Agricultural and Forest Meteorology 310 (2021) 108631

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

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

Carbon dioxide and water vapor fluxes of multi-purpose winter wheat production systems in the U.S. Southern Great Plains

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ARTICLE INFO

Keywords:
Eddy covariance
Evapotranspiration
Grazing
Net ecosystem CO_2 exchange
Spatio-temporal variability

ABSTRACT

Eddy fluxes collected during 2016 to 2019 from eight production-scale multi-purpose winter wheat fields (grain only, graze-grain, and graze-out), managed under conventional till (CT) and no-till (NT), were synthesized to determine seasonality, daily magnitudes, seasonal, and annual budgets of carbon dioxide (CO_2) fluxes and evapotranspiration (ET), and to investigate spatio-temporal variability of the fluxes. Maximum daily net ecosystem CO_2 exchange (NEE), gross primary production (GPP), and ecosystem respiration (ER) approximated -11, 19, and 12 g C m^{-2}, respectively, and daily ET approximated 7 mm. Wheat fields, including graze-out, were large sinks of CO_2 (ranged from -149 ± 8 to -564 ± 9 g C m^{-2}) during growing seasons (October–May). Wheat fields, left fallow during summer, were from near neutral to large sinks of CO_2 at annual (calendar year) scales. Cumulative annual NEE was up to -242 ± 12 g C m^{-2} in a NT and -183 ± 12 g C m^{-2} in a CT field, which had grain-only wheat in spring followed by graze-grain wheat in fall. Cumulative seasonal ET ranged from 260 mm to 521 mm, and maximum annual ET approximated 800 mm. In general, ET was smaller under NT than CT. Eddy fluxes showed stronger relationships with remotely-sensed enhanced vegetation index and in-situ biometric variables in grain-only fields than grazed fields. Across-site analysis for grain-only wheat showed biomass and leaf area index alone explained >80% of variations in NEE, GPP, and ET, and ~70% of variations in ER. Similarly, Canopy coverage explained >80% of variations in NEE and GPP, and ~60% of variations in ER and ET. Strong relationships of biometric observations with the fluxes demonstrated their potential to model and explain spatio-temporal variability of CO_2 fluxes and ET. Results also indicated huge implications of management practices on carbon and water budgets by altering vegetative properties.

1. Introduction

The Southern Great Plains (SGP) region of the United States (U.S.) experiences seasonal, interannual, and persistent multi-year variations in air temperature and precipitation (Garbrecht and Rossel, 2002). Average annual precipitation within the region ranges from 184 mm on the western edge (eastern New Mexico) to 890 mm on the eastern edge (eastern Oklahoma); monthly average maximum daily temperature ranges from 8 to 33°C during calendar years. Prolonged droughts (Patrignani et al., 2014), extreme precipitation events (Kunkel et al., 2013), and frequency of dipole events (*i.e.*, wet years following drought years) (Christian et al., 2015) have been increasing in the region. These climatic variabilities drive the dynamics and productivity of agro-ecosystems, which play an important role in terrestrial carbon and water cycles.

Winter wheat (*Triticum aestivum* L.) is one of the major grain crops in the world, and is a major annual crop in the U.S. SGP, with ~30% of nation's total wheat production occurring in the region (Lollato and Edwards, 2015). Due to unique climatic characteristics (*i.e.*, favorable fall and winter temperatures for significant wheat growth), winter wheat in the SGP is largely managed for different purposes: grain-only (no grazing), graze-grain (dual purpose wheat – grazing by yearling stocker cattle from mid-November to late February until hollow stem emergence), and graze-out (no grain production – grazing from

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https://doi.org/10.1016/j.agrformet.2021.108631
Received 6 April 2021; Received in revised form 27 August 2021; Accepted 29 August 2021
0168-1923/Published by Elsevier B.V.

mid-November through April) (Fieser et al., 2006; Phillips et al., 1999). Dual purpose (graze-grain) and graze-out winter wheat is planted approximately one month earlier (early September) than grain-only wheat (early October), and is grazed at an average stocking density of 0.81 animal per hectare (Fieser et al., 2006; Phillips et al., 1999).

It is common to manage winter wheat in the region as a continuous wheat, with summer fallow to conserve moisture, without any crop rotations (Edwards et al., 2011; Redmon et al., 1995). Consequently, winter wheat production in the region has been greatly affected by infestations of winter annual grasses, particularly Italian ryegrass (*Lolium multiforum*), and different annual bromes (*Bromus* spp.) (Barnes et al., 2001). Crop rotation has been considered as a potential approach to manage weeds, insect pests, and diseases in winter wheat (Daugovish et al., 1999). In the past decade, interest in using winter canola (*Brassica napus* L.) as a break crop in rotation with winter wheat has increased in the SGP (Dean and Weil, 2009; Duke et al., 2009; Lofton et al., 2010). In addition to weed control purpose, increasing demands for healthy oils is another driving factor for expansion of winter canola in the SGP (Begna et al., 2017). Consequently, winter canola coverage in the region increased from 20,000 ha in 2009 to >73,000 ha in 2012 (Boyles et al., 2012). Similarly, the area planted to winter canola in Oklahoma increased more than double from 2010 to 2015 (from 24,000 to 56,000 ha) (USDA-ESMIS, 2016).

Winter wheat–canola crop rotations can improve short-term soil fertility, reduce incidence of wheat diseases and insect pests, improve herbicide options for winter annual weed control, increase wheat forage and grain yields following canola, and improve farm income from selling a more diverse range of products (wheat, canola, and cattle) (Boyles et al., 2004a; Boyles et al., 2004b; Bushong et al., 2012; DeVuyst et al., 2009). However, winter canola has seen highs and lows in production in the SGP during past decade due to price fluctuations and market issues.

Increasing demands for agricultural commodities from shrinking lands coupled with changing climates necessitate increasing production yields and resource use efficiencies, and development of best management practices (BMPs) (Lal et al., 2011; West et al., 2009). In recent years, renewed interest in conservation-tillage (e.g., no-till, minimum-till, reduced-till, residue management) practices coupled with dynamic crop rotations that improve production and reduce negative impacts on the environment has increased. However, inconsistent and contradictory results have been reported from conventional till (CT) and no-till (NT) experiments (Derpsch et al., 2014), most likely due to other confounding factors such as differences in climate, soil types, and other management practices. Toliver et al. (2012) evaluated data from 442 paired tillage experiments (including winter wheat) across the U.S. and reported that soils and environmental factors affected yields more in NT than CT systems. Overall, NT winter wheat had greater yields, but NT wheat produced lower yields compared to CT wheat in sandy soils (Toliver et al., 2012). Under most growing conditions in Oklahoma, predicted wheat grain yields were slightly greater under CT than NT, but they did not significantly differ between tillage systems (Vitale et al., 2014). However, both CT and conservation tillage or NT are common for winter wheat in the SGP (Hossain et al., 2004).

The rising concentration of atmospheric CO_2 and increasing scarcity of water resources has resulted in growing interest in measuring carbon dioxide (CO_2) and water (H_2O) vapor fluxes (*i.e.*, evapotranspiration, ET) of agroecosystems using eddy covariance (EC) systems (Liu et al., 2015; Medvigy et al., 2010; Schimel, 1995). A better understanding of carbon and water budgets of differently managed (e.g., tillage, grazing, crop management) agroecosystems will help refine managements of on-farm resources to increase production potential and resource use efficiencies, while improving resilience and minimizing environmental impacts. To address this knowledge gap, long-term (*i.e.*, multiple years) measurements are needed from a cluster of EC systems that can account for the effects of management, soil type, landscape position, and inter-annual climatic variability. However, comparative studies of CO_2 fluxes and ET in differently managed winter wheat under the same climatic regime is scarce. The general objective of this study was to determine seasonality, daily magnitudes, and seasonal (October–May) and annual (January – December) budgets of CO_2 fluxes [net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (ER)] and ET of multi-purpose winter wheat production systems in the SGP of the U.S. using EC systems. The expected order for carbon and water budgets is grain only > graze-grain > graze-out wheat, based on the levels of biomass and canopy coverage. Quantitative relationships of CO_2 fluxes and ET against satellite-derived enhanced vegetation index (EVI) and ground-measured biometric variables (leaf area index, dry biomass, and canopy coverage) were also determined to explain variability in fluxes across sites and years.

2. Materials and methods

2.1. Site descriptions

As parts of the GRL-FLUXNET (a network of 16 integrated flux measurement systems) at the United States Department of Agriculture – Agricultural Research Service (USDA–ARS), Grazinglands Research Laboratory and USDA's Long-Term Agroecosystem Research (LTAR) network, EC towers were installed in eight winter wheat fields in the Grazinglands Research on agroEcosystems and ENvironment (GREEN) farm (Wagle et al., 2019; Wagle et al., 2018). The GREEN farm occupies 178-ha of cropland at the USDA–ARS, Grazinglands Research Laboratory, El Reno, Oklahoma. This study area was in continual use for production of different annual and perennial forages since the mid-20th century. The size of the eight research fields used in this study ranged from ~10 to 22 ha (Fig. 1).

The research fields were paired within each of four zones based on landscape exposure: northern, southern, eastern, and a rolling upland landscape without a dominant exposure. The area of each exposure was sub-divided into two paired fields to assign either conservation or conventional tillage management. For ease of presentation and comparison, we use the term conventional till (CT) and no-till (NT) where NT refers to the minimum or reduced tillage practice using USDA, Natural Resources Conservation Service (NRCS), Conservation Practice Code 345 as a guide (USDA-NRCS, 2016). Two fields (C1 and C2) were assigned to graze-out winter wheat pastures by yearling stocker cattle each year as a control, which is a typical management practice in Oklahoma. The remaining fields followed a four-year crop rotation that included canola and three forms of management (grain-only, graze-grain, and graze-out)

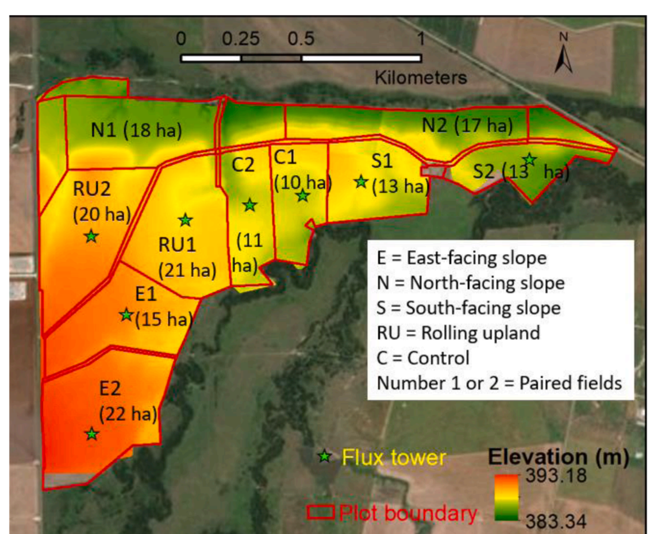

Fig. 1. Locations of flux towers in eight fields of GREEN Farm at the USDA-ARS, Grazinglands Research Laboratory, El Reno, Oklahoma, USA.

applied to winter wheat. Treatments for a four-year rotation cycle were: graze-out wheat (year 1), canola for grain (year 2), grain-only wheat (year 3), and graze-grain wheat (year 4). Canola was planted after graze-out wheat to limit the negative impacts of wheat residues on canola establishment and productivity. Grain-only wheat was planted after canola to take advantage of weed control and improvement in wheat grain yield (Bushong et al., 2012). The crop rotation and tillage treatment were initiated in 2015, while grazing began from the 2016-2017 growing season. The crop rotation schedule from 2015 to 2019 is presented in Table 1.

The primary soils within the area are a complex of Mollisols, including Renfrow-Kirkland silt loams, Bethany silt loams, and Norge silt loams with an average pH ≤ 5.8, electrical conductivity < 300 μS cm^{-1}, and soil bulk density of 1.34-1.45 g cm^{-3} (USDA-NRCS, 1999). For the 2015-2016 growing season, winter wheat (*cv.* WB-4458 @ 90 kg seeds ha^{-1}) was sown at ~19 cm row spacing. All wheat fields were planted after mid-October in 2015 for grain-only wheat production as a pre-treatment growing season. From 2016 onward, winter wheat (*cv.* Gallagher @ 90 kg seeds ha^{-1}) was sown at ~19 cm row spacing at different times to meet management requirements. If weather allowed, wheat fields to be grazed were sown by mid-September, while grain-only wheat fields were sown in mid-October. In general, wheat fields assigned to wheat production were harvested by mid-June. Depending on the purpose of wheat, the fields were kept fallow from three to four months during summer. Round-up tolerant canola (*cv.* DKW46-15 at ~6 kg seeds ha^{-1}) was also sown at ~19 cm row spacing in October and harvested in June. Commonly used management practices (e.g., application of variables rates of fertilizers and agricultural lime based on soil tests, and application of herbicides and pesticides as needed) were performed in all fields to maintain high production potentials with a yield goal of at least ~2.7 t ha^{-1}. For example, fields received variable rates of nitrogen from 48.2 to 78.5 kg ha^{-1} during the 2016-2017 growing season. Similarly, only few fields received variable rates of phosphorus and lime based on soil tests.

2.2. Eddy covariance and meteorological measurements

All eight EC towers were deployed by the beginning of the 2016-2017 growing season (October 2016). All EC systems (2.5 m tall), comprised of a 3-D sonic anemometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA) and an open path infrared gas analyzer (LI-7500-RS, LI-COR Inc., Lincoln, NE, USA), were installed near the center of each fields, with fetch lengths varying from >100 m to few hundred meters in all directions. Maximum canopy heights were observed up to ~1.25 m for grain-only wheat in spring 2017, but they were ≤1.0 m in other seasons even for grain-only wheat. During peak growth in spring 2017, a footprint model (Kljun et al., 2004) showed that 86-91% of CO_2 fluxes (non-gap filled best quality fluxes of flag 0 only) were received from <100 m radius of the EC systems (Wagle et al., 2018). It illustrated that fetch lengths were large enough for EC systems in all fields. Without accounting for stored energy in soil and plant canopy, energy balance of 0.75-0.76 was observed in grain-only wheat fields, while it was slightly lower (0.65-0.69) in grazed fields (Wagle et al., 2018). Eddy covariance systems and all soil sensors (including soil heat flux plates) were installed inside fences for protection from cattle, but net radiometers were mounted on the edges of fences to measure net radiation over grazed areas. Underestimation of soil heat fluxes due to more biomass inside enclosures probably resulted in slightly lower values of energy balance closure in grazed fields. Since the reasons for energy imbalance are still not fully understood, we did not correct fluxes for energy balance closure.

Soil heat flux (using HFT3, REBS Inc., Bellevue, WA, USA at ~8 cm depth), soil water content (using Hydra Probe, Stevens Water Monitoring Systems Inc., Portland, OR, USA at ~5 cm), and soil temperature (using thermocouples at 2 and 6 cm depths) were measured at each site. We also measured above canopy air temperature and relative humidity (using HPM45C, Vaisala, Helsinki, Finland), infrared surface temperature (using infrared thermometer, Apogee Instruments Inc., Logan, UT, USA), net radiation (using NRLite, Kipp & Zonen, Delft, The Netherlands), and incoming photosynthetic photon flux density (using LI-190 quantum sensor, LI-COR Inc., Lincoln, NE, USA). Average 30-min values of meteorological variables were recorded in data loggers (CR 1000, 3000 or 5000, Campbell Scientific, Logan, UT, USA). Rainfall data were obtained from the Oklahoma El Reno Mesonet Station (http://mesonet.org/), which is located in a pasture within 1.3 km of the study area.

Table 1
Crop rotations and grain yields (t ha^{-1}, in parenthesis) during 2015 to 2019 at eight eddy covariance flux sites. Grazing was initiated during the 2016-2017 growing season. Graze-out wheat fields were not harvested for grains.

Site	2015-2016	2016-2017	2017-2018	2018-2019
E2 (CT)	Canola	Grain-only wheat (4.86)	Graze-grain wheat (1.67)	Graze-out wheat
E1 (NT)	Canola	Grain-only wheat (3.53)	Graze-grain wheat (1.55)	Graze-out wheat
RU2 (CT)	Grain-only wheat (4.69)	Canola	Grain-only wheat (2.94)	Graze-grain wheat
RU1 (NT)	Grain-only wheat (5.4)	Canola	Grain-only wheat (2.61)	Graze-grain wheat (1.98)
C2 (CT)	Grain-only wheat (3.68)	Graze-out wheat	Graze-out wheat	Graze-out wheat
C1 (NT)	Grain-only wheat (5.41)	Graze-out wheat	Graze-out wheat	Graze-out wheat
S1 (NT)	Grain-only wheat (4.73)	Graze-grain wheat (0.98)	Graze-out wheat	Canola
S2 (CT)	Grain-only wheat (4.62)	Graze-grain wheat (1.08)	Graze-out wheat	Canola

CT: Conventional till, NT: No-till (conservation tillage)

2.3. Eddy covariance data processing

We computed 30-min fluxes from high frequency (10 Hz) raw data collected using EddyPro software (LI-COR Inc., Lincoln, Nebraska, USA) version 7.0.6 in express mode (*i.e.*, default settings). We excluded poor quality fluxes with flag 2 (*i.e.*, a bad quality flag based on a combination of partial flags for steady state and turbulent condition tests in EddyPro) and physically unreliable flux values such as CO_2 fluxes beyond ±50 μmol m^{-2} s^{-1}, and sensible heat and latent heat fluxes outside the range of -200 to 500 W m^{-2} and -200 to 800 W m^{-2}, respectively (Sun et al., 2010; Wagle and Kakani, 2014; Zeeman et al., 2010). In addition, statistical outliers (*i.e.*, beyond ±3.5 standard deviation based on two-week running windows) were removed (Wagle et al., 2019; Wagle et al., 2020a). To retain reliable pulses in fluxes during special events (e.g., rain), four or more consecutive reliable flux values beyond ±3.5 standard deviation on a day were retained (Wagle et al., 2020b).

The REddyProc package was used to fill gaps in eddy fluxes and meteorological variables. Look-up tables, mean diurnal course, and marginal distribution sampling procedures are implemented for gap filling in REddyProc (Wutzler et al., 2018). The REddyProc package fills gaps in fluxes and meteorological variables by exploiting the covariation of fluxes with meteorological variables, and their temporal autocorrelation based on look-up tables and mean diurnal course methods (Falge et al., 2001; Reichstein et al., 2005). The most widely used nighttime-based flux partitioning method (Reichstein et al., 2005), using an Arrhenius-type (Lloyd and Taylor, 1994) temperature response function of nighttime NEE (which is equivalent to ER), was used to partition NEE into GPP and ER. The gap-filled 30-min time series NEE data were summed to calculate cumulative NEE for daily, seasonal, and annual timescales. Uncertainty (gap filling) estimates of cumulative NEE (± SD, standard deviation) were determined from the standard deviations of data points used for gap filling. Negative NEE indicates the fields are CO_2 sinks.

2.4. Biometric measurements and remote sensing data

During the active growing seasons (*i.e.*, before and after winter dormancy), periodic measurements (approximately every two weeks) of leaf area index (LAI, using LAI-2200C plant canopy analyzer, LI-COR Inc., Lincoln, Nebraska, USA) and percent of canopy cover [Canopy%, using Canopeo app, http://www.canopeoapp.com/ (Patrignani and Ochsner, 2015)] were collected from a minimum of five random locations in a transect within a 100 m radius of the EC towers. Aboveground biomass samples were destructively collected from the same five 0.5 × 0.5 m^2 quadrats to determine dry biomass weight (harvested samples were oven dried for 48-72 hours at 70°C). All five observations of biometric measurements were averaged for each sampling.

Landsat-derived enhanced vegetation index (EVI, a proxy of vegetation canopy greenness) at 30 m spatial resolution was integrated for each field to extract mean EVI values using ENVI software. We obtained Landsat surface reflectance products from both Landsat 7 ETM+ and Landsat 8 from the USGS EarthExplorer (http://earthexplorer.usgs.gov/) to compare crop phenology among fields. Image artifacts due to cloud, cloud shadow, and aerosols were excluded using quality assessment information. Consequently, clear pixels as shown by the pixel quality band were used.

2.5. Regression analysis of EVI and biometric variables with CO_2 fluxes and ET

We examined quantitative relationships of 7-day average (3-days before and 3-days after the sampling or Landsat overpass dates) values of NEE, GPP, ER, and ET with Landsat-derived EVI and ground-measured biometric variables (biomass, LAI, and Canopy%) individually across winter wheat fields. To avoid multicollinearity (*i.e.*, correlations of independent variables to each other), we did not use two or more biometric variables in the same regression model. Best regression models (polynomial or linear functions) were selected based on the highest level of significance (p-value) and fit statistics (the coefficient of determination, R^2).

3. Results and discussion

3.1. Weather conditions

The climate is temperate continental, with the 30-year mean (1981-2010) annual temperature ~15 °C and rainfall ~925 mm (Wagle et al., 2018). Cumulative monthly rainfall and monthly average air temperature from 2015 to 2019 are compared with the 30-year mean values in Figure 2. Mean (30-year) growing season (from October to May of the following year) rainfall for winter wheat was 567 mm. Cumulative rainfall amounts were 494 mm, 517 mm, 264 mm, and 896 mm during the 2015-2016, 2016-2017, 2017-2018, and 2018-2019 growing seasons, respectively. Fall (September–November) 2016 was relatively drier (118 mm rainfall) compared to the 30-year mean of 247 mm. Fall 2015, 2017, and 2018 received 0.81, 0.93, and 1.4 times of the 30-year mean rainfall. Spring (March–May) 2018 was severely dry with cumulative rainfall of 105 mm compared to the 30-year mean of 286 mm. Spring 2016 and 2017 received cumulative rainfall of 219 and 343 mm, respectively. Spring 2019 was exceptionally wet with cumulative rainfall ~600 mm (~400 mm in May).

3.2. Crop growth and grain yields

During the 2015-2016 growing season, six fields were planted with winter wheat (grain-only) and two fields were planted with canola. Wheat grain yield was the lowest (3.68 at t ha^{-1}) at C1 (CT), but ranged from 4.6 to 5.4 t ha^{-1} in the other five wheat fields (Table 1).

During the 2016-2017 growing season, six fields were planted with wheat (a pair of CT and NT for each purpose: grain-only, graze-grain, and graze-out) and two fields (CT and NT) were planted with canola for grain harvest. Wheat grain yield ranged from ~1 (graze-grain fields) to 4.86 t ha^{-1} (grain-only CT field) in 2017. Reductions in grain yield associated with grazing ranged from 0.27 to 0.94 t ha^{-1} in a long-term (1991-2011) study conducted in Marshall, Oklahoma (Edwards et al., 2018). In their study period, an average grain yield reduction for graze-grain wheat was ~18% compared to grain-only wheat. Poor vegetation stands due to armyworm (*Spodoptera frugiperda*) infestation and replanting of wheat caused substantially lower yields in the graze-grain fields of our study. The EVI, LAI, and biomass data also illustrated poor vegetation growth in graze-grain fields. Seasonal dynamics of EVI were similar in CT and NT grain-only wheat fields, with maximum EVI of ~0.8 in peak growth (*i.e.*, mid-March, Fig. 3a). Peak LAI reached ~7-7.5 m^2 m^{-2} and dry biomass reached ~1.3 kg m^{-2} in both grain-only wheat fields. In comparison, peak EVI during mid-March approximated 0.7 and 0.4 in CT and NT graze-grain wheat fields, respectively (Fig. 4a). Peak LAI reached ~3.3 and 2.7 m^2 m^{-2} at the end of March in CT and NT graze-grain wheat fields, respectively. Maximum-recorded dry biomass approximated 0.6 and 0.3 kg m^{-2} in CT and NT graze-grain wheat fields, respectively. Peak EVI values during mid-March were ~0.6 and 0.45 in CT and NT graze-out fields, respectively (Fig. 5a). Graze-out wheat fields had higher values of LAI (~4 m^2 m^{-2} in both CT and NT fields) at the end of March than those at the graze-grain wheat fields. Maximum-recorded dry biomass was ~0.6 and 0.26 kg m^{-2} in CT and NT graze-out wheat fields, respectively.

During the 2017-2018 growing season, all eight fields were planted with wheat (one pair of CT and NT each for grain-only and graze-grain, and two pairs of CT and NT for graze-out). Grain yields of 1.67 (CT) and 1.55 (NT) t ha^{-1} for graze-grain fields in 2018 were ~40% less than those of 2.94 (CT) and 2.61 (NT) t ha^{-1} for grain-only fields. Substantially lower grain yields were recorded in all harvested fields in 2018 compared to 2016 and 2017. This response was likely attributed to poor germination caused by overly wet conditions during and after planting. For example, wheat was planted in mid-October in 2016 but in late October in 2017 due to wet conditions (cumulative rainfall of 480 mm during August–October 2017, compared to 154 mm in 2016). Additional rainfall after planting added to the poor germination in fall 2017. For grain-only wheat fields, maximum EVI values were ~0.54 (CT) and 0.38

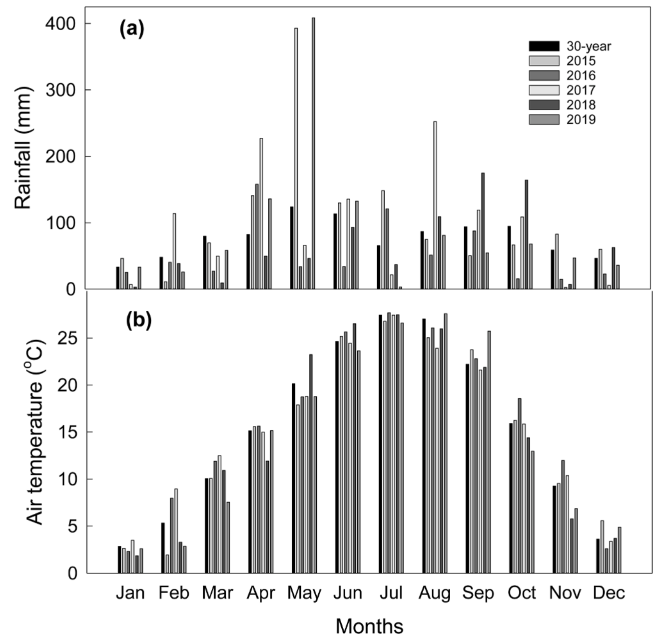

Fig. 2. Comparison of cumulative monthly rainfall and monthly average air temperature during 2015 to 2019 as compared to the 30-year (1981-2010) monthly mean values.

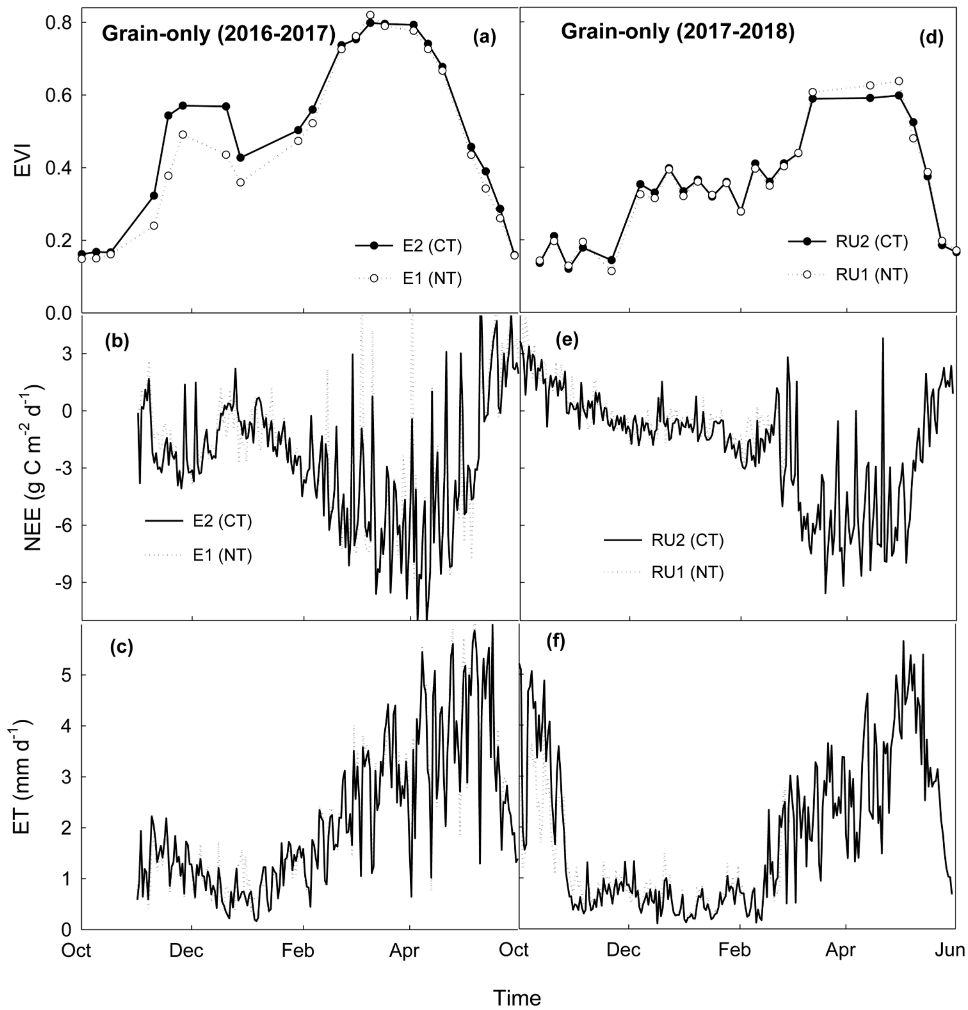

Fig. 3. Seasonal dynamics of Landsat-derived enhanced vegetation index (EVI) and eddy covariance measured daily net ecosystem CO_2 exchange (NEE) and evapotranspiration (ET) for grain-only wheat fields.

(NT) during mid-November 2016 (Fig. 3a), but were 0.12-0.14 during mid-November 2017 (Fig. 3d). In addition, the January–April period of 2018 was substantially drier (cumulative rainfall of 101 mm compared to 398 mm in 2017). Further, the January–April period was cooler in 2018 (an average T_a of ~7°C compared to ~10°C in 2017). Consequently, large differences were observed in crop growth between spring 2017 and 2018. For example, LAI approximated 7 m^2 m^{-2} at the end of March 2017 in both (CT and NT) grain-only wheat fields, but it was only ~3.5 m^2 m^{-2} at the end of March 2018 in both grain-only fields. Similarly, peak EVI for grain-only wheat during mid-March 2018 reached ~0.6 (Fig. 3d) compared to ~0.8 during mid-March 2017 (Fig. 3a). Dry biomass was 0.63-0.66 kg m^{-2} at the end of March 2017 compared to 0.19-0.20 kg m^{-2} at the end of March 2017 in grain-only wheat fields.

During the 2018-2019 growing season, six fields were planted for wheat (two pairs of CT and NT for graze-out wheat and a pair of CT and NT for graze-grain wheat) and two fields (a pair of CT and NT) were planted for canola. No fields were planted for grain-only wheat. Grain yield of ~2 t ha^{-1} was recorded in a graze-grain field in 2019.

The maximum grain yields of ~5 t ha^{-1} or higher in this study were higher than the average yield (~3.0 t ha^{-1}) recorded for the Oklahoma, Texas, and Kansas portions of the SGP (Patrignani et al., 2014). We observed larger reductions in grain yield for dual-purpose (graze-grain) wheat than the reported reductions of <20% in a long-term study within Oklahoma (Edwards et al., 2018), due to contrasting weather conditions and influence of other factors (e.g., insect pests, poor germination, and grazing pressure) over our study period. Thus, additional years of grain yield data from grain-only and graze-grain wheat fields are required to determine reductions in grain yield associated with grazing.

3.3. Seasonality and daily magnitudes of NEE, GPP, ER, and ET

Highly variable seasonality (Figs. 3-5) and magnitudes (Table 2) of eddy fluxes were found across winter wheat fields managed for different (grain-only, graze-grain, and graze-out) purposes. Large variations in seasonality and daily magnitudes of fluxes were observed even for the same purpose wheat (e.g., grain-only) in different fields and different growing seasons due to differences in tillage practices, crop growth and development, and meteorological conditions. Over the study period, daily maximum values of NEE, GPP, ER, and ET for grain-only wheat reached -10.7 g C m^{-2}, 18.7 g C m^{-2}, 10.8 g C m^{-2}, and 5.8 mm, respectively, under CT, and -10.5 g C m^{-2}, 18.3 g C m^{-2}, 12.3 g C m^{-2}, and 6.1 mm, respectively, under NT management (Table 2). For graze-grain wheat, daily maximum values of NEE, GPP, ER, and ET reached -9.3 g C m^{-2}, 15.0 g C m^{-2}, 11.5 g C m^{-2}, and 6.7 mm, respectively, under CT, and -7.4 g C m^{-2}, 11.1 g C m^{-2}, 7.7 g C m^{-2}, 4.5 mm, respectively, under NT. For graze-out wheat, daily maximum values of NEE, GPP, ER, and ET reached -8.4 g C m^{-2}, 16.1 g C m^{-2}, 11.3 g C m^{-2}, and 6.6 mm, respectively, under CT, and -6.5 g C m^{-2}, 11.6 g C m^{-2}, 9.0 g C m^{-2}, and 6.4 mm, respectively, under NT.

Similar seasonality and magnitudes of fluxes were observed between CT and NT wheat fields when vegetation stands were identical (for example, fields E2 and E1 during the 2016-2017 growing season,

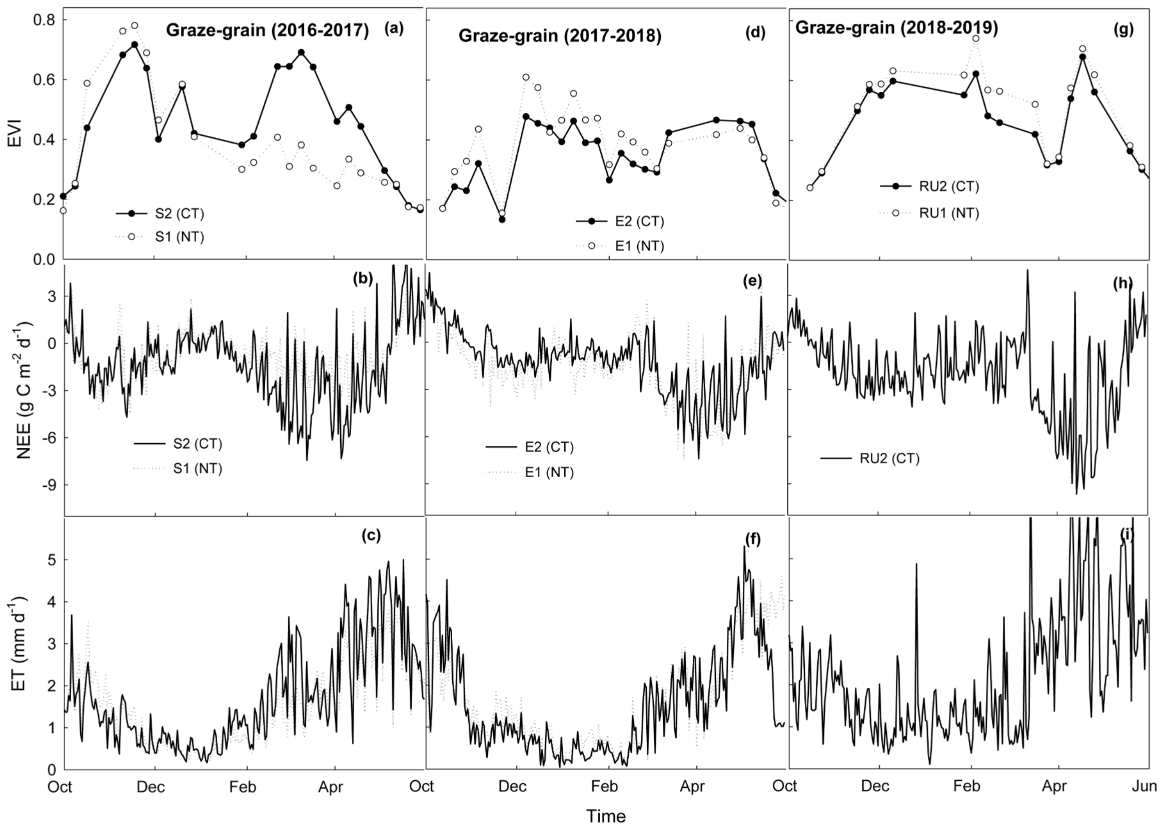

Fig. 4. Seasonal dynamics of Landsat-derived enhanced vegetation index (EVI) and eddy covariance measured daily net ecosystem CO_2 exchange (NEE) and evapotranspiration (ET) for graze-grain wheat fields.

Fig. 3b, 3c). Thus, variable rates of fluxes in CT and NT fields during the same growing season were mainly caused by differences in crop growth and development due to tillage as well as external factors such as pest infestations and water drainage issues in some areas under wet conditions. For example, poor vegetation growth caused by armyworm infestation in the NT graze-grain field (S1) led to substantially lower flux values as compared to the counterpart CT graze-grain field (S2) during the 2016-2017 growing season (Fig. 4a–4c). The results indicated other factors had larger impacts on crop phenology and fluxes than tillage systems.

Overall, grain-only wheat fields had the largest magnitudes of eddy fluxes due to higher biomass and canopy coverage. In general, flux magnitudes followed the expected order: grain only > graze-grain > graze-out. A previous study, based on the 2016-2017 growing season only, reported that Canopy%, LAI, and biomass were key variables for explaining across-field variations in NEE, GPP, and ER, respectively, at these wheat fields (Wagle et al., 2018). Grazing reduces tiller number, internode elongation, canopy height and coverage, LAI, and biomass in wheat (Virgona et al., 2006), resulting in lower values of CO_2 fluxes and ET.

The maximum daily NEE for winter wheat in our study approximated -11 g C m^{-2}, which was comparable to -10 g C m^{-2} reported for rainfed winter wheat in Ponca City and Billings, Oklahoma, USA (Arora, 2003; Fischer et al., 2007) and -12 g C m^{-2} reported for rainfed winter wheat in Germany (Anthoni et al., 2004a; Schmidt et al., 2012). Daily NEE up to -13.3 g C m^{-2} was observed for well-watered wheat in Boardman, Oregon, USA (Baldocchi, 1994) as irrigation generally results in greater production due to lack of water stress. We observed a maximum daily GPP of ~19 g C m^{-2}, which was similar to the maximum GPP reported for winter wheat in Germany (Schmidt et al., 2012), France (Béziat et al., 2009), and Ponca City, Oklahoma (Falge et al., 2002). The observed maximum daily ER rates of 11-12 g C m^{-2} in our study were similar to reported values (11.5 g C m^{-2}) for winter wheat in South West France (Béziat et al., 2009), but higher than the ER rate of ~8 g C m^{-2} in Germany (Aubinet et al., 2009) probably due to lower temperature (mean annual temperature of ~10°C compared to ~15°C in our study) and radiation in Germany due to higher latitude (50° N). Metabolic activity of soil microbial communities is strongly influenced by temperature (Allison et al., 2010). Schmidt et al. (2012) recorded ER rates of approximately 12 and 4 g C m^{-2} d^{-1} at 20 and 10°C, respectively, for winter wheat in Germany. The maximum daily ET in our study reached 6-7 mm d^{-1}, which was similar to reported values (up to 7 mm d^{-1}) for rainfed winter wheat in north-central Oklahoma, USA (Burba and Verma, 2005). Daily ET of 7.3 mm d^{-1} was observed for an irrigated wheat field in Morocco (Aouade et al., 2016). In comparison, the maximum daily ET was only ~5 mm d^{-1} for winter wheat in Thuringia, Germany (Anthoni et al., 2004b) though NEE rates were similar or even little higher than in our study. Lower ET rates in Germany can be attributed to lower temperature and rainfall (annual rainfall of ~500 mm compared to ~900 mm in our study).

Overall, the magnitudes of CO_2 fluxes and ET in this study agree with those reported for winter wheat in other parts of the world. However, the magnitudes of fluxes can vary greatly from season to season for the same location as seen in this study. Different magnitudes of fluxes across different studies can be expected for differences in crop varieties and their vegetation properties, climatic regions and conditions, growing season, and management activities. Therefore, we recommend that studies report detailed information about crop variety, site location (e.g., latitude, longitude, and elevation), mean annual temperature and rainfall, vegetation characteristics (e.g., maximum LAI and biomass), grain yield, and management practices (e.g., tillage, grazing or biomass removal, and irrigation) to better explain discrepancies in fluxes for the same crop across-sites worldwide.

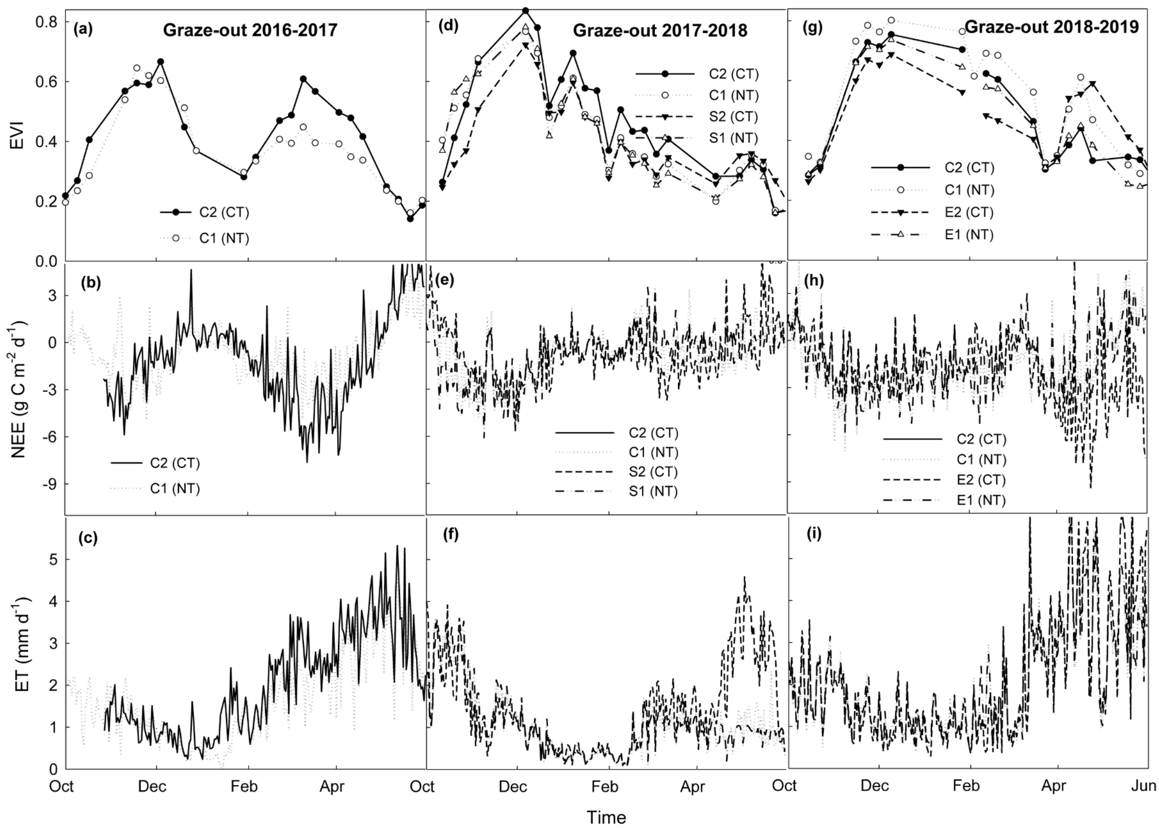

Fig. 5. Seasonal dynamics of Landsat-derived enhanced vegetation index (EVI) and eddy covariance measured daily net ecosystem CO_2 exchange (NEE) and evapotranspiration (ET) for graze-out wheat fields.

Table 2
The magnitudes (average of 3-maximum daily values) of net ecosystem CO_2 exchange (NEE, g C m^{-2} d^{-1}), gross primary production (GPP, g C m^{-2} d^{-1}), ecosystem respiration (ER, g C m^{-2} d^{-1}), and evapotranspiration (ET, mm d^{-1}) during 2016-2019 measuring period in multi-purpose wheat fields. Crop rotations are shown in Table 1.

Site	2016-2017				2017-2018				2018-2019			
	NEE	GPP	ER	ET	NEE	GPP	ER	ET	NEE	GPP	ER	ET
E2 (CT)	-10.7	18.7	10.8	5.8	*-6.7*	*10.5*	*6.1*	*4.9*	**-8.4**	**16.1**	**10.4**	**6.6**
E1 (NT)	-10.5	18.3	12.3	6.1	*-7.4*	*11.1*	*7.7*	*4.5*	**-5.5**	**11.6**	**8.2**	**6.1**
RU2 (CT)	Canola				-9.1	11.1	6.4	5.5	*-9.3*	*15.0*	*11.5*	*6.7*
RU1 (NT)	Canola											
C2 (CT)	**-7.3**	**13.7**	**9.5**	**5.2**								
C1 (NT)	**-4.8**	**8.5**	**6.6**	**4.4**	**-5.2**	**8.6**	**6.1**	**3.6**	**-6.5**	**11.3**	**9.0**	**6.4**
S1 (NT)	*-4.4*	*8.8*	*7.4*	*3.9*	**-5.4**	**8.7**	**5.7**	**3.5**	Canola			
S2 (CT)	*-7.2*	*13.5*	*9.8*	*4.9*	**-5.0**	**9.9**	**11.3**	**4.3**	Canola			

CT: Conventional till, NT: No-till (conservation tillage). Regular fonts: grain-only, italic fonts: graze-grain, and bold fonts: graze-out wheat.

3.4. Seasonal budgets of NEE, GPP, ER, and ET

Highly variable seasonal budgets of NEE, GPP, ER, and ET were found across winter wheat fields managed for different (grain-only, graze-grain, and graze-out) purposes (Table 3), due to different meteorological conditions, management activities, and levels of crop development among growing seasons. Over the study period, seasonal cumulative values of NEE for grain-only wheat ranged from -429 ± 9 to -564 ± 9 g C m^{-2} under CT and reached -510 ± 10 g C m^{-2} under NT. For graze-grain wheat, seasonal cumulative values of NEE ranged from -295 ± 8 to -484 ± 10 g C m^{-2} under CT and from -151 ± 7 to -379 ± 8 g C m^{-2} under NT. For graze-out wheat, seasonal cumulative values of NEE ranged from -149 ± 8 to -468 ± 9 g C m^{-2} under CT and from -155 ± 7 to -351 ± 9 g C m^{-2} under NT. Graze-out fields were not harvested for grains. In general, seasonal budgets of NEE followed the expected order: grain only > graze-grain > graze-out, based on the levels of biomass and canopy coverage. However, some differences were observed due to the influence of other factors (e.g., armyworm infestation, meteorological conditions, and grazing pressure) on vegetation growth. Consistent with our results, large variations in seasonal sums of NEE were reported by previous studies. Schmidt et al. (2012) and Aubinet et al. (2009) reported large seasonal (October/November–July/August) NEE sums of -445 to -502 g C m^{-2}, and -630 and -730 g C m^{-2} for winter wheat (grain-only) in Germany and Belgium, respectively. Seasonal (October–June) NEE sums ranged from -78 to -152 g C m^{-2} for winter wheat (grain-only) in the North China Plain (Li et al., 2006). Similarly, another study reported seasonal (October–August) NEE sums of -303 and -395 g C m^{-2} for winter wheat (grain-only) in the North China Plain (Lei and Yang, 2010). Large differences in seasonal NEE budgets among studies may be explained by differences in climate and management practices.

Our results showed that all winter fields, including graze-out, were large sinks (ranged from -149 ± 8 to -564 ± 9 g C m^{-2}) of CO_2 during

Table 3
Seasonal (October-May) cumulative values of net ecosystem CO_2 exchange (NEE, g C m^{-2}), gross primary production (GPP, g C m^{-2}), ecosystem respiration (ER, g C m^{-2}), and evapotranspiration (ET, mm) during 2016-2019 measuring period in multi-purpose wheat fields. Crop rotations are shown in Table 1. Uncertainty (gap filling) estimates of cumulative NEE (± SD, standard deviation) were determined from the standard deviations of data points used for gap filling.

Site	2016-2017				2017-2018				2018-2019			
	NEE	GPP	ER	ET	NEE	GPP	ER	ET	NEE	GPP	ER	ET
E2 (CT)	-564 ± 9	1596	1032	459	*-295 ± 8*	*918*	*623*	*365*	**-468 ± 9**	**1388**	**920**	**515**
E1 (NT)	-510 ± 10	1526	1016	469	*-379 ± 8*	*1085*	*706*	*403*	**-351 ± 9**	**1398**	**1047**	**502**
RU2 (CT)	Canola				-429 ± 9	987	558	439	*-484 ± 10*	*1373*	*889*	*521*
RU1 (NT)	Canola											
C2 (CT)	**-229 ± 14**	**859**	**630**	**431**								
C1 (NT)	**-178 ± 9**	**961**	**674**	**410**	**-155 ± 7**	**888**	**649**	**267**	**-309 ± 9**	**1371**	**1063**	**499**
S1 (NT)	*-151 ± 7*	*1046*	*895*	*370*	**-211 ± 7**	**899**	**688**	**260**	Canola			
S2 (CT)	*-329 ± 9*	*1385*	*1056*	*418*	**-149 ± 8**	**1066**	**917**	**345**	Canola			

CT: Conventional till, NT: No-till (conservation tillage). Cumulative values were for November-May for E2, E1, and C2 for the 2016-2017 growing season. Regular fonts: grain-only, italic fonts: graze-grain, and bold fonts: graze-out wheat.

growing seasons (Table 3). When removal of carbon from grain harvest was accounted, assuming 40% of carbon content in wheat grains (Kumar et al., 2014), the loss of carbon is estimated to be 40 g C m^{-2} for removal of 1 t ha^{-1} (100 g m^{-2}) grains. Net ecosystem carbon balance (NECB), calculated as the difference between net ecosystem production (NEP = -NEE) and carbon removal through grain harvest, would range from 311 to 370 g C m^{-2} for grain-only wheat and from 112 to 317 g C m^{-2} for graze-grain wheat. Graze-out wheat fields were grazed for the entire season (*i.e.*, no grain harvests). Farmers and ranchers in the region graze wheat to diversify income, minimize production risk under unfavorable climatic conditions, and increase overall profitability of wheat production systems. This study did not consider direct additional benefits of cattle grazing such as nutrient cycling and animal gains.

Over the study period, seasonal cumulative values of ET for grain-only wheat ranged from 439 to 459 mm under CT and reached 469 mm under NT. For graze-grain wheat, seasonal cumulative values of ET ranged from 365 to 521 mm under CT and from 370 to 403 mm under NT. For graze-out wheat, seasonal cumulative values of ET ranged from 345 to 515 mm under CT and from 260 to 502 mm under NT. Seasonal ET followed the expected order: grain only > graze-grain > graze-out in general, with some exceptions due to external factors mentioned above. During the 2016-2017 growing season, seasonal ET ranged from ~70% to 90% of seasonal rainfall. During the 2017-2018 growing season, seasonal ET ranged from approximately 98% in graze-out wheat fields to 166% in grain-only wheat fields when compared to seasonal rainfall. During the 2018-2019 growing season, seasonal ET values in wheat fields were ~56-58% of seasonal rainfall due to higher seasonal rainfall of 896 mm. During the 2017-2018 growing season, a larger percentage of ET with respect to rainfall was due to substantially lower seasonal rainfall (264 mm). Likewise, a smaller percentage of ET with respect to rainfall for the 2018-2019 growing season was due to substantially higher rainfall (seasonal rainfall of 896 mm with 408 mm rainfall in May).

3.5. Annual budgets of NEE, GPP, ER, and ET

Winter wheat fields, left fallow during summer, were from near CO_2 neutral to large sinks of CO_2 at annual (calendar year: January–December) scales (Table 4), without accounting for the removal of carbon from grain harvest. As expected, maximum (negative sign convention) cumulative annual NEE was observed for grain-only wheat followed by graze-grain systems. Cumulative annual NEE was up to -242 ± 12 g C m^{-2} in E1(NT) and -183 ± 12 g C m^{-2} in E2 (CT) in 2017 as those fields had grain-only wheat in spring and graze-grain wheat in fall of 2017. Grain-only wheat in both spring and fall seasons could increase carbon sink potentials in our study. If removal of carbon from grain harvest was

Table 4
Cumulative values of net ecosystem CO_2 exchange (NEE, g C m^{-2}), gross primary production (GPP, g C m^{-2}), ecosystem respiration (ER, g C m^{-2}), and evapotranspiration (ET, mm) in multi-purpose wheat fields for annual and fallow periods. Crop rotations are shown in Table 1. Annual sums were not reported if measurements were missing for any month or if canola was part of the cropping system. Uncertainty (gap filling) estimates of cumulative NEE (± SD, standard deviation) were determined from the standard deviations of data points used for gap filling.

Site	2017				2019			
Annual (calendar year: January-December)								
	NEE	GPP	ER	ET	NEE	GPP	ER	ET
E2 (CT)	-183 ± 12	1970	1787	732				
E1 (NT)	-242 ± 12	1938	1696	676	79 ± 8	1854	1933	760
RU2 (CT)					-163 ± 8	1726	1563	778
RU1 (NT)								
C2 (CT)								
C1 (NT)	-5 ± 10	1569	1564	644	24 ± 9	1540	1564	796
S1 (NT)	-29 ± 10	1605	1576	554				
S2 (CT)	15 ± 12	1919	1034	648				
Fallow period (June-September)								
E2 (CT)	299 ± 8	386	685	216	104 ± 5	1300	1404	270
E1 (NT)	263 ± 7	325	588	146	168 ± 5	801	969	258
RU2 (CT)	226 ± 8	409	635	237	165 ± 4	499	664	259
RU1 (NT)	363 ± 8	319	682	215				
C2 (CT)								
C1 (NT)	226 ± 5	484	710	194	223 ± 5	402	625	296
S1 (NT)	222 ± 8	475	697	146	122 ± 6	1097	1219	284
S2 (CT)	356 ± 9	501	857	193				

considered then NECB for 2017 would be -11 g C m^{-2} yr^{-1} (loss of carbon) and 101 g C m^{-2} yr^{-1} (gain of carbon) in E1 and E2, respectively. Considering carbon loss through grain harvest and some uncertainties in the measured NEE, our results indicate that wheat fields, with summer fallow, can be a small source to sinks of carbon at annual scales depending on harvested quantity (*i.e.*, large or small).

Similar to our results, Anthoni et al. (2004) reported annual (calendar year: January–December) NEE from -185 to -245 g C m^{-2} and Schmidt et al. (2012) reported annual NEE of -270 g C m^{-2} for winter wheat (grain-only) in Germany. In Schmidt et al. (2012) and Anthoni et al. (2004), wheat fields were fallow for about 2.5 months from August to October. Wheat fields in our study were fallow for about 3.5-4 months depending on form of management (June–September/October).

Annual (calendar year) cumulative ET for multi-purpose wheat ranged from 554 to 732 mm in 2017 (50% to 66% of annual rainfall) and from 758 to 796 mm in 2019 (70-73% of annual rainfall). Higher proportion of ET to rainfall in 2019 could be attributed to more ET during the fallow period due to greater weed growth, as shown by the larger carbon fluxes (both GPP and ER) in Table 4. In general, ET was smaller in NT than in CT fields, illustrating the role of crop residues reducing ET loss. For example, during the 2017 summer fallow period when weed control was more effective, E1 (NT) had 32% less ET loss compared to its CT counterpart (E2), and S1 (NT) had 24% less ET loss compared to its CT counterpart (S2). The fallow period of 2019 was a more difficult year to control pigweeds (*Amaranthus spp.* L.) due to constant recurrence of weed growth during summer. Fallow period ET accounted for 22% to 33% of annual ET in 2017, but accounted for 33% to 37% in 2019, illustrating that better weed management during the fallow period could help reduce ET loss. Non-growing or fallow period for winter wheat occurs during summer months (June–September) with high evaporative demand. Moisture stress and management of weeds during the summer fallow period can result in large differences in the proportions of growing season to annual ET, and also the proportions of ET to rainfall.

An earlier study reported annual ET for grain-only rainfed wheat in north-central Oklahoma ranged from 714 to 750 mm, which was 55-61% of annual rainfall (Burba and Verma, 2005). Cumulative ET during July to February accounted for ~50% annual ET, and cumulative ET from March to June (active growing period to harvesting) ranged from 357 to 409 mm in their study. In comparison, cumulative ET for the same period in our study was ~350 mm in two grain-only wheat fields in 2017.

Most studies report eddy fluxes for one or two growing seasons for one or two sites only. Our study provides four seasons of flux data for eight multi-purpose wheat fields. For the entire study period, our wheat fields were kept fallow from June to September/October. The fields released large quantities of carbon (up to 363 ± 8 g C m^{-2}) during fallow periods (Table 4). Our new research initiatives began in summer 2021 to examine how growing cover crops during the summer fallow period affect annual carbon and water budgets, and subsequent wheat crop due to reduced availability of soil water. Long-term measurements from a cluster of EC systems over multi-purpose wheat fields need to be continued to quantify and report carbon and water budgets from other representative crop rotations and future climatic conditions. Additionally, such type of datasets are helpful to account for the effects of management, soil type, landscape position, and other non-climatic factors.

3.6. *Relationships of EVI and biometric variables with CO_2 fluxes and ET*

Across grain-only wheat fields, the EVI explained 72-73% of variations in NEE and GPP, but explained only 27% and 15% variations in ER and ET, respectively (data not shown). Across graze-grain wheat fields, the EVI explained 37% of variations in NEE and <5% of variations in GPP, ER, and ET. Across graze-out wheat fields, the EVI explained 43% of variations in NEE and <10% of variations in GPP, ER, and ET. Similar to the EVI, biometric variables such as LAI, Canopy %, and biomass also showed strong relationships with fluxes in grain-only wheat fields (Table 5), but they were poorly correlated (*i.e.*, none of the relationships had R^2 values of 0.5 or more) with CO_2 fluxes and ET in graze-grain or graze-out fields (data not shown).

Across-site analysis for grain-only wheat showed that aboveground biomass had strong quadratic relationships with NEE ($R^2 = 0.88$), GPP ($R^2 = 0.82$), ER ($R^2 = 0.69$), and ET ($R^2 = 0.81$). Quadratic relationships can be explained by difference in the timings of peak fluxes (April) and maximum biomass (May). The LAI showed strong linear relationships with NEE ($R^2 = 0.92$), GPP ($R^2 = 0.83$), and ER ($R^2 = 0.70$), but a polynomial (*i.e.*, quadratic) relationship with ET ($R^2 = 0.80$), as LAI and CO_2 fluxes peaked in April but ET peaked in May. Canopy% also explained 81% and 84% of variations in NEE and GPP, respectively, but explained 56% and 62% of variations in ER and ET, respectively. Overall, our results indicated that biomass and LAI alone explained >80% of variations in NEE, GPP, and ET. Similarly, Canopy% alone explained >80% of variations in NEE and GPP, and ~60% of variations in ER and ET.

Table 5
Regression analyses of 7-day average daily net ecosystem CO_2 exchange (NEE), gross primary production (GPP), ecosystem respiration (ER), and evapotranspiration (ET) against ground-measured leaf area index (LAI), aboveground dry biomass, and Canopy% across grain-only wheat fields. The units were g C m^{-2} d^{-1} for CO_2 fluxes, mm d^{-1} for ET, and kg m^{-2} for biomass.

S. No.	Regression equations	Model	R^2
Dependent variable: NEE			
1	$7.16\ \text{Biomass}^2 - 13.79\ \text{Biomass} - 0.14$	PR	0.88
2	$-1.01\ \text{LAI} - 0.46$	LR	0.92
3	$-0.086\ \text{Canopy\%} + 1.94$	LR	0.81
Dependent variable: GPP			
1	$-12.28\ \text{Biomass}^2 + 24.57\ \text{Biomass} + 2.1$	PR	0.82
2	$1.89\ \text{LAI} + 1.99$	LR	0.83
3	$0.15\ \text{Canopy\%} - 1.88$	LR	0.84
Dependent variable: ER			
1	$-4.68\ \text{Biomass}^2 + 10.92\ \text{Biomass} + 1.16$	PR	0.69
2	$0.95\ \text{LAI} + 1.24$	LR	0.70
3	$0.069\ \text{Canopy\%} - 0.14$	LR	0.56
Dependent variable: ET			
1	$-2.3\ \text{Biomass}^2 + 5.63\ \text{Biomass} + 0.81$	PR	0.81
2	$-0.11\ \text{LAI}^2 + 1.28\ \text{LAI} + 0.027$	PR	0.80
3	$0.04\ \text{Canopy\%} - 0.36$	LR	0.62

LR: linear regression, PR: polynomial regression, and R^2: the coefficient of determination.

Weaker relationships of biometric variables with ER than with NEE and GPP can be attributed to complex processes and interactions of ER with different drivers, which are still not fully clear (Migliavacca et al., 2015). The integrated measurement of ER includes both autotrophic and heterotrophic respirations, which are regulated differently by different drivers. Stronger relationships of satellite-derived EVI and ground-measured biometric variables with eddy fluxes for non-grazed fields than in grazed-fields could be related to different proportions of reduction in EVI or biometric variables compared to fluxes. Reductions in EVI or biometric variables due to the loss of the most photosynthetically active (younger) vegetation by cattle grazing can be smaller, compared to the contribution of removed vegetation on eddy fluxes. In addition, older vegetation left in the grazed fields tends to have lower photosynthesis rates due to decay in photosynthetic mechanisms. Meteorological conditions (*i.e.*, mainly rainfall), grazing density, and grazing duration can greatly influence regrowth of vegetation and eddy fluxes (Zhou et al., 2017). Thus, multiple years of data and further consideration on interactive effects of grazing and meteorological conditions on carbon and water dynamics are needed.

Strong relationships of remotely-sensed EVI and in-situ biometric observations with eddy fluxes demonstrated their potential to not only track phenology of winter wheat but also to model and explain spatio-temporal variability in CO_2 fluxes and ET. Since ground-based measurement of biometric variables (biomass, LAI, and Canopy%) is time consuming and laborious, it is not possible to collect such data at all times in all places. Development of accurate estimation methods of biomass, LAI, and Canopy% from remotely-sensed spectral reflectance (Asrar et al., 1984) could be viable options for extrapolating in-situ flux measurements at larger spatial and finer temporal scales.

4. Conclusions

Highly variable seasonality and magnitudes of CO_2 fluxes (NEE, GPP, and ER) and ET were found across winter wheat fields managed for different (grain-only, graze-grain, and graze-out) purposes. Large variations in fluxes were observed among years even for the same purpose wheat (e.g., grain-only) in different fields due to differences in meteorological and field conditions. The magnitudes of daily NEE, GPP, and ER of approximately -11, 19, and 12 g C m^{-2}, respectively, and daily ET of ~7 mm observed for grain-only wheat in this study were comparable to the reported values for winter wheat in the literature. As expected based on the levels of biomass and canopy coverage, carbon and water budgets generally followed the order of grain only > graze-grain > graze-out wheat. Winter wheat fields, including graze-out, were large sinks of CO_2 during growing seasons, gaining up to ~370 g C m^{-2} after accounting for removal of carbon from grain harvest. Considering the loss of carbon through grain harvest, results indicated that wheat fields, left with summer fallow, could be a small source to sinks of carbon at annual (calendar year) scales, depending on harvested grain quantity. Our new research initiatives of planting cover crops from summer (fallow period of wheat) 2021 can greatly alter carbon sink or source potentials of these multi-purpose wheat production systems. Weaker relationships of fluxes with biometric variables and remotely-sensed EVI in grazed wheat fields necessitates additional data and further investigation on interactive effects of grazing and meteorological conditions on carbon and water dynamics. These findings along with long-term measurements in future will aid in understanding and providing refinement options for development of more sustainable wheat production systems and crop rotations that enhance carbon sequestration and water use efficiency. It will be useful to provide a sound scientific basis for carbon credit programs as well.

Disclaimer

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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.

Acknowledgments

This study was supported in part by the USDA-ARS Office of National Programs (Project number: 3070-21610-003-00D) and USDA-LTAR (Long-Term Agroecosystem Research) Network. The authors would like to thank a farm management team (Craig Mittelstaedt, Mark Smith, Scott Schmidt, Clendon Tucker, and Stephen Teet), and Jeff Weik, Kory Bollinger, and Shelby Robertson for assistance in data collection.

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