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ORIGINAL ARTICLE

Employment of Eddy Covariance technique for the analysis of Carbon dioxide, Water vapor and Energy fluxes over alfalfa field under Hyper-arid conditions

[1]**Rangaswamy Madugundu, [1]ElKamil Tola, [1,2]Khalid A. Al-Gaadi**
[1]Precision Agriculture Research Chair, King Saud University, Riyadh, Saudi Arabia
[2]Department of Agricultural Engineering, College of Food and Agriculture, King Saud University, Riyadh, Saudi Arabia

ABSTRACT
This study reported results on carbon dioxide (CO_2), water vapor (H_2O) and energy fluxes over a center pivot irrigated alfalfa field in the Eastern region of Saudi Arabia. The experimental work was carried out during winter (November 2013 to January 2014) and summer (February to May 2014) seasons, using an Eddy Covariance system. Continuous fast response measurements of the above-canopy CO_2, H_2O and heat fluxes were recorded at a frequency of 10 Hz. Subsequently, the collected observations were averaged out at 30 minutes. Simultaneous measurements of meteorological parameters (wind speed, wind direction, air temperature, relative humidity, vapor pressure deficit (VPD), incoming solar radiation and soil heat flux) were also carried out. Diurnal and seasonal variations of CO_2, H_2O and heat fluxes were analyzed and correlated with the meteorological variables.The diurnal and seasonal mean weekly variations of CO_2 flux above the crop canopy indicated that a maximum CO_2 flux (−35 μmol/m²/s) was recorded during summer and gradually decreased to −6 μmol/m²/s with the progress of winter season towards December. Energy flux analysis (weekly mean) showed more energy being portioned into sensible heat during winter (489 W/m², 71%) and into latent heat during summer (614 W/m², 68%) during full coverage of alfalfa crop. The highest crop water use efficiency (WUE)of 1.61 kg/m³was obtained during November 2013, while, the lowest WUE (0.37 kg/m³) was recorded in May 2014.
Keywords; *Center pivot irrigation, Dry climate, Eddy covariance, Photosynthesis, Saudi Arabia*

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INTRODUCTION

Modern agricultural systems provide accurate estimates of crop acreage and productivity for the optimum use of irrigation water and fertilizers. However, significant variations in the seasonal water use and total carbon dioxide (CO_2) uptake are common, especially in multi-cut forage crops such as alfalfa. In general, crop yields are basically driven by the photosynthetic rate and the assimilation of adequate amounts of CO_2 and water vapor (H_2O). The rate of photosynthesis is associated with the phenology and the length of the day. Therefore, measurements of CO_2, $H_2O$and heat fluxes across the vegetation–atmosphere interface are essential to underst and the major processes controlling carbon storage in agriculture fields. There is a remarkable evolution in the technological approaches used for measuring the carbon fluxes at the leaf level [1,2], at the whole plant level [3]and at the ecosystem scale using modernmethods such as Eddy Covariance (EC) system [4-6]. Most of the research studies which used the EC technique concentrated on monitoring the net ecosystem exchange (NEE) of CO_2 to understand the various processes affecting the fluxes. The advantages of using the EC system are that it is scale-appropriate, directly measures the CO_2 flux of the canopy-atmosphere interface [7,8]and provides information over the tower footprint across different time scales [9-11].

Biomass stocks produce indirect estimates of the net primary productivity (NPP), using standard measurement relationships to measure the incremental changes in the NPP estimates at field and farm levels [12]. The corase time resolution of the biomass stocks prevents their use in addressing issues related to the dynamics of ecosystem physiology [11]. Soil respiration (CO_2 efflux), the main pathway of carbon moving from the ecosystem to the atmosphere, has a strong impact on the net ecosystem production (NEP) as well CO_2 uptake from the atmosphere[13]. As described by Bekku et al. [14], four major methods are used for measuring soil respiration include: (i) the alkali absorption method (AA-method): carbon dioxide passes from the soil through a closed chamber is absorbed in a caustic solution, (ii) the open flow infra-red gas analyzer method (OF-method): air flows through a chamber, and CO_2 flux is estimated as a difference between the concentrations of the inlet- and outlet-air, (iii) the closed chamber method (CC-method): the efflux is calculated from the rate of increase of CO_2 concentration in the chamber, and (iv) the dynamic closed chamber method (DC-method): air is circulated from the gas analyzer and returned to the chamber. These chamber-based methods, used for measuring CO_2 efflux from the soil, are prone to bias errors resulting from local pressure disturbance, the wind and CO_2 concentration, as well as from the changes in heat and water balance of the soil [15]. On the other hand, the spatial range sampled by a chamber or a group of chambers is relatively small compared to the spatial variation of CO_2 flow from the ecosystem [16].

In general, the EC technique provides an alternative and direct way to measure CO_2 exchange over the crop canopy and thus provides an efficient tool for studying the ecosystem over a range of time periods extending from hours to years, and across a relatively wide spatial range [9,10]. Similarly, Wu et al. [17]reported that the EC system provides efficient means of measuring CO_2 exchange at ecosystem scales, which can be used for estimating the Gross primary production (GPP) through modeling the ecosystem respiration component. Therefore, the objective of this study was to employ the EC techniques for measuring and analyzing the temporal dynamics of CO_2, H_2O and energy fluxes over a center pivot irrigated alfalfa field, for the assessment of crop water use efficiency under the hyper-arid climate of the Eastern region of Saudi Arabia.

MATERIALS AND METHODS

Study Area

This study was carried out during the period from November 2013 to May 2014 on a 50 ha alfalfa field (ID: TE11) in Todhia Arable Farm (TAF) in Eastern region of the Kingdom of Saudi Arabia. The farm was located between the latitudes of 24° 10' 22.7" and 24° 12' 37.2" N and the longitudes of 47° 56' 14.6" and 48° 05' 08.56" E (**Figure 1**). The experimental field, of sandy loam soil, was cultivated with an alfalfa crop (Green Master) sown on December 6th, 2012 at a seeding rate of 20 kg/ha, and was irrigated with groundwater through a center pivot system. Two alfalfa harvests/cuts in the year 2013 (October 23rd and December 15th) and three harvests in the year 2014 (January 27th, March 13th and April 22nd) were selected for this study.

The study area is located within an arid region of hot summers (40 ± 1.7 °C) and cold to moderate winters (15 ± 1.3 °C), with a mean air temperature of 35°C and average annual rainfall of around 90 mm. Due to the high crop water demand, because of the dry nature and the lack or irregular rainfall in the study area, the crops were irrigated using groundwater through center pivot irrigation systems [18]. The field crops cultivated in the experimental farm were wheat, alfalfa, Rhodes grass, corn and barley [19].

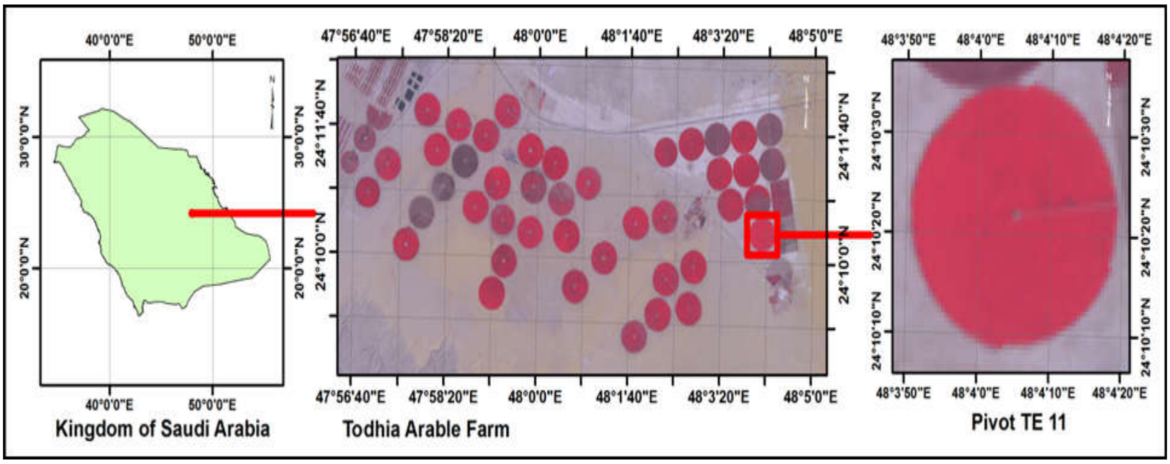

Figure 1. Location map of the study area, Tawdeehia Arable Farm.

Irrigation Schedules

Irrigation water requirement was worked out based on daily mean ET values extracted from the meteorological records of the study farm for the previous 15 years (1998-2013). Irrigation water was applied at a frequency of one to four days, based on the crop age and the cropping season. Crop water requirement (CWR), or crop evapotranspiration (ET_c), was calculated by multiplying the reference crop evapotranspiration (ET_o) by the crop coefficient (K_c) as in Equation (1) described by Allen et al. [20].

$$CWR = ET_c = ET_o \times K_c \quad (1)$$

Eddy Covariance (EC) System

The EC system was installed over the experimental field at a measuring height of 3.67 m. The EC data collected in the period from November 2013 to May 2014 was used for this study. As listed in detail in Table 1, the EC tower was equipped with response sensors (slow and fast) including an open-path gas analyzer, a 3-axis ultrasonic anemometer, soil heat flux plates, a pyranometer and a quantum sensor.

At the time of installation, the EC tower was placed closer to the downwind (Northern) edge of the site to gain upwind distance and to increase the measurement height. Continuous fast responses of CO_2, H_2O and heat fluxes above the alfalfa canopy were measured at a frequency of 10 Hz. The system was setup so that the collected observations were averaged over a period of 30 minutes. Similarly, slow response measurements of meteorological parameters (such as wind speed, wind direction, air temperature, relative humidity, solar radiation and soil heat flux) were recorded and averaged for every 30 minutes.

Table 1 Components of Eddy Covariance system.

No.	Item/ Sensor	Description
1	System	Open path system
2	3-axis Ultrasonic anemometer (GILL)	Measurement of wind speed& air temperature
3	Open path analyzer (IR Hygrometer LI-COR LI7500)	Measurement of water vapor&CO_2 flux
4	Measurement Height	3.67 m
5	Soil heat flux plates (HFP01)	Measurement of soil heat flux
6	Pyranometer (CNR-4 of Kipp & Zonen)	Measurement of solar radiation flux density
7	Quantum Sensor (Li-COR)	Measurement photosynthetic photon flux density
8	ThetaProbe ML2x (4 Nos.)	Measurement of soil moisture

Eddy Covariance data collection and Analysis

Continuous fast responses of CO_2, H_2O and heat fluxes above the alfalfa canopy were measured by an open-path gas analyzer at a frequency of 10 Hz. Subsequently, slow response measurements of meteorological parameters (such as wind speed, wind direction, air temperature, relative humidity, vapor pressure deficit (VPD), incoming solar radiation and soil heat flux) were recorded and averaged for every 30 minutes. Flux computations, utilizing the collected raw data, were carried out using Eddypro Express post-processing software program (version 5.0). During the analysis, correction of low-pass filtering effects and spike removal were carried out, and the options were set for allowing the omission of 10% of missing samples [21].

The collected data were subjected to quality check, and hence, data gaps due to system failure or data rejection were filled in by using standardized methods to provide complete data sets [22]. The recorded CO_2 and H_2O fluxes, expressed as g/m^2, were utilized to calculate the daily, cut-wise and seasonal sums. Subsequently, the corrected CO_2 flux was partitioned into GPP, NEP and ecosystem respiration (ER) as described by Gilmanov *et al.* [23]. Thereafter, WUE was calculated as a ratio of productivity (i.e. GPP, NEP) and evapotranspiration (ET). The latent heat (LE, W/m^2) fluxes were used to obtain water loss (ET, mm/d) as outlined in Tang et al. [24].

RESULTS AND DISCUSSION

The diurnal and the seasonal (mean weekly) variations of CO_2 flux above the crop canopy are presented in Figure 2a and Figure 2b, respectively. Results indicated that the maximum CO_2 flux (-35 $\mu mol/m^2/s$) was recorded during summer at noon time (11:00–12:00) due to the peak photosynthetic activity. However, CO_2 assimilation reached up to -6 $\mu mol/m^2/s$ during winter, and this may be due to the limited physiological activities associated with the alfalfa dormancy and winter hardiness. The results also showed a shift in the peak CO_2 assimilation time from 11:00–12:00 (November and December) to 12:00–14:00 (January–May) as illustrated in Figure 2a.

The monthly averaged diurnal variations of H_2O flux across the study period are presented in Figure 3. Results indicated that the peak water vapour flux during both the winter season (15–20 mmol/m²/s)and the dry period (about 5 mmol/m²/s) were observed during mid-day (11:00–15:00) as a result of the peak canopy transpiration during this time.

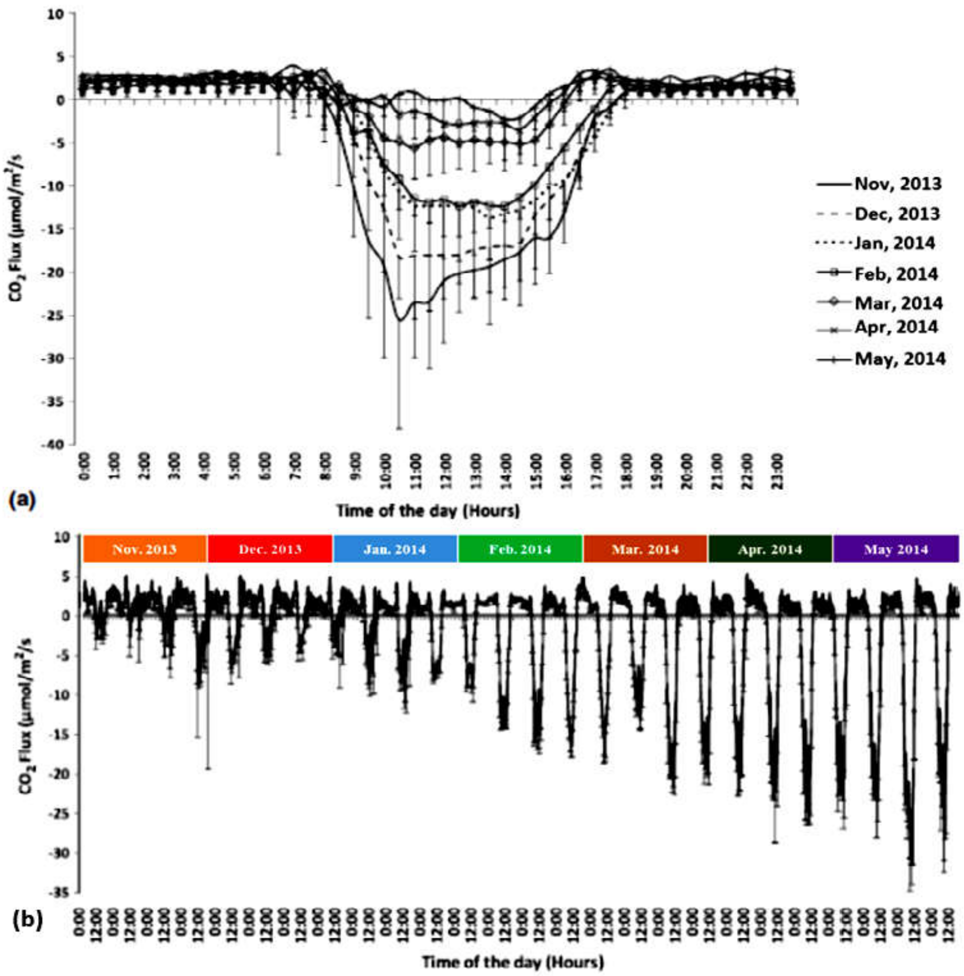

Figure 2. (a) diurnal CO_2 fluxes and (b) mean weekly seasonal CO_2 fluxes over alfalfa field, for the period from November 2013 to May 2014.

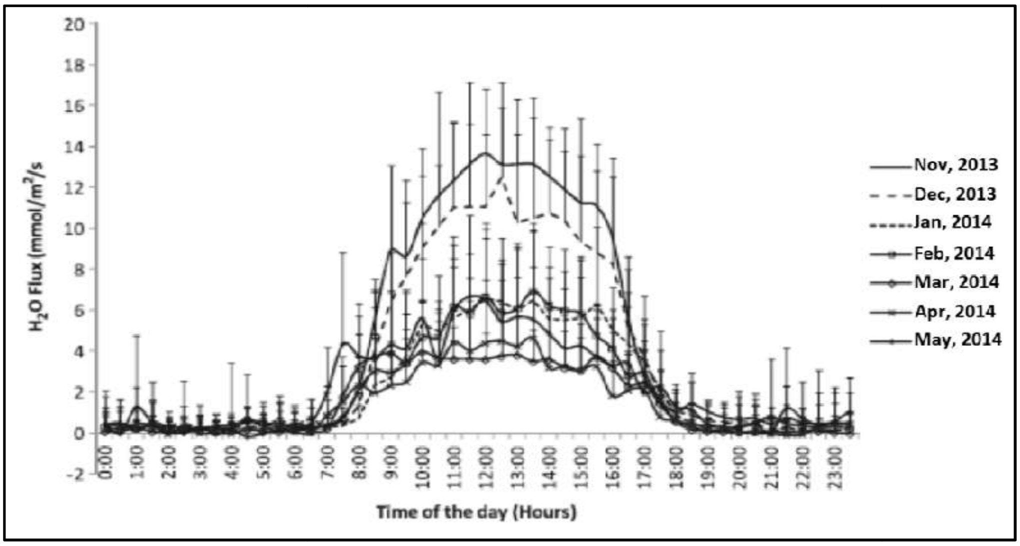

Figure 3. Monthly averaged diurnal variations of H_2O flux across the study period.

The diurnal variations of latent heat and sensible heat fluxes showed a linear relationship with the incoming solar radiation (Figure 4). Energy partitioning between latent heat and sensible heat fluxes across the seasons indicated that more heat has been partitioned into latent heat flux (maximum weekly mean of 614 W/m^2) during winter season, compared to the low values of sensible heat flux (maximum weekly mean of 489 W/m^2). This is attributed to the dominance of canopy level transpiration associated with the presence of peak leaf stage. Almost an inverse trend was observed during the dry season, as the maximum weekly mean sensible heat of 614 W/m^2 is higher than the maximum weekly mean latent heat flux of 489W/m^2. Both latent and sensible heat fluxes showed diurnal peaks during 12:00–13:00, resulted in positive correlation with the high solar radiation during the noon time.
The diurnal variability of air temperature reviled that air temperature above the canopy (0.2 m and 0.8 m) was relatively low compared to the below canopy levels during day hours, which is attributed to the removal of heat by vegetation for transpiration. However, the above canopy temperatures were high compared to the below canopy levels during nighttime because of the released heat energy during respiration. On the other hand, the diurnal variability of the relative humidity showed high levels of moisture content above the canopy level during the day hours because of the released water vapour during transpiration, while an inverse trend was observed during the night hours. Results of seasonal variations of EC-measured GPP and ET of alfalfa crop are shown in Figure 5. The peak GPP value (4.46 gC/m^2/s) was observed in April 2014, and the lowest value (0.27 gC/m^2/s) was recorded in January 2014. However, the highest ET (0.37 g H_2O/m^2/s) was observed in May 2014.

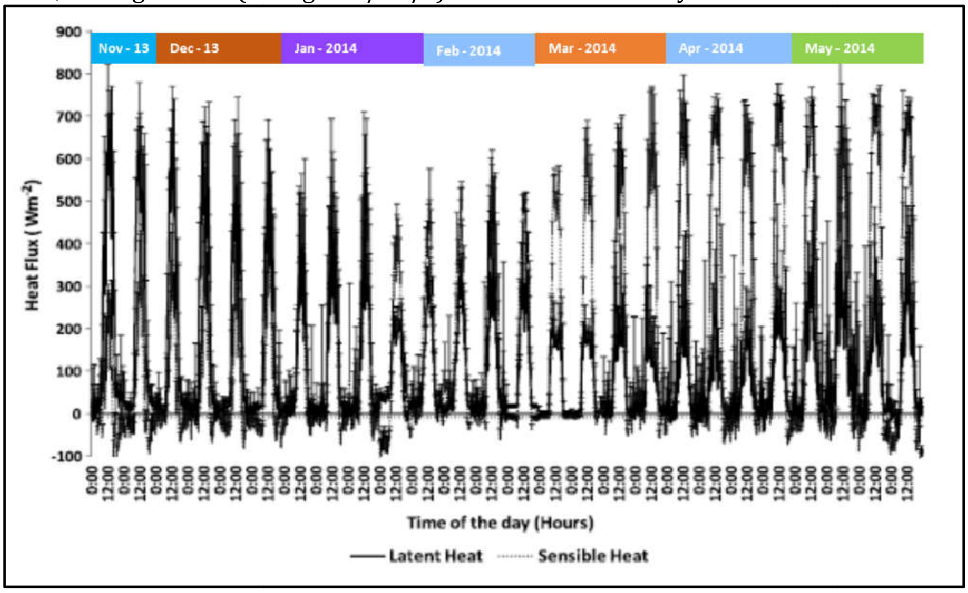

Figure 4. Seasonal variations of EC recorded heat flux over alfalfa field during the study period.

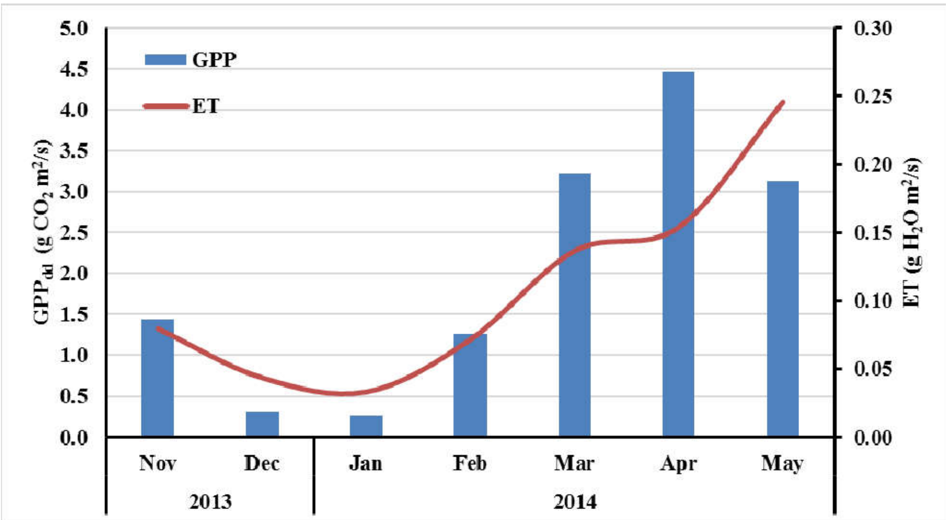

Figure 5. Seasonal variations of the daily GPP (GPP$_{dd}$)and Evapotranspiration (ET) over alfalfa field.

The amount of applied water is calculated based on the traveling time of the pivot (hours) and the discharge rate. The total actual amount of the applied irrigation water was determined at 15,189 m^3/ha for the five alfalfa harvests (minimum of 598 m^3 ha^{-1} and maximum of 5459 m^3/ha during Dec. 2013 and May 2014 respectively. The harvested (cumulative for Fourcuts) alfalfa hay yield was 10,274 kg/ha. The highest yield was harvested in May 2014 (4,392 kg/ha), while, about 1,730 kg/ha was obtained during November 2013. The actual mean value of the WUE of alfalfa was calculated at 0.88 kg/m^3. The highest WUE (1.61 kg/m^3) was obtained during November 2013, while, the lowest WUE (0.37 kg/m^3) was recorded in May 2014.

Table 2: Temporal dynamics of CO_2 fluxes of alfalfa represented as GPP and NEP along with ET and water use efficiency.

Year	Month	GPP (gC/m^2)	NEP (gC/m^2)	ER (gC/m^2)	ET (H_2O/ kg/m^2)	WUE_{GPP}	WUE_{NEP}
2013	November	308.80	144.00	164.80	79.65	3.88	1.81
	December	72.35	32.00	40.35	43.41	1.67	0.74
2014	January	65.13	26.60	38.53	33.06	1.97	0.80
	February	186.67	126.00	60.67	71.73	2.60	1.76
	March	494.26	321.40	172.86	186.83	2.65	1.72
	April	895.15	446.00	449.15	317.89	2.82	1.40
	May	568.08	313.00	255.08	346.11	1.64	0.90

As expected, crop water use of alfalfa showed variations across the study period based on changes in the climatic conditions. Crop water use was low in winter because of cool temperatures and slow growth, especially in December 2013 and January 2014. However, alfalfa crop started to use more water in March, and water requirements increased in April as it got warmer. The results of CO_2 fluxes over the alfalfa field during the study period revealed that the seasonal GPP ranged between 135 and 895 g C/m^2. As provided in **Table 2**, the cumulative monthly NEP was positive for the entire study period, with the greatest CO_2 uptake in April (446 gC/m^2). The NEP was low during winter (eg. it was 27 gC/m^2 in January) and drastically increased from March (321 gC/m^2) through May (313 gC/m^2). This large amount of variation may be attributed to the influence of the seasonal climatic variations in ET, alfalfa productivity and water use efficiency. The midday CO_2/water flux ratio (i.e. WUE_{NPP}) also showed significant seasonal variation, which was maximum during winter (1.76 in February) and minimum during summer (0.90 in May). The EC based NPP and WUE values were similar to those reported in earlier studies Gilmanov [23] with NEP ranged from 546 and 1175 gC/m^2/Yr. The WUE_{NEP} of alfalfa observed in this study concurred with the previously reported values 0.18 – 0.60 kg/m^3 by Ismail and Al-Marshadi [25], 0.38–0.43 kg/m^3 by Patil et al. [19], 3.46 kg/m^3 byDuan et al.[26] and 1.56-2.44 kg/m^3 (WUE_{GPP}) by Bellague et al. [27].
The WUE_{GPP} was higher than the WUE_{NPP} since some amount of the photosynthate was consumed by nocturnal respiration and some was translocated to the roots. On the other hand, large variations were observed in seasonal water use and total CO_2 uptake compared to the actual applied water and harvested alfalfa. In the case of EC measured data, the yield of a crop is mainly driven by photosynthetic rate, assimilation of adequate amount of CO_2 and H_2O. The rate of photosynthesis may also differ with the phenology and the length of the day. During the study period, water use of alfalfa was high in summer season because of dense canopy and high photosynthetic assimilation. Therefore, the amount of water utilized by alfalfa varied temporally and mainly depends on the seasonal dynamics of temperature, wind, humidity and the amount and intensity of light.

CONCLUSION

In the present study, eddy flux tower measurements over alfalfa field were collected and analyzed. Seasonal variation in CO_2, H_2O and heat fluxes during the period from November 2013 to May 2014 were continuously monitored. The results indicated that the alfalfa crop acted as a CO_2 sink during summer season (-35 μmol/m^2/s), while, very less CO_2 fixation was observed during winter (−6 μmol/m^2/s). Analysis of heat flux partitioning inferred that more energy has been partitioned into latent heat flux, because of the high transpiration rate of leaves during summer season.Energy flux analysis (mean weekly) showed that more energy was portioned into latent heat during winter (489 W/m^2) and sensible heat during summer (614 W/m^2). The highest crop WUE (1.61 kg/m^3) was obtained during November 2013, while, the lowest WUE (0.37 kg/m^3) was recorded in May 2014. The results of this study provided an overview of the seasonal dynamics of CO_2, H_2O and energy fluxes over alfalfa agro-ecosystem, which can be helpful in the prediction of carbon sequestration and H_2O or evapotranspiration rates.

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