing crop production from available resources, distributing plants equidistant over the given land area is critical for reducing inter-plant competition for nutrients, water, and light in the land-atmosphere environment for growth. In the raised-bed or ridges in the furrow-ridge configuration of planting crops, narrowing row widths has been considered a feasible way to achieve more plants per unit area of land, thereby increasing crop productivity from available resources (Bruns et al., 2012). However, when higher plant densities carry a potential for enhanced crop yields, in mechanized agriculture with drive-through planters, cultivators, harvesters, and other equipment, neither equidistant planting nor planting of the whole land area is feasible (Bruns et al., 2012; Kurt et al., 2017; Liang and Yoshihira, 2022).

In corn cropping systems practiced in the USA, planting with interrow spacing less than 76 cm (30-in) was not considered feasible due to difficulties in operating drive-through planters and harvester operations for crop management (Grichar, 2007; Bruns et al., 2011a). It was estimated that in a 76-cm row-spacing corn production system, only about 14.5% of the land area is planted for the crop. The rest is used for operating mobile equipment for planting, cultivating, and harvesting (Mahanna and Thomaks, 2015). However, in attempts to enhance planting density, planting corn on 76-cm row spacing with 15 cm apart twin rows (centered at 76 cm) failed to improve corn yield at multiple locations in the USA (Kratochvil and Taylor, 2005). For similar reasons and problems related to soil and climate, mostly, corn in the Lower Mississippi Delta region of the USA (LMD) was planted in row spacings 97 cm (38 in) or 102 cm (40 in) (Bruns, a, b, 2011).

The LMD is an important row-crop production region in the USA, and soybean, cotton, corn, and rice are favored crops. Inter-row spacing in vogue in this region was 97 and 102 cm. The Mississippi River Valley

* Corresponding author.
E-mail address: Saseendran.anapalli@usda.gov (S.S. Anapalli).

https://doi.org/10.1016/j.agwat.2023.108235
Received 22 December 2022; Received in revised form 9 February 2023; Accepted 15 February 2023

Aquifer underlying this area is being exploited beyond its recharge capacities for irrigating crops, which led to the fast decline of this shallow aquifer (Yasarer et al., 2020). Enhancing crop yields with minimum pumping from the aquifer has been an emphasis in the region for sustainable irrigated crop production (Anapalli et al., 2022a; b; Pinnamaneni et al., 2020a; b). Planting crops in twin rows, in which the rows are 15–20 cm apart, replacing the SR on raised-ridge seedbeds in the ridge-furrow system has been recognized for boosting yields and economic returns in the region (Bruns et al., 2011a,b; Smith et al., 2019; Pinnamaneni et al., 2020a; b). In the region, the 15–38 cm apart TR cropping system with 97–102 cm inter-row spacing is more accepted as a profitable planting system than narrow rows with inter-row spacing below 76 cm -row spacing (Stephenson et al., 2011). Farmers often find the twin-row system more advantageous for their net returns than switching to narrow-row systems. Planting crops in twin rows on the same seedbed was more economical than narrow-row cropping because the planter was the only piece of equipment needed to be replaced. Moreover, the same sprayer and corn head can be used for wider rows. Twin rows, like narrow rows, have also been touted as providing improved weed control (quicker soil shading) and increased grain yield (Stephenson and Brecke, 2010; Bruns, 2011a).

The TR planting in cotton was advantageous in closing the canopy earlier and controlling weeds by about 35%, enhancing lint yield by 23% in the LMD (Reddy and Boykin, 2010). Early LAI development with canopy closure was reported as another advantage of TR over SR (Kipling et al., 2011). Notwithstanding, TR did not affect hybrid corn yield, nitrogen uptake, and LAI development in a two-year study in Brazil (Sangoi et al., 2020). It is popularly known that TR planting provides more growing room for plants to develop a better canopy for light capture and to have roots spread over larger areas for nutrients and water capture than SR for growth. However, only minimal insights were generated through research on the advantages of TR planting over the conventional SR in soil-water-energy conservation (Kratochvil and Taylor, 2005; Grichar, 2007; Bruns, 2011a; https://www.farmprogress.com/twin-rows-help-boost-yields).

Research that quantifies and contrasts the carbon and water dynamics of the twin-row (TR) system to the single-row (SR) system for sustainable water management recommendations to producers in the region was lacking. In the few studies reported, the growth and yield of corn (maize) under TR were analyzed, but no attempts to measure the crop water requirements or WUE advantages of this system over the conventional SR system (Bruns, 2011a; Sangoi et al., 2020; Haegele et al., 2014). One major hindrance to quantifying, comparing, and selecting cropping systems for enhanced WUE was the difficulty in accurately quantifying temporal and spatial variations in crop water use (ET) in response to climate and soils across various cropping systems in a given region. In this context, the eddy covariance method for quantifying fluxes of water and CO_2 from cropping systems offers reasonably accurate estimates of crop water requirements continuously over time and space for assessing and comparing alternative management systems (Runkle et al., 2017; Fong et al., 2020; Anapalli et al., 2018, 2019, 2020, 2022a; b). Our objectives of this investigation were to quantify and compare ET, net ecosystem exchange of CO_2 (NEE), gross primary productivity (GPP), and WUE (WUE_{NEE} and WUE_{GY}) in TR and SR planted corn based on data collected in large-scale farm fields using the EC method.

2. Material and methods

2.1. Experiment

The study was conducted in two large-scale (above 100 ha) farmers' fields located in the LMD, about 20 miles from the Sustainable Water Management Unit, USDA ARS, Stoneville, Mississippi, USA (33° 27′ N, 90° 88′ W, ~37 m above sea level). The LMD is characterized by a humid subtropical climate with mild winters and warm summers (Kottek et al., 2006). The farmlands planted to corn in the study were predominantly silty clay loam to a depth of about 1.2 m (https//casoilresource.lawr.ucdavis.edu/gmap/). The land area has slopes under 2%, with average groundwater table depths at about 71 cm. The local farmers managed the two fields planted with corn in TR and SR planting pattern. All the soil-crop-water-nutrient management followed were those recommended by the Mississippi State University extension service and generally followed by the corn farmers in the region (http://extension.msstate.edu/agriculture/crops/corn). Conventional tillage operations were followed for land management. In the fall, the soil was tilled using a shallow disc harrow after harvest of the summer crop and tilled again before planting in the next crop season (March or April). The planting rate was about 80,000 seeds ha^{-1} in both TR and SR planting patterns.

Corn seeds were planted on ridges 96.52 cm (38 in) apart using a grain drill about 5 cm deep in the soil. Corn seeds in the SR planting were at the center of flattened-top ridges 12–20 cm high from furrow bottoms. In the TR planting system, corn was planted in two rows about 20 cm apart, replacing a single row in the SR plantings or ridge tops. The number of seeds planted remains the same in the TR and SR systems. Corn hybrid 'Dekalb 6205′ was planted in the TR and DKC 67–44 in the SR planting systems; however, both have similar growth and yield potentials for comparisons (https://cornsouth.com/articles/2022-corn-hybrids/).

The corn hybrids were planted on March 19, 2020, in the TR and on March 20, 2020, in the SR system. The corn seedlings emerged from the soil 9 and 8 days after planting in the TR and SR; that means seedlings in both systems emerged on the same day. Irrigations were furrow applied through lay-flat polyethylene pipes in which water delivered at the head of the furrow ran across to the foot of the furrow before the water supply was cut. In both systems, irrigations were applied well enough to grow the crop under water-stress-free conditions. Both the fields were maintained free of weeds, pests, and diseases by following Mississippi state university extension service recommendations for spraying insecticides (http://extension.msstate.edu/agriculture/crops/corn). The N (224 kg ha^{-1}) applied was Urea Ammonium Nitrate, injected into the soil in two doses (2–3 weeks apart) of 112 kg ha^{-1} about two weeks after the seedling emerged from the soil.

For monitoring CO_2 and H_2O fluxes from the soil-corn canopy system, towers for holding the eddy covariance sensors were established in the center of corn fields, such that there were crop canopies of uniform height distributed over a flat ground of about 500 m in length in all directions; thus, providing enough fetch to the micrometeorological sensors, omnidirectional 3-D anemometer, and infrared gas analyzers for CO_2 and H_2O installed on the tower. Sensor heights were adjusted periodically to position the 3-D anemometer and gas analyzers in the constant flux layer (about 1.5 times corn height above mean crop height) above corn canopies (Burba and Anderson, 2005). When the corn reached its maximum height of 2.1 m, these sensors were positioned about 3.5 m above the crop canopy. Past wind direction measurements for the location were not available, so not able to develop a wind rose diagram for investigating prevailing wind directions for the location and provide the data supporting this investigation.

2.2. Crop growth and development measurements

The crop's leaf area growth (LAI, leaf area index) was estimated biweekly using an LP-80 LAI meter (METER Group Inc.). Plant heights were also measured along with LAI measurements. Plant height data was used in determining EC sensor placement above the corn canopy, as described below. All plant-related measurements were repeated in the field in 6–12 random locations. The crop was harvested using a combine harvester equipped with load cells, driven through the field, and the total grain yield was reported at 13.5% moisture.

2.3. Quantifying corn ET, NEE, GPP, and R_{eco} using the eddy covariance method

In the eddy covariance method, the vertical flux of an entity of interest from the cropping system is represented as a covariance between the vertical velocity of air eddies originating from the system and the concentration of the entity of interest in it [36]. Detailed physical principles and derivation of the equations used for quantifying fluxes using the EC method and limitations of the method and techniques used to overcome those limitations are available elsewhere (Burba, 2021; Foken, 2008; Charuchittipan et al., 2014; Isaac et al., 2017; Eshonkulov et al., 2019).

For computing the fluxes of latent heat (for computing ET), sensible heat, and CO_2 from the soil-crop-air system, the speed of vertical transport of the eddies (vertical component of the wind vector) from the soil-crop-air system was measured at a 10 Hz frequency using an omnidirectional 3D sonic anemometer (Gill Windmaster, Gill Instruments, Lymington, UK). The CO_2 and water vapor concentrations, representing the same eddies, were measured using open-path infrared gas analyzers (LI-7500 DS, LICOR Inc., USA). The eddy covariance theory requires that the sensors for measuring the above properties of eddies must be positioned in the constant flux layer of the planetary boundary layer of the earth, which roughly starts from about 1.5 times the canopy height above the canopy of the crop (Burba and Anderson, 2005). We maintained the sensors at this height by installing the sensors on height-adjustable, telescopic, four-leg supported towers. The four-leg system assures more stability to avoid the possibility of the tower tilt due to winds. Plant canopy microclimate data was collected to partition NEE into GPP and Reco, gap-filling the missing data (4% of the total data collected were gap-filled) and interpreting the estimated flux results. The microclimate data collected also helps compute net heat energy (Rn, net solar radiation, which is the balance of the incoming and outgoing solar and earth radiation) balances in the soil-crop-atmosphere system. Micrometeological sensors used were from Vaisala (Helsinki, Finland) for air temperature and humidity, Hukseflux (Finland) for soil heat flux (Three sensors were installed at 6 cm depth, one each on either side and middle of the planting ridge), CNR4-L radiometer (Kipp&Zonen B.V., The Netherlands) for solar radiation (installed along with the infrared gas analyzer and sonic anemometer on the cross-arm of the EC tower), tipping bucket rain gauge from (Texas Electronics, USA) for rainfall, Quantum Sensor (LI-COR, USA) for photosynthetic photon flux density measurements (installed on the cross arm on the EC tower along with the solar radiation sensors). Microclimate data collected every 5 s were averaged every 30 min and recorded on a data logger (Sutron Xlite, Germany).

The raw air turbulence data collected by the sonic anemometer and water and CO_2 densities in air collected by the infrared gas analyzers at 10 Hz intervals were processed every 30 min and output for data quality control and computing final error-free fluxes of latent heat for ET, sensible heat (H), CO_2, and ground heat (G) fluxes using the EddyPro v 6.1.0 software provisioned in a Smartflux microprocessor (LI-COR Inc., USA) installed on the data logger. The EC towers carrying the infrared gas analyzer for measuring CO_2 and H_2O concentrations in the air and 3 D sonic anemometer for quantifying vertical components of wind vector sensors were centrally located in the large farm-scale (~ 100 ha) field. Further investigations on directional wind impacts on footprints of the CO_2 and H_2O gas detected by the sensors on those towers were not investigated because such centrally located sensors in the large farm fields would have large enough fetch to keep footprints of measured scalars within the crop field of interest. This way, the footprint size is equal in all directions around the EC tower. Corn ET was computed from the quality-controlled and gap-filled estimates (the quality control and gap-filling methods are discussed in the following section) of LE using latent heat of water evaporation modified for air temperature variations. The GPP represents the total amount of CO_2 fixed above photorespiration in the Calvin-Benson cycle of photosynthesis (CO_2 fixing reactions) process in plants (Michelet et al., 2013). The plant expends part of GPP as heterotrophic and autotrophic respiration (R_{eco}) for the maintenance and growth of tissues. To partition the NEE computed above into GPP and R_{eco}, we used the Lasslop et al. (2010) method with additional inputs from the micrometeorological data representing the crop canopy. The algorithm used in this method for computing R_{eco} form NEE uses a hyperbolic light response curve fitted to the daytime-NEE, modified to accommodate air temperature sensitivity of respiration and vapor pressure deficit impacts on photosynthesis or GPP. In this study, all the flux partitioning-related computations were performed using the Lasslop et al. (2010) method available within the Tovi (LI-COR Inc., USA) software. Further, GPP was computed by adding NEE and R_{eco} (if NEE was expressed as a -ve quantity, it needs to be subtracted from the negative values of R_{eco} to obtain GPP).

2.4. Quality control of measured and computed latent heat of evaporation (LE), sensible heat (H), and ground heat (G) fluxes, and micrometeological data

The Tovi™ software developed by LI-COR Inc., USA, based on the OzFlux method (Isaac et al., 2017), was used for data quality control and gap-filling the 30 min interval data output by the EddyPro software. In the Tovi, the Mauder and Foken (2006) method was used to remove epochs with negligible air turbulence due to light wind speeds. The De Roo et al. (2018) technique was used for correcting imbalances between measured input and measured or derived output energies. The EddyPro processed latent heat of evaporation (LE) and sensible heat H) fluxes were classified with quality flags, 0. 1 and 2 (0 indicates highest quality and 2 lowest quality) (Mauder and Foken, 2011). Using the man-machine interactive interface available within the Tovi software, the LE and H fluxes with quality flags of 2 were discarded. The fluxes were further filtered to keep within the realistic range from − 200–500 W m^{-2} for H and − 200–800 W m^{-2} for LE. Measured G was corrected for values outside the possible range of − 100–100 W m^{-2}. Monitored air and soil temperatures were checked and corrected for data outside the range possible in the location's climate. Similarly, soil water values were corrected for values outside the possible range for the soil at the site. Filling gaps in the sensible and latent heat fluxes was achieved using the marginal distribution sampling method (Reichstein et al., 2005; https://www.licor.com/env/support/Tovi/topics/configurable-mds-gap-filling.html).

3. Results and discussion

3.1. Observed weather conditions

As stated above, weather (air temperature, relative humidity, solar radiation, wind) was monitored at 2 m above the corn canopy in SR and TR plantings. In both systems, plants emerged from the soil on March 28, 2020. The crop in both SR and TR systems reached physiological maturity (stage R6) 110 days after seedling emergence from the soil (DAE) (Table 1). The accumulated growing degree days [GDD =$\sum$(Ta - 8), Ta is average daily air temperatures measured over the SR and TR systems, and 8 is the base temperature for corn (Hatfield and Preuger (2005)] was 1584 °C -day. During its 110 days of active growth, the crop received 361 mm of rainfall in 33 days but erratically distributed in time through the season; for that reason, farmers irrigated the crops often enough (roughly, irrigated once if rain was absent for about 10 days) to assure water-stress-free growth (Fig. 1a). Highest daily rainfall received was 39.2 mm on DAE 75. Fifty percent of the rain received was 10 mm per day or less, and the rest was between 10 mm and 39.2 mm. These low-intensity rainfall amounts were highly effective for replenishing the soil water removed by the plant roots to meet ET demands continuously.

At the beginning of the growing season, up to about 26 DAE, air temperatures (Ta) over the corn canopies in both SR and TR plantings were roughly the same (Fig. 2a). After about 26 DAE, Ta measured above

Table 1
Observed phenology and growing degree days (GDD) in twin-row (TR) vs. single-row (SR) planted corn in 2020. As the observed growth stages coincided across TR and SR plantings, one data set represented both. GDD was computed using a base temperature of 8 °C. SR and TR corn seedlings emerged from the soil on March 28, 2020.

Phenological growth stages	DAP, day	GDD, °C –day in SR	GDD, °C –day in TR	Plant height, m	Average EC sensor height, m
Emergence (VE)	8	63	65	0.0	2.0
Tasseling (VT.)	69	834	799	2.0	4.0
Silking (R1)	73	908	871	2.0	5.0
Blister (R2)	79	1012	975	2.0	5.0
Milk (R3)	86	1135	1092	2.0	5.0
Dough (R4)	92	1242	1197	2.0	5.0
Dent (R5)	100	1393	1344	2.0	5.0
Physiological Maturity (R6)	110	1584	1528	2.0	5.0

DAP is days after planting.

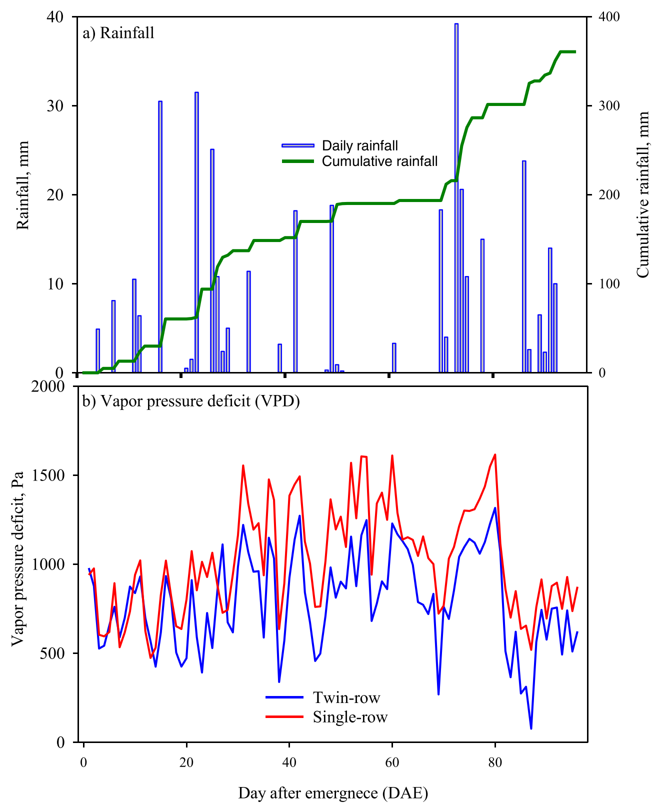

Fig. 1. Average daily (a) rainfall and (b) air vapor pressure deficit measured at 2 m above the canopy in twin-row (TR) vs. single-row (SR) planted corn in 2020.

the canopy, generally, were slightly higher over the SR planted to corn than the TR planted. The higher recorded Ta over the SR planting can be attributed to a higher area of soil (soil has much lower heat capacity compared to plant leaves), as reflected in lower LAI measured under this treatment, exposed for absorption of direct solar radiation and heating the air-canopy environment (Fig. 3). The TR planting, effectively distributed plants more evenly over the soil so that the growing plant canopy successively expanded over more area over the soil as reflected in the higher measured LAI. Ta measured over both TR and SR plant canopies varied between about 16 °C at the beginning of the season to about 28 °C towards the end of the season (Fig. 2). Ta in the canopy environment affects corn plant growth and grain yield substantially

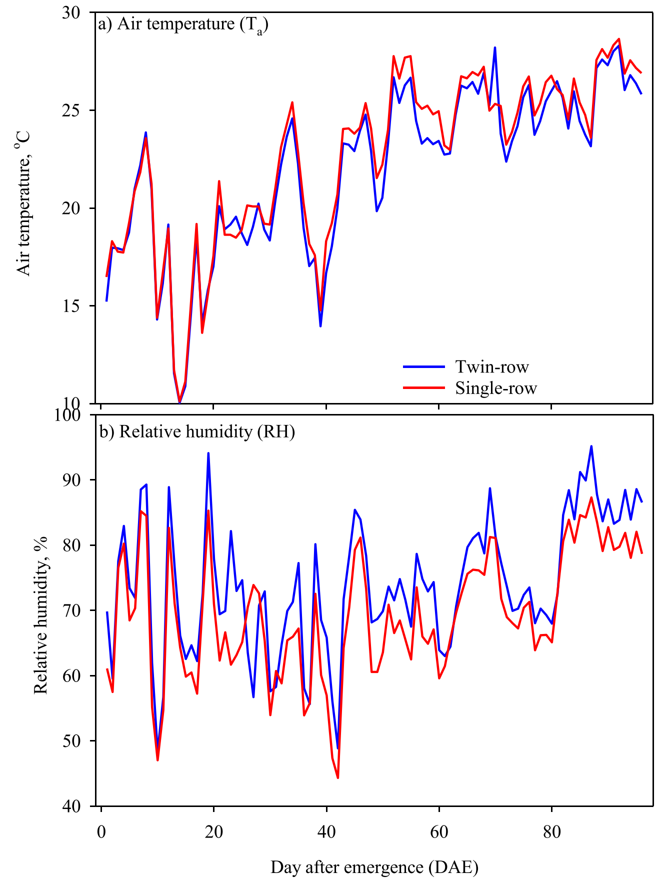

Fig. 2. Comparison of daily average (a) air temperature and (b) relative measured at 2 m above the plant canopy in twin-row (TR) vs. single-row (SR) planted corn in 2020.

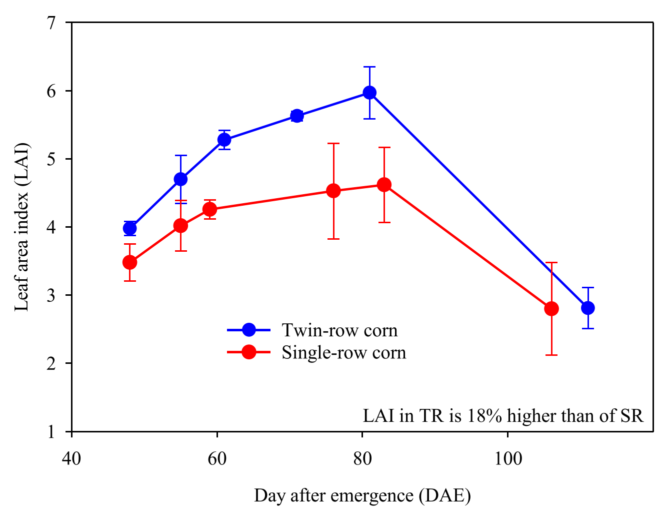

Fig. 3. Comparison of leaf area index (LAI) measured in twin-row (TR) vs. single-row (SR) planted corn in 2020.

(Hatfield and Preuger, 2015). The lower critical temperature below and an upper temperature above which the corn growth ceases completely were reported as 8 and 38 °C, respectively (Kiniry and Bonhomme, 1991; Hatfield and Preuger, 2015). The crops in the experiments were not subjected to temperatures below or above the upper air temperature threshold (measured Ta varied between 16 and 28 °C), which might have affected their yield potential substantially.

Better even spatial distribution of plants in the TR planting helped the crop grow and establish more LAI in the available space earlier in the TR system than plants in the SR system (Fig. 3). More LAI led to more transpiration water flux (ET) from the TR system, which enhanced the air relative humidity (reduced vapor pressure deficit in the air) above the TR system more than over the SR system (Figs. 1b, 2b). The average daily relative humidity recorded over the TR system varied between 48% and 95%. But, over the SR plant canopy, it ranged between 44% and 87% (Fig. 2b). In response to the higher amount of water vapor (as reflected in relative humidity) present in the air, the air above the TR-planted corn was characterized with less VPD compared to the air above SR plantings (Fig. 1b). A negative correlation between VPD and ET water fluxes, as observed in this study (discussed in sections below) from landscapes, was illustrated by Dalton (1802) over two centuries ago. Daily average VPD over the TR plantings ranged between 75 and 1270 Pa when it ranged between 508 and 1608 Pa in the SR system. A larger VPD over the SR system with higher Ta can produce larger water deficit stress for corn plants, as also reported by Grossiord et al. (2020).

3.2. Corn phenology, LAI, and yield

The LAI measured between DAE 57, and physiological maturity (R6 stage) ranged between 3.5 and 4.6 cm^2 cm^{-2} under SR plantings and between 4.0 and 6.0 cm^2 cm^{-2} in TR plantings (Fig. 3). The leaf area available for harvesting light energy from the sun is a vital plant attribute that determines plant biomass growth and yield (Alimuddin et al., 2019). The higher LAI observed under the TR planting was due to the enhanced leaf growth in the system with less competition from neighboring plants for light, water, and other nutrients for growth and more open space for expansion growth (Duncan, 1984; Barbieri et al., 2000, 2008). Pettigrew (2015) found early season leaf growth advantage in twin-row planted corn in the Mississippi Delta region of the USA, but this growth advantage diminished with time and coincided with the SR pattern by about mid-season, but no cotton yield advantages were reported. However, Robles et al. (2012), Bruns et al. (2012), and Modolo et al. (2015) reported an increase in LAI and grain yield with twin-row plantings in corn.

Ta has been widely accepted as the critical environmental variable determining occurrences of different plant phenological growth stages progressively with time (Bewick et al., 1988). Occurrences of visual phenological growth stages of corn occurred on the same DAE across TR and SR (Table 1). Due to the slight difference in the Ta measured above the corn canopy, the GDD computed for the different phenological stages differed slightly in the two plantings. However, the differences were not large enough to be reflected in the calendar days required for reaching different growth stages (Table 1). Corn emerged on the eighth day after planting, with a GDD of 63 °C-day in the SR planting and 65 °C-day in the TR planting. Plants reached physiological maturity on 110 DAP in both SR and TR. Harvested corn yield, reported at 13.5% moisture level, from the TR planting was higher by 19% than that harvested from SR planting (13,244 and 11,110 kg ha^{-1}) (Table 2).

3.3. Evapotranspiration

The exact balance between the energy inputs (net solar radiation) and the energy outputs (soil heat flux, latent heat flux, sensible heat flux, and other heat storage in the soil-air-canopy) from the cropping system was considered a reliable measure of accuracy in the measured fluxes using the eddy covariance method (Liu et al., 2017; Leuning et al., 2012). Monitored inputs of solar radiation on the SR and TR-planted corn canopy nearly coincided, indicating that both the systems received identical amounts of light and radiation energy for growth (Fig. 4a). However, the sensible heat fluxes (H) from the SR-planted corn was consistently higher than H measured over the TR grew corn canopy (Fig. 4b). During the crop season, the daily maximum measured H under SR and TR were 4211 and 3818 W m^{-2}, and the minimum measured were − 1811 and − 1799 W m^{-2}, respectively. These detected differences can be attributed to the more soil (soil minerals have lower heat capacity, so higher temperature achieved from the heating of solar radiation) exposed under the SR planted corn (plants have higher heat capacity, so lower temperature achieved from the heating of the same amount of solar radiation) with much lower LAI than TR planted corn (Fig. 3).

The slope of the linear regression between the energy inputs and energy outputs from the soil-air-corn canopy system expressed as a percentage was generally accepted as a measure of this 'energy balance closure (EBC) (Mauder and Foken, 2006; Anapalli et al., 2018). As reported in the literature in measurements under various crop-soil systems, this closure varied between 70% and 97% (Moorhead et al., 2019; Anapalli et al., 2022). In this study, after applying De Roo et al. (2018) technique for correcting imbalances between input and output energies from the system, we obtained 97% (slope of linear regression = 0.97)

Table 2
Comparison of SR and TR planted corn for evapotranspiration (ET), gross primary productivity (GPP), net ecosystem exchange of CO_2 (NEE), ecosystem respiration (R_{ec}), grain yield, and water use efficiencies (WUE) quantified using the eddy covariance method.

Planting method	Average daily values					Seasonal total	Seasonal WUE
	April	May	June	July	Average		
Evapotranspiration (ET), mm							
SR	3.1	3.3	5.9	6.7	4.8	426	-
TR	4.5	5.6	6.2	6.7	5.8	518	-
% change due to TR	31	70	5	0	21	22	
Gross primary production (GPP), Mg CO_2 ha^{-1}							Mg CO_2 ha^{-1} mm^{-1}
SR	0.03	0.41	1.18	0.17	0.45	43.85	0.10
TR	0.27	1.03	1.10	0.17	0.64	61.62	0.12
% change due to TR	800	151	-7	0	42	41	20
Net ecosystem exchange (NEE), Mg CO_2 ha^{-1}							Mg CO_2 ha^{-1} mm^{-1}
SR	0.02	0.22	0.55	0.08	0.22	19.71	0.05
TR	0.07	0.72	0.66	0.09	0.39	37.39	0.07
% change due to TR	250	227	20	13	77	90	40
Ecosystem respiration (R_{ec}), Mg CO_2 ha^{-1}							
SR	0.01	0.20	0.64	0.09	0.24	24.14	-
TR	0.18	0.31	0.44	0.08	0.25	24.23	-
% change due to TR	1700	55	-31	-11	4	0	-
Grain yield Mg ha^{-1}							Mg corn ha^{-1} mm^{-1}
SR	-	-	-	-	-	11.11	0.026
TR	-	-	-	-	-	13.24	0.026
% change due to TR						19	0

WUE = water use efficiency.

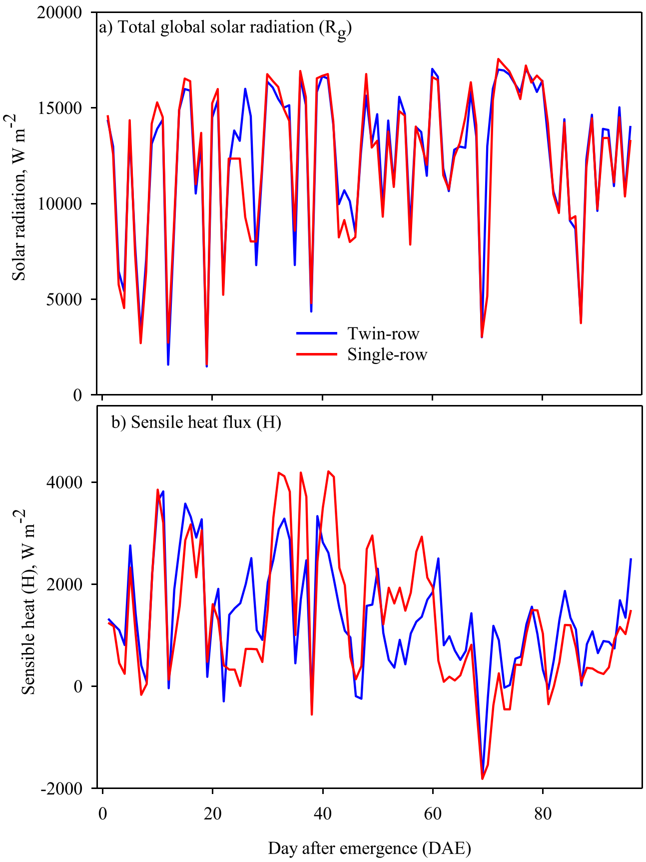

Fig. 4. Daily (a) total global solar radiation (Rg) and (b) eddy covariance estimated sensible heat flux (H) monitored above the plant canopy in twin-row (TR) vs. single-row (SR) planted corn in 2020.

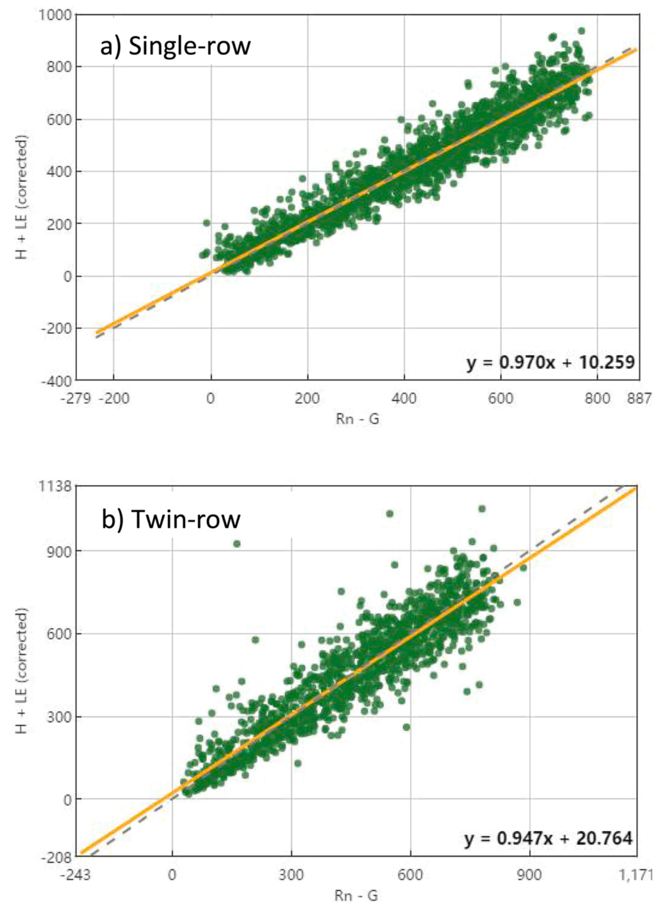

Fig. 5. Linear regressions between 30-minute interval energy inputs and outputs from the (a) Single-row (SR) and (b) Twin-row (TR) grown corn canopies. H = sensible heat flux (W m^{-2}), LE = latent heat energy flux (W m^{-2}), Rn = net solar radiation (W m^{-2}), and G = ground heat flux (W m^{-2}).

EBC in measurements conducted under SR and 95% (slope of linear regression = 0.95) under TR planted corn (Fig. 5a,b). The levels of EBC obtained in our measurements show that the eddy covariance data collected are accurate enough for comparing CO_2 and ET (water) fluxes from corn under the SR and TR planting systems.

Owing to the higher LAI growth, as discussed above, the daily and seasonal ET in the TR system was substantially higher than those measured under the SR system (Table 2; Figs. 3, 6a). Under TR planted corn, the monthly average daily ET across April, May, June, and July were between 4.5 mm in April to 6.7 mm in July, and its seasonal average (April – July) was 5.8 mm (Table 2; Fig. 7a-d). Under the SR planting, the average daily ET varied from 3.1 mm in April to 6.7 mm in July. The lower ET measured in the SR system was due to less transpiration loss of water from the lower leaf area the corn plants attained under this treatment for transpiring water – which means less net number of stomata available in leaf epidermal cells for transpiring water through those. The maximum difference in ET between the two planting systems occurred during the vegetative stages of the crop, that is, in April and May (Table 1; Figs. 6a, 7a-d).

The seasonal average daily ET from the SR planting was 4.8 mm, which was 21% less than the seasonal daily average ET under TR (5.8 mm). Seasonal total ET under the SR (426 mm) was 22% less than ET under the TR (518 mm) (Table 2; Fig. 6a). Monthly average hourly values of ET showed larger differences in their diurnal ranges during April through June, which diminished with time in July (Fig. 7). The lowest values of hourly ET were in July, which coincided with the R5 (dent stage) and physiological maturity (R6) stages of the crop when the crop was actively senescing (Fig. 7d; Table 1). ET measured under TR was constantly above those measured under SR, starting from crop emergence until physiological maturity (Fig. 7a-d).

3.4. NEE, R_{eco}, GPP, and WUE_{NEE}, WUE_{GY}

NEE quantifies the amount of CO_2 absorbed from the air and fixed in biomass after accounting for maintenance and growth respiration requirements for crop growth. In eddy covariance measurements, this quantity, by convention, is shown as -ve, as the gas (CO_2) is removed from the air (Fig. 7); however, NEE is real and positive, so we are representing this term as a positive entity in this paper. In general, the NEE of CO_2 – the amount of CO_2 removed from the atmosphere and sequestered in plant biomass - was much higher in the TR planting than in the SR (Figs. 6b, 8; Table 2). The higher NEE observed in the TR was mainly due to higher leaf area, as reflected in the measured LAI, which helped the crops to harvest a higher amount of solar-light energy over a given land area and fix more CO_2 in the photosynthesis process. Suyker et al. (2004) examined relationships between seasonal variations in GPP, R_{eco}, and NEE with various environmental factors. They reported that the green LAI of the corn plants explained about 95% of the variability in seasonal GPP and NEE.

In April, the crop was in its seedling stage and getting established for active growth; as such, the measured NEE in this month was the lowest during the season, with the least diurnal amplitude in the amount of CO_2 fixed (Fig. 8a). In this month, corn seedlings were in the initial stages of leaf expansion growth; as such, less leaf area was available for harvesting light energy for CO_2 assimilation in the photosynthesis process. The maximum daily amplitude of NEE in April, May, June, and July were 0.26. 1.24, 1.27, and 0.24 Mg CO_2 ha^{-1}, respectively, in TR plantings, and 0.07, 0.41, 1.08, and 0.19 Mg CO_2 ha^{-1} in SR planting (Fig. 8a-d). In July, the plants were between R5 and R6 stages, as such

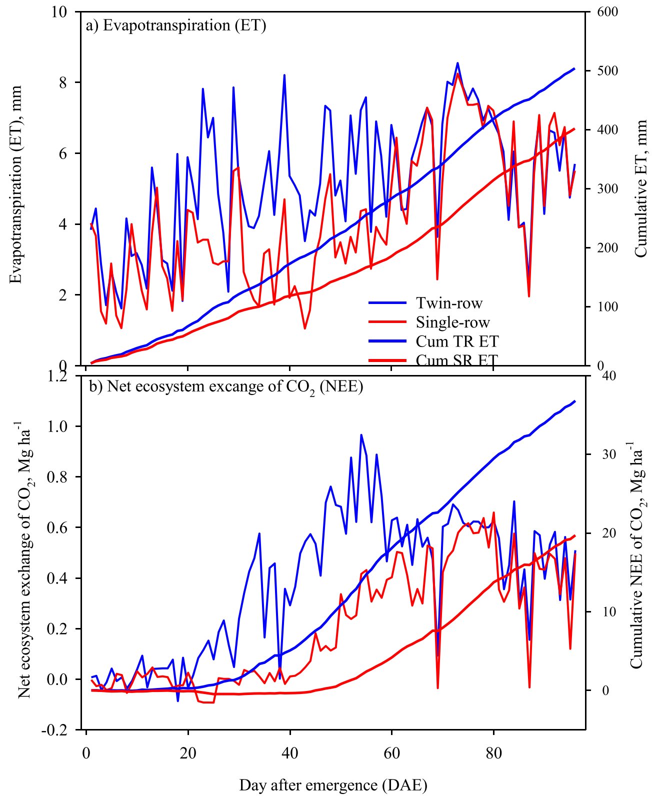

Fig. 6. Comparison of daily (a) evapotranspiration (ET) and cumulative ET, and (b) daily net ecosystem exchange of CO_2 (NEE) and cumulative (cum.) daily NEE, quantified using the eddy covariance method in twin-row (TR) vs. single-row (SR) planted corn in 2020.

fast senescing with very little CO_2 assimilations.

The total seasonal NEE in the TR system (37.39 Mg CO_2 ha^{-1}) was 90% higher than those measured in the SR system (19.71 Mg CO_2 ha^{-1}) (Table 2). Anapalli et al. (2018) reported 31.33 Mg CO_2 ha^{-1} of NEE from a TR-planted corn ecosystem in 2017 in the same climate but a clay soil. Higher LAI attained in the TR system than in the SR system possibly helped the plants to maintain a higher amount of carbon assimilation through photosynthesis throughout the crop growth period to achieve higher NEE. Daily, averaged across the season, NEE in the TR planting (0.39 Mg CO_2 ha^{-1}) was 81% higher than that measured in SR planting (0.22 Mg CO_2 ha^{-1}) (Table 2). In the TR planting, monthly averaged values of NEE varied between 0.07 Mg CO_2 ha^{-1} in April and 0.72 Mg CO_2 ha^{-1} in May, with an average of 0.39 Mg CO_2 ha^{-1} across the four months of the crop season (Table 2). In the SR planting, the lowest NEE was 0.02 Mg CO_2 ha^{-1} in April, and the highest was 0.55 Mg CO_2 ha^{-1} in June. To our knowledge, no reported study previously compared NEE between SR and TR planting. Notwithstanding, in the past, the NEE between crop fields and the atmosphere was used to quantify the carbon sequestration potentials of various cropping systems and best management practices (Baldocchi et al., 2001; Baker et al., 2007).

In the literature, estimates of GPP and NEE were used to quantify cropping systems' carbon sequestration potentials in response to conservation management systems (Falge et al., 2002). The GPP estimates in the TR and SR plantings were 61.62 and 43.85 Mg CO_2 ha^{-1}, respectively, and R_{eco} were 24.23 and 24.14 Mg CO_2 ha^{-1} (Table 2; Fig. 9a,b). The amount of CO_2 used in R_{eco} was about 39% and 55% of GPP in TR and SR plantings, respectively. The higher VPD, Ta, and lower relative humidity observed over the TR favored more relative respiration (higher percentage) use of the GPP - CO_2 fixed in the photosynthesis process (Figs. 1b, 2a, b). Enhancements in plant respiration loss of GPP with air temperatures have been well established in the literature

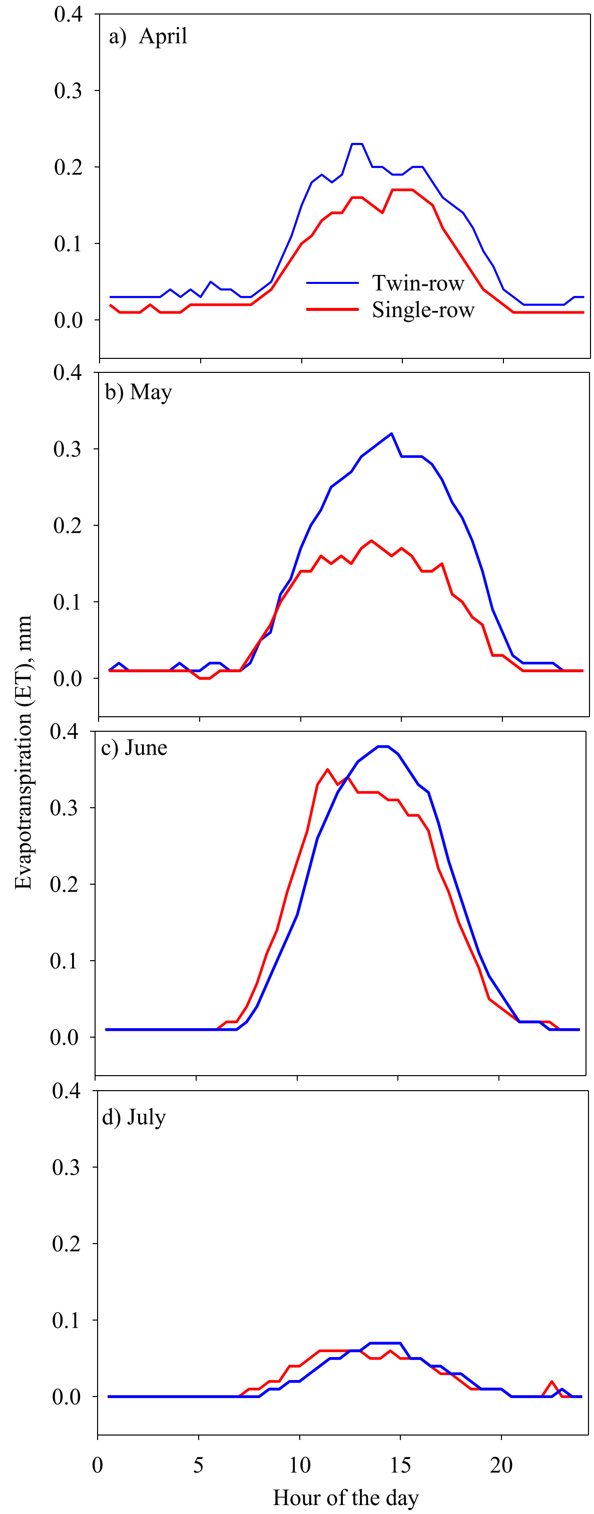

Fig. 7. Comparison of monthly (April, May, June, and July) averaged diurnal variations in evapotranspiration (ET) quantified using the eddy covariance method in twin-row (TR) vs. single-row (SR) planted corn in 2020.

(Hatfield and Dold, 2019). A doubling of respiration with every 10 °C rise in air temperatures is generally accepted in plant tissues (Gifford, 1995; Lomander et al., 1998).

WUE_{NE} computed as seasonal NEE to ET ratio was 40% higher under TR planting than under SR planting. WUE_{NE} in TR and SR planted corn were 0.07 and 0.05 Mg CO_2 ha^{-1} mm^{-1}, respectively. However, WUE_{GY} - computed as grain yield to ET ratio - in both TR and SR plantings were

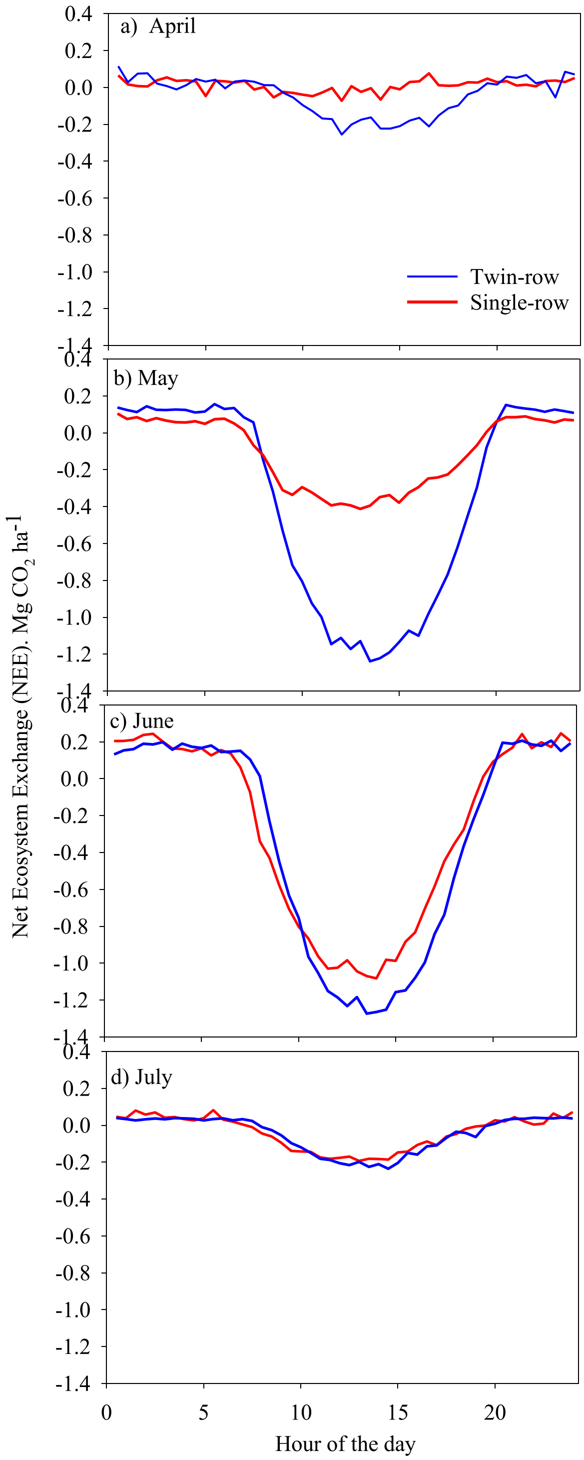

Fig. 8. Comparison of monthly (April-July) averaged diurnal variations in net ecosystem exchange of CO_2, quantified using the eddy covariance method, in twin-row (TR) vs. single-row (SR) planted corn in 2020.

about 0.026 Mg ha^{-1} mm^{-1}. In summary, TR planting enhanced grain yield by 19% compared to SR planting, spending 22% more water in terms of ET. WUE_{GY} across TR and SR planting remained constant when there was a substantial increase in grain yield, ET, NEE, and WUE_{NE} in the TR-panted corn production system compared to the SR system.

4. Conclusions

The CO_2 and water dynamics and WUE advantages of switching from

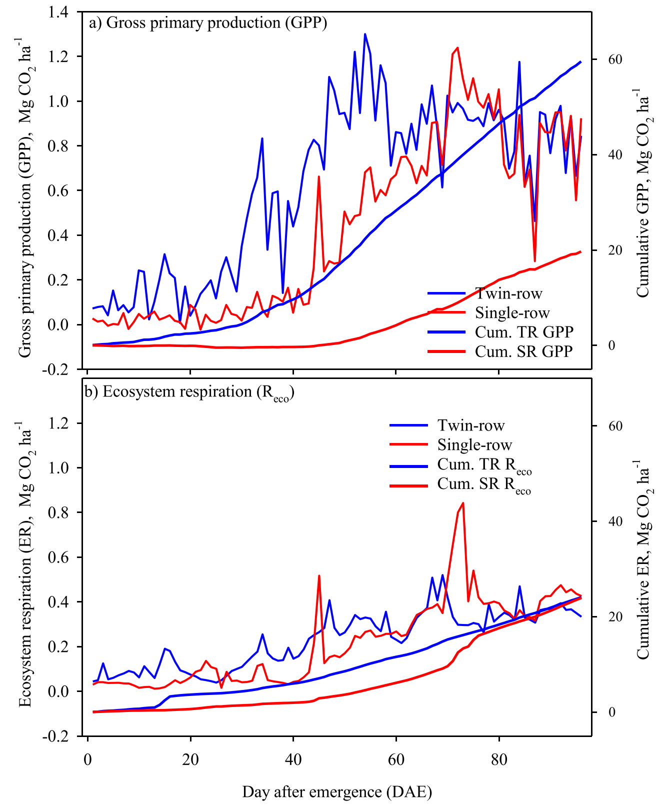

Fig. 9. Comparison of cumulative half hourly (a) gross primary production (GPP) and (b) ecosystem respiration R_{eco}, quantified using the eddy covariance method, in twin-row (TR) vs. single-row (SR) planted corn in 2020.

conventional SR to TR planting patterns were investigated by monitoring the ET, NEE_{NE}, GPP, R_{eco}, and grain yield in corn grown on farm-scale fields using the eddy covariance method. The study demonstrated that changing the corn planting pattern from SR to TR could result in a larger seasonal NEE of CO_2 (net CO_2 fixed in the ecosystem) by about 40% and grain yield by about 19%; however, with an additional ET expenditure of about 22%. When the TR system enhanced WUE_{NE} by about 40%, WUE in grain production did not change. The enhanced NEE of CO_2 in the TR system renders it a better planting pattern for corn with a higher potential to mitigate CO_2 build-up in the atmosphere. The study presented was based on research conducted on large-scale farmer's fields without interfering with the agronomic operations in growing corn for optimum yields; as such, the study is more reliable for a recommendation for crop management than results based on small-plot-based trials.

Disclaimer

Trade names were necessary to report factually on available data; however, the United States Department of Agriculture (USDA) does not guarantee or warrant the standard of the product or service. Using the name by USDA implies no approval of the product or service to exclude others that may also be suitable.

Declaration of Competing 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.

Data Availability

The authors do not have permission to share data.

Acknowledgement

We want to thank Mr. Jonathan Corser, Agricultural Research Technician, Sustainable Water Management Research Unit, USDA ARS, for his assistance in collecting data related to this experiment.

References

Alimuddin, S., Musa, Y., Azrai, M., Asrul, L., 2019. Effect of double rows plant system on plant growth, yield components and grain yield in prolific and non-prolific hybrid maize. IOP Conf. Ser. Earth Environ. Sci. 473 (2020) https://doi.org/10.1088/1755-1315/473/1/012013.

Anapalli, S.S., Fisher, D.K., Reddy, K.N., Wagle, P., Gowda, P.H., Sui, R., 2018. Quantifying soybean evapotranspiration using an eddy covariance approach. Agric. Water Manag. 209, 228–239. https://doi.org/10.1016/j.agwat.2018.07.023.

Anapalli, S.S., Fisher, D.K., Reddy, K.N., Krutz, J.L., Pinnamaneni, S.R., Sui, R., 2019. Quantifying water and CO_2 fluxes and water use efficiencies across irrigated C_3 and C_4 crops in a humid climate. Sci. Total Environ. 633, 338–350. https://doi.org/10.1016/j.scitotenv.2018.12.471.

Anapalli, S.S., Fisher, D.K., Pinnamaneni, S.R., Reddy, K.N., 2020. Quantifying evapotranspiration and crop coefficients for cotton (Gossypium hirsutum L.) using an eddy covariance approach. Agric. Water Manag 233. https://doi.org/10.1016/j.agwat.2020.106091.

Anapalli, S.S., Pinnamaneni, S.R., Reddy, K.N., Sui, R., Singh, G., 2022a. Investigating soybean (Glycine max L.) responses to irrigation on a large-scale farm in the humid climate of the Mississippi Delta region. Agric. Water Manag. 262. https://doi.org/10.1016/j.agwat.2021.107432.

Anapalli, S.S., Pinnamaneni, S.R., Reddy, K.N., Sui, R., Singh, G., 2022b. Eddy covariance quantification of corn water use and yield responses to irrigations on farm-scale fields. Agron. J. 114 (4), 2445–2457. https://doi.org/10.1002/agj2.21130.

Baker, J.M., Ochsner, T.E., Venterea, R.T., Griffis, T.J., 2007. Tillage and soil carbon sequestration – what do we really know? Agric. Ecosyst. Environ. 118 (1–4), 1–5. https://doi.org/10.1016/j.agee.2006.05.014.

Baldocchi, D., Falge, E., Gu, L.H., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X.H., Malhi, Y., Meyers, T., Munger, W., Oechel, W., U, K.T.P., Pilegaard, K., Schmid, H.P., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. FLUXNET: A new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bull. Am. Meteorol. Soc. 82 (11), 2415–2434. https://doi.org/10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2.

Barbieri, P.A., Saínz Rozas, H.R., Andrade, F.H., Echeverría, H.E., 2000. Row spacing effects at different levels of nitrogen availability in maize. Agron. J. 92 (2), 283–288. https://doi.org/10.2134/agronj2000.922283x.

Barbieri, P.A., Echeverría, H.E., Saínz Rozas, H.R., Andrade, F.H., 2008. Nitrogen use efficiency in maize as affected by nitrogen availability and row spacing. Agron. J. 100 (4), 1094–1100. https://doi.org/10.2134/agronj2006.0057.

Bewick, T.A., Binning, L.K., Yandell, B., 1988. A degree-day model for predicting the emergence of swamp dodder in cranberry. J. Am. Soc. Hort. Sci. 113 (6), 839–841. https://doi.org/10.21273/JASHS.113.6.839.

Bruns, H.A., 2011a. Comparisons of single-row and twin-row soybean production in the Mid-South. Agron. J. 103 (3), 702–708. https://doi.org/10.2134/agronj2010.0475.

Bruns, H.A., 2011b. Planting date, rate, and twin-row vs. single-row soybean in the Mid-South. Agron. J. 103 (5), 1308–1313. https://doi.org/10.2134/agronj2011.0076.

Bruns, H.A., Ebelhar, M.W., Abbas, H.K., 2012. Comparing single-row and twin-row corn production in the Mid South. Online Crop Manag. 11 (1), 1–8. https://doi.org/10.1094/CM-2012-0404-01-RS.

Burba, G., 2021. Eddy covariance method for scientific, regulatory, and commercial applications. LI-COR Biosciences. Burba, G., Anderson, D., 2005. Introduction to the eddy covariance method: general guidelines and conventional workflow. LI-COR Biosci. https://doi.org/10.13140/RG.2.1.3723.5683.

Charuchittipan, D., Babel, W., Mauder, M., Leps, J.P., Foken, T., 2014. Extension of the averaging time in eddy-covariance measurements and its effect on the energy balance closure. Bound. -Layer. Meteorol. 152 (3), 303–327. https://doi.org/10.1007/s10546-014-9922-6.

Dalton, J., 1802. Experimental essays on the constitution of mixed gases; on the force of steam or vapor from water and other liquids in different temperatures, both in a Torricellian vacuum and in air; on evaporation; and on the expansion of gases by heat. Mem. Lit. Philos. Manch. 5, 535–602.

De Roo, F., Zhang, S., Huq, S., Mauder, M., 2018. A semi-empirical model of the energy balance closure in the surface layer. PloS One 13 (12). https://doi.org/10.1371/journal.pone.0209022.

Duncan, W.G., 1984. A theory to explain the relationship between corn population and grain yield. Crop Sci. 24 (6), 1141–1145. https://doi.org/10.2135/cropsci1984.0011183×002400060032x.

Eshonkulov, R., Poyda, A., Ingwersen, J., Wizemann, H.D., Weber, T.K.D., Kremer, P., Högy, P., Pulatov, A., Streck, T., 2019. Evaluating multi-year, multi-site data on the energy balance closure of eddy-covariance flux measurements at cropland sites in southwestern Germany. Biogeosciences 16, 521–540. https://doi.org/10.5194/bg-16-521-2019.

Falge, E., Tenhunen, J., Baldocchi, D., Aubinet, M., Bakwin, P., Berbigier, P., Bernhofer, C., Bonnefond, J.M., Burba, G., Clement, R., Davis, K.J., Elbers, J.A., Falk, M., Goldstein, A.H., Grelle, A., Granier, A., Grunwald, T., Guðmundsson, J., Hollinger, D., Janssens, I.A., Keronen, P., Kowalski, A.S., Katul, G., Law, B.E., Malhi, Y., Meyers, T., Monson, R.K., Moors, E., Munger, J.W., Oechel, W., U, K.T.P., Pilegaard, K., Rannik, Ü., Rebmann, C., Suyker, A., Thorgeirsson, H., Tirone, G., Turnipseed, A., Wilson, K., Wofsy, S., 2002. Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements. Agric. . Meteorol. 113 (1–4), 75–95. https://doi.org/10.1016/S0168-1923(02)00103-X.

Foken, T., 2008. The energy balance closure problem: an overview. Ecol. Appl. 18 (6), 1351–1367. https://doi.org/10.1890/06-0922.1.

Fong, B.N., Reba, M.L., Teague, T.G., Runkle, B.R., Suvocarev, K., 2020. Eddy covariance measurements of carbon dioxide and water fluxes in U.S. mid-south cotton production. Agric., Ecosyst. Environ. 292. https://doi.org/10.1016/j.agee.2019.106813.

Gifford, R.M., 1995. Whole plant respiration and photosynthesis of wheat under increased CO_2 concentration and temperature: long-term vs. short-term distinctions for modeling. Glob. Change Biol. 1 (6), 385–396. https://doi.org/10.1111/j.1365-2486.1995.tb00037.x.

Grichar, W.J., 2007. Row spacing, plant populations, and cultivar effects on soybean production along the Texas Gulf Coast. Crop Manag. 6 (1), 1–6. https://doi.org/10.1094/CM-2007-0615-01-RS.

Grossiord, C., Buckley, T.N., Cernusak, L.A., Novick, K.A., Poulter, B., Siegwolf, R.T.W., Sperry, J.S., McDowell, N.G., 2020. Plant responses to rising vapor pressure deficit. N. Phytol. 226 (6), 1550–1566. https://doi.org/10.1111/nph.16485.

Haegele, J.W., Becker, R.J., Henninger, A.S., Below, F.E., 2014. Row arrangement, phosphorus fertility, and hybrid contributions to managing increased plant density of maize. Agron. J. 106 (5), 1838–1846. https://doi.org/10.2134/agronj2013.0382.

Hatfield, J.L., Dold, C., 2019. Water-use efficiency: advances and challenges in a changing climate. Front. Plant Sci. 10 (103) https://doi.org/10.3389/fpls.2019.00103.

Hatfield, J.L., Preuger, J.H., 2015. Temperature extremes: effect on plant growth and development. Weather Clim. Extrem. 10 (A), 4–10. https://doi.org/10.1016/j.wace.2015.08.001.

Isaac, P., Cleverly, J., McHugh, I., van Gorsel, E., Ewenz, C., Beringer, J., 2017. OzFlux data: Network integration from collection to curation. Biogeosciences 14 (2), 2903–2928. https://doi.org/10.5194/bg-14-2903-2017.

Kiniry, J.R., Bonhomme, R., 1991. Predicting maize phenology. In: Hodges, T. (Ed.), Predicting Crop Phenology. CRC Press, Boca Raton, pp. 115–131.

Kottek, M., Grieser, J., Beck, C., Rudolf, B., Rubel, F., 2006. World Map of the Köppen-Geiger climate classification updated. Meteorol. Z. 15 (3), 259–263.

Kratochvil, R.J., Taylor, R.W., 2005. Twin-row corn production: An evaluation in the mid-Atlantic Delmarva region. Crop Manag. 4 (1), 1–7. https://doi.org/10.1094/CM-2005-0906-01-RS.

Kurt, C., Bakal, H., Gulluoglu, L., Arıoglu, H., 2017. The effect of twin-row planting pattern and plant population on yield and yield components of peanut (*Arachis hypogaea* L.) at main crop planting in Cukurova region in Turkey. Turk. J. Field Crops 22 (1), 24–31. https://doi.org/10.17557/tjfc.301768.

Lasslop, G., Reichstein, M., Papale, D., Richardson, A., Arneth, A., Barr, A., Stoy, P., Wohlfahrt, G., 2010. Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation. Glob. Chang. Biol. 16 (1), 187–208. https://doi.org/10.1111/j.1365-2486.2009.02041.x.

Leuning, R., van Gorsel, E., Massman, W., Isaac, P., 2012. Reflections on the surface energy imbalance problem. Agric. . Meteorol. 156, 65–74. https://doi.org/10.1016/j.agrformet.2011.12.002.

Liang, S., Yoshihira, T., 2022. Effect of nitrogen topdressing on planting density response of grain yield in maize with different planting pattern cultivation. Grassl. Sci. 68 (3), 286–297. https://doi.org/10.1111/grs.12364.

Liu, X., Yang, S., Xu, J., Zhang, J., Liu, J., 2017. Effects of heat storage and phase shift correction on energy balance closure of paddy fields. Atmosfera 30 (1), 39–52. https://doi.org/10.20937/ATM.2017.30.01.04.

Lomander, A., Katterer, T., Andren, O., 1998. Modelling the effects of temperature and moisture on CO_2 evolution from top and subsoil using a multi-compartment approach. Soil Biol. Biochem. 30 (14), 2023–2030. https://doi.org/10.1016/S0038-0717(98)00077-7.

Mahanna, B., Thomaks E.V., 2015. Twin-row corn yielded mixed results. Hay & Forage Grower. ⟨https://hayandforage.com/article-19-twin-row-corn-yielded-mixed-results.html⟩.

Mauder, M., Foken, T., 2006. Impact of post-field data processing on eddy covariance flux estimates and energy balance closure. Meteorol. Z. 15 (6), 597–609. https://doi.org/10.1127/0941-2948/2006/0167.

Mauder M., Foken, T., 2011. Documentation and instruction manual of the Eddy-Covariance Software Package TK3. Universität Bayreuth, Abteilung Mikrometeorologie 46, ISSN 1614–8924, 60 pp.

Michelet, L., Zafafagnini, M., Morisse, S., Sparla, F., Pérez-Pérez, M.E., Francia, F., Danon, A., Marchand, C.H., Fermani, S., Trost, P., Lemaire, S.D., 2013. Redox regulation of the Calvin-Benson cycle: something old, something new. Front. Plant Sci. 4 (470) https://doi.org/10.3389/fpls.2013.00470.

Modolo, A.J., Junior, E.M., Storck, L., Vargas, T.O., Dallcort, R., Baesso, M.M., Brandelero, E.M., 2015. Development and yield of maize (*Zea mays*) under plant densities using simple and twin-row spacing. Afr. J. Agric. Res. 10 (11), 1344–1350.

Moorhead, J.E., Marek, G.W., Gowda, P.H., Lin, X., Colaizzi, P.D., Evett, S.R., Kutikoff, S., 2019. Evaluation of evapotranspiration from eddy covariance using large weighing lysimeters. Agronomy 9 (2), 99. https://doi.org/10.3390/agronomy9020099.

Pettigrew, W.T., 2015. Twin-row production of cotton genotypes varying in leaf shape. J. Cotton Sci. 19, 319–327.

Pinnamaneni, S.R., Anapalli, S.S., Fisher, D.K., Reddy, K.N., 2020a. Irrigation and planting geometry effects on Cotton (Gossypium hirsutum L.) yield and water use. J. Cotton Sci. 24, 87–96.

Pinnamaneni, S.R., Anapalli, S.S., Reddy, K.N., Fisher, D.K., Quintana-Ashwell, N.E., 2020b. Assessing irrigation water use efficiency and economy of twin-row soybean in the Mississippi Delta. Agron. J. 112 (5), 4219–4231. https://doi.org/10.1002/agj2.20321.

Reddy, K.N., Boykin, J.C., 2010. Weed control and yield comparisons of twin- and single-row glyphosate-resistant cotton production systems. Weed Technol. 24 (2), 95–101. https://doi.org/10.1614/WT-D-09-00044.1.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grünwald, T., Havránková, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., Valentini, R., 2005. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. Glob. Change Biol. 11 (9), 1424–1439. https://doi.org/10.1111/j.1365-2486.2005.001002.x.

Robles, M., Ciampitti, I.A., Vyn, T.J., 2012. Responses of maize hybrids to twin-row spatial arrangement at multiple plant densities. Agron. J. 104 (6), 1747–1756. https://doi.org/10.2134/agronj2012.0231.

Runkle, B.R.K., Rigby, J.R., Reba, M.L., Anapalli, S.S., Bhattacharjee, J., Krauss, K.W., Liang, L., Locke, M.A., Novick, K.A., Sui, R., Suvocarev, K., White, P.M., 2017. Delta-Flux: an eddy covariance network for a climate-smart Lower Mississippi Basin. Agr. Environ. Lett. 2 (1) https://doi.org/10.2134/ael2017.01.0003.

Sangoi, L., Schmitt, A., Junior, M.C.M., Kuneski, H.F., Coelho, A.E., 2020. Narrow and twin-row plantings do not increase maize yield. Agron. Colomb. 38 (3), 342–349. https://doi.org/10.15446/agron.colomb.v38n3.86117.

Smith, R.M., Kaur, G., Orlowski, J.M., Singh, G., Chastain, D., Irby, T., Krutz, L.J., Falconer, L., Cook, D.R., 2019. Narrow-row production system for soybeans in Mississippi Delta. Crop, Forage, Turfgrass Manag. 5 (1), 1–6. https://doi.org/10.2134/cftm2019.02.0015.

Stephenson, D.O., Brecke, B.J., 2010. Weed management in single-vs. twin-row cotton (Gossypium hirsutum). Weed Technol. 24 (3), 275–280. https://doi.org/10.1614/WT-D-09-00056.1.

Stephenson, D.O., Barber, L.T., Bourland, F.M., 2011. Agronomy and soils: Effect of twin-row planting pattern and plant density on cotton growth, yield, and fiber quality. J. Cotton Sci. 15 (3), 243–250.

Suyker, A.E., Verma, S.B., Burba, G.G., Arkebauer, T.J., Walters, D.T., Hubbard, K.G., 2004. Growing season carbon dioxide exchange in irrigated and rainfed maize. Agric. . Meteorol. 124 (1–2), 1–13. https://doi.org/10.1016/j.agrformet.2004.01.011.

Yasarer, L.M.W., Taylor, J.M., Rigby, J.R., Locke, M.A., 2020. Trends in land use, irrigation, and streamflow alteration in the Mississippi River Alluvial Plain. Front. Environ. Sci. 8 (66), 1–13. https://doi.org/10.3389/fenvs.2020.00066.