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Seasonal dynamics of surface energy fluxes over a center-pivot irrigated cropland in Saudi Arabia

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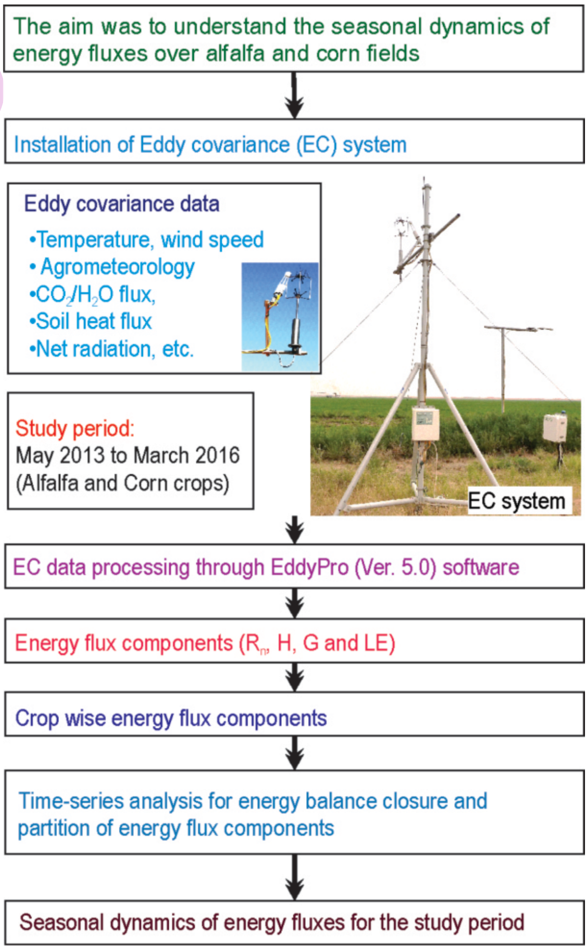
Abstract

Aim: This study focused on the seasonal dynamics of energy fluxes over selected agro ecosystems (alfalfa and corn crops) to understand the role of energy partitioning in determining the mechanisms controlling the crop water requirement and irrigation schedules.

Methodology: Eddy Covariance (EC) flux tower was installed on a center pivot irrigated field located in the Eastern Region of Saudi Arabia. EC data of nearly three years (May 2013 to March 2016) was analysed for variations in agro-climatic conditions, energy fluxes and their partition under both cropped (alfalfa and corn) and non-cropped (fallow) scenarios.

Results: Three-year mean net radiation (R_n) varied from 106.8 to 816.54 Wm^{-2}, while the recorded sensible heat, soil heat (G) and latent heat fluxes were 291.6, 158 and 3.8 Wm^{-2}, respectively. The latent heat was more during the crop growing season (381.38 W m^{-2}) compared to fallow (23.89 W m^{-2}); while, sensible heat showed an opposite trend compared to latent heat. The sensible heat recorded during the growing season (38.42 W m^{-2}) was much lower than for the fallow season (281.35 W m^{-2}).

Interpretation: There was contrasting variations in sensible heat and latent heat fluxes across seasons and corresponding to the changing climate and surface conditions of the field. In the case of silage corn, the proportions of partitioned energy to sensible heat (12.4%) and latent heat (18%) were higher than alfalfa. However, during the alfalfa post-harvest practices, the latent heat flux was always less as the available energy was partitioned as sensible heat rather than latent heat flux.



Introduction

Since 1980s, studies on energy and water exchange fluxes between land surface and atmosphere has been widely conducted by both scientists and decision makers (IPCC, 2007; Jing and Li, 2016). Numerous studies have been carried out to understand the seasonal dynamics of energy fluxes for boreal, temperate and tropical forests, grasslands and agroecosystems (Gondim *et al.,* 2015; Chi *et al.,* 2016) around the globe. However, limited studies are performed over hyper-arid regions such as Saudi Arabia.

During the last two decades, the Kingdom of Saudi Arabia has undertaken substantial developmental activities on both social as well as economic strategies. The agricultural sector has given priority under sustainable development project. The program was succeeded and substantially enhanced the food security of the Nation. However, in view of hyper-arid conditions (*i.e.,* high temperatures and limited (or) less rainfall), agricultural production mainly depends on groundwater. About 85% of fresh water is being used by agriculture sector from the country's limited ground water resources for irrigation (Alzahrani *et al.,* 2012). Hence, the efficient use of available water resources, knowledge on energy fluxes, evapotranspiration, soil infiltration rates in conjunction with magnitude and variability of agrometeorological information are essential for the determination of crop water requirements and implementation of irrigation schedules (Chen and Xie, 2012; Bezerra *et al.,* 2015).

Evapotranspiration (ET), along with land surface energy components such as net radiation (R_n), sensible heat (H), soil heat (G) and latent heat (LE) fluxes, plays a critical role in the quantification of crop water requirements and preparation of irrigation schedules. Hence, the seasonal dynamics of ET and energy fluxes over agriculture fields is essential for the efficient agricultural water management (Santanello *et al.,* 2013; Irmak *et al.,* 2014). However, energy fluxes and ET varies across the crop growth period as the vegetative cover has potential to change energy partitioning due to its effect on the seasonal pattern and magnitude of radiation balance and albedo (Rodrigues *et al.,* 2013).

Energy partitioning in the form of LE, H and G fluxes is the feedback of the boundary-layer exchange between climate and vegetation cover (*i.e.,* agriculture lands) with respect to regional climates. For example, an increase in the atmospheric vapor pressure deficit (VPD) may enhance the atmospheric evaporative demand, which in turn increases the rate of plant transpiration (Clifton-Brown and Jones, 1999). The VPD of agricultural field increases from the fallow state (after harvest of the crop) to the fully cropped area. Hence, the increased LE will be noticed when compared to baresoil/residual crop condition. In addition, longer duration of dry season (fallow state of a field) causes more dryness which affects the boundary-layer condition and destabilizes moisture regimes, VPD and surface water availability (Wizemann *et al.,* 2015). Moreover, the change in land cover (cropped area to fallow area) affects the pattern of radiation fluxes of agricultural fields (Evrendilek *et al.*, 2008; Rodrigues *et al.*, 2013). The effect of climatic events (seasonal/annual and inter-annual variations) triggers the variation in energy fluxes across the crop growth stages. Therefore, understanding the dynamics of energy and the cause of their unevenness over agricultural fields are essential for effective usage of water resources on long-term.

Accurate and reliable estimates of ET and land surface energy components can be obtained through soil water balance, lysimeter and meteorological methods such as Eddy Covariance (EC), Scintillo meter and Bowen ratio. Of which, the EC method has been widely used in terrestrial energy flux studies in order to measure continuous boundary-layer exchanges between land surface and atmosphere (Irmak *et al.,* 2014; Imukova *et al.,* 2016). Most of the EC measurements are used for the short-term (few weeks up to a few months) and long-term (several years up to decades) studies over forest lands and natural vegetation. However, few studies have used the multi-year data of energy fluxes over agro-ecosystems (Pihlatie *et al.,* 2015; Wizemann *et al.,* 2015; Chi *et al.,* 2016). Therefore, the present study focused on the seasonal dynamics of energy fluxes observed by EC flux tower to understand the seasonal dynamics of energy fluxes and their role in energy partitioning over a center pivot irrigated fields (alfalfa and silage corn), under hyper-arid conditions of Saudi Arabia determining crop water requirements.

Materials and Methods

Study site : A center-pivot irrigated agricultural field (pivot ID: TE-11) of Todhia Arable Farm (TAF) was selected for the study. The experimental farm is located within the latitudes of 24°10' 22.77" and 24°12' 37.25" N and the longitudes of 47°56' 14.60" and 48°05' 08.56" E between Al-Kharj and Haradh cities in the Eastern Region of Saudi Arabia (Fig. 1). The climate of the study area is hyper-arid with hot summers (42 ± 4°C) and cold to moderate winters (12 ± 4 °C). The average annual precipitation is about 98±20 mm; most of which occurs during the period from November to February. The soil type of the experimental field was sandy loam with mean values of soil pH and electrical conductivity of 7.58 and 2.36 dSm^{-1} respectively. The soil nitrogen, phosphorus and potassium nutrients were 213.43 (± 77.75) mg kg^{-1}, 5.95 (± 1.76) mg kg^{-1} and 51.81 (± 21.35) mg kg^{-1}. The ground water used for irrigation, which was from under groundwater dwelling through the bore wells, had mean values of EC, pH and Sodium Absorption Ratio of 2.917 dS m^{-1}, 7.82 and 1.42, respectively. The major crops cultivated in the study area were forage (alfalfa, Rhodes grass and silage corn) and vegetable crops (carrot, onion and lettuce). This study was carried out between May 2013 and March 2016. During the study period, alfalfa and silage corn were cultivated as rotation crops in the

experimental field, where Eddy Covariance (EC) and automatic weather station systems were installed. In the fallow period, the field surface was covered with short vegetation composed of crop residues and weeds.

Eddy covariance data : An eddy covariance (EC) flux tower of 4 m height was installed on the experimental field on May 27th, 2013 for measuring CO_2/H_2O and energy fluxes over the cultivated crops. The eddy covariance system is powered by solar panels with rechargeable batteries. Micrometeorological and gas exchange measurements were made at a height of 3.45 m. A three-dimensional fast-response sonic anemometer (3D Master Pro, Gill Instruments, Lymington, UK) was used to measure high-frequency wind velocity components and sonic temperature (T). An open-path infrared gas analyzer (IRGA) (LI-7500, LI-COR Biosciences, Lincoln, USA) was installed for measuring the densities of CO_2 and H_2O. Additional environmental variables, such as net radiation (CNR-4, Kipp and Zonen, Delft, the Netherlands) and incoming photosynthetic active radiation (PAR, LI-190SB; Li-COR, Lincoln, USA) measured at a height of 3.2 m and utilized to provide estimates of the incoming and outgoing longwave ($L_\downarrow$ and $L_\uparrow$) and short wave ($K_\downarrow$ and $K_\uparrow$) radiation and net all-wave radiation. Soil heat flux (HFP01, Hukseflux) was measured at various depths (5, 10, 15, 20, 25 and 30 cm). The sonic anemometer and IRGA was set to record flux data logged at 10 Hz (CR3000, Campbell Scientific Ltd) and stored as 30 min files. On the other hand, the meteorological data was also measured and averaged to 30 min blocks. Data on crop condition, growth and phenological parameters was also recorded on frequent visits.

The EC system collected flux data (May 2013 to March 2016) was processed using Eddy Pro Advanced (v.6.0.0, LI-COR) software program. As described in the user manual (Licor, 2015), despiking of raw data, correction for angle of attack, de-trending, time-lag anomalies, double coordinate rotation, correction of sonic temperature for humidity and high- and low-frequency spectral corrections (Moncrieff *et al.,* 1997; Wilczak *et al.,* 2001) were carried out along with the density corrections. Of the potential periods, 8% of the data was missing due to power failure, and 18% was missing due high temperature (especially in summer months). The data sets were analysed on daily and seasonal time scales. The daily averages were compared to illustrate the seasonal variations of the meteorological variables (air temperature, relative humidity, vapor pressure deficit and energy flux components). Also, the maximum half-hourly measured R_n, H, G and LE were averaged over the 00:00–24:00 (GTC+3) period for the assessment of seasonal variation of mean diurnal dynamics. After quality control, 72% of R_n, 82% of H, 76% of LE and 69% of G data were used for this study.

Energy balance: The energy balance closure was assessed by comparing the total energy inputs and changes in heat storage (R_n - G) to the outputs through turbulent fluxes (LE + H), according to the surface energy budget described in Equation 1.

$$Rn - G = H + LE \qquad (1)$$

Where, R_n is the net radiation (W m^{-2}) and G is the ground heat flux (W m^{-2}). The net radiation was measured by CNR-4 and soil heat flux by the self-heat flux plates. The latent (LE) and sensible (H) heat fluxes were computed from the EC system data using the covariances of the turbulent components of scalars and vertical wind velocity (Eq. 2 and 3), Rosenberg *et al.*(1983).

$$H = p_a\, C_{pa}\, \overline{T'w'} \qquad (2)$$

$$LE = p_a\, L_v\, \overline{q'w'} \qquad (3)$$

Where, ρ_a (kg m^{-3}) is the density of air, C_{pa} (1004 J kg^{-1} K^{-1}) is the specific heat of air at a constant pressure and L_v (2.54 X 106 J kg^{-1}) is the latent heat of vaporization. The *T'*, *q'* and *w'* values represent the deviations from sonic air temperature (°K), water vapor mixing ratio (kg kg^{-1}) and vertical wind velocity (m s^{-1}), respectively.

Results and Discussion

The climate of the study area was hot during summer and humid in winter across the study period. Scarce precipitation, low air humidity and high vapor pressure deficit (VPD) are the main driving climatic factors of agricultural crops in the study area.

Variations of air temperature (T_a) was observed across the study period. Air temperature decreased continuously from its maximum (46±2 °C) in August and reached its annual lower value (14±4 °C) in January (Table 1). During the earlier and late summer periods, the observed sharp humidity variations are linked to changes in wind direction. In case of summer mean temperatures, there was an increase of about 1.6 °C every year for the period 2013 (44°C) to 2016 (48°C).While, for winter periods (November to February), the recorded T_{max} ranged between 10.0 °C (2016) and 12.1 °C (2013). However, the recorded night time temperatures varied from 37.6 (summer) to 0.2 °C (winter). Overall, the analyzed temperatures for the period 2013 to 2016 revealed that there was an increase of about 0.8 °C of annual temperature compared to the recorded long-time mean T_a (30.5°C) for the period 1996 to 2012 (TAF weather records). The mean daily Vapour Pressure Deficit (VPD) for the period from January to December 2015 varied between 0.6 kPa and 5.4 kPa.

The higher mean annual value of VPD (3.30 kPa) was recorded in 2015. While, the monthly mean VPD its peak in July, with the recorded values of 5.2, 4.9 and 5.4 kPa for the years 2013, 2014 and 2015, respectively. The VPD was more and directly related with T_a in crop growth periods (3.2±0.8 kPa) compared to the non-growing season (1.2±0.6 kPa). In case of corn growth period, the recorded VPD (3.8±1.45 kPa) was higher than that of alfalfa period (2.71±0.28 kPa).

Table 1 : Monthly mean values of the recorded weather parameters for the experimental farm for the period May 2013 to April 2016

Parameter	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Mean
Air temperature (°C)	2013	-	-	-	-	30.3	32.6	40.0	44.0	31.0	33.0	22.6	12.1	30.7
	2014	18.0	24.0	32.0	33.0	34.0	36.0	42.0	46.0	32.0	30.0	24.0	18.0	30.8
	2015	12.0	24.0	29.0	34.8	36.4	38.0	44.0	48.0	42.0	31.0	24.0	18.0	31.8
	2016	10.0	24.0	26.0	29.0	-	-	-	-	-	-	-	-	22.3
VPD (kPa)	2013	-	-	-	-	3.2	4.6	5.2	3.9	2.8	1.9	1.2	0.8	2.95
	2014	0.6	0.9	1.3	2.2	3.4	3.8	4.9	4.2	2.6	2.2	1.8	1.2	2.43
	2015	0.9	1.4	2.2	2.9	3.6	4.8	5.4	5.2	4.4	3.2	2.6	1.8	3.30
	2016	1.2	2.2	1.6	2.4	-	-	-	-	-	-	-	-	1.85
Precipitation (mm)	2013	-	-	-	-	-	-	-	-	-	18.2	54.6	9.3	82.1
	2014	1.8	2.2	-	-	-	-	-	-	-	-	18.4	74.2	96.6
	2015	-	-	-	-	-	-	-	-	-	-	45.9	16.7	62.6
	2016	22.6	29.8	18.4	-	-	-	-	-	-	-	-	-	70.8

Table 2 : Observed evapotranspiration and amount of irrigated water over alfalfa (May 2013 to January 2015) and corn (February 2015 to April 2016)

Parameter	Year	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Mean
ET (mm h^{-1})	2013	-	-	-	-	1.64	2.12	2.19	1.70	1.53	1.10	0.77	0.61	1.44
	2014	0.58	0.86	1.14	1.58	1.79	2.13	2.08	1.84	1.55	1.02	0.81	0.45	1.32
	2015	0.68	1.06	1.20	1.10	2.11	2.13	2.12	2.22	1.63	0.97	0.63	0.52	1.37
	2016	0.69	0.99	1.17	-	-	-	-	-	-	-	-	-	0.95
Irrigation (mm)	2013	61	141	240	310	365	356	360	362	320	256	158	100	3029
	2014	81	137	230	321	380	366	416	338	348	265	178	-	3058
	2015	153	130	161	402	416	402	161	329	402	402	60	-	3017
	2016	81	85	155	-	-	-	-	-	-	-	-	-	321

The seasonal precipitation during the study period showed two kinds of hydrological years (Table 1). The study year 2015 was characterized as the driest year of the study period with a total precipitation of 62.6 mm, which was 36.7% below the long-term mean value of 98 mm for the period 1996–2011. The study years of 2013, 2014 and 2016 were characterized as normal hydrological years, with a total amount of precipitation of 82, 97 and 71 mm, respectively. The monthly amount of precipitation showed that the highest precipitation was in November for the years 2013 (54.6 mm) and 2015 (74.2 mm), December for the year 2014 (45.9 mm) and February for the year 2016 (29.8 mm).

Seasonal variation in energy fluxes were estimated from the integration of 30 min daily averages (6:00 to 17:00 hrs) of EC data. The EB values are expressed as net radiation (R_n), stored or soil (G) sensible (H) and latent (LE) heat fluxes. The annual pattern of net radiation (R_n) increased gradually from ~186 Wm^{-2} (daily mean) at the beginning of the year to ~816 Wm^{-2} till the end of June, where it reached the maximum value. During late August, it reached about 604 Wm^{-2} and then started to decrease till December when it roughly reached ~106 Wm^{-2}. This pattern of R_n was well defined with seasonal changes in the combination of surface incoming and outgoing shortwave and longwave fluxes over cropped and non-cropped periods. On the other hand, the maximum R_n was about 817 W m^{-2} and 485 W m^{-2} for the cropping and fallow periods, respectively. As depicted in Fig. 2, The peak values of R_n was observed in July (719 W m^{-2}) and August (817 W m^{-2}) months, while the minimum R_n was recorded during January (106.8 W m^{-2} in 2014 ; 196.4 W m^{-2} in 2016) and February (182.2 W m^{-2} in 2015). These seasonal dynamics of R_n were likely due to variations in leaf area index along with air temperature and soil moisture conditions (Zhang *et al.,* 2013).

Seasonal dynamics of soil heat flux (G) followed a similar trend as in R_n, however with H and LE, there were large variations. G exhibited wider variations during the cropping season ranging between 10.09 W m^{-2} (2015) and 16.13 W m^{-2} (2013), with a mean value of 14.22 W m^{-2}. While for the fallow periods, it increased to 35.93 W m^{-2} (2015) and 97.15 W m^{-2} (2014) with a mean value of 73.22 W m^{-2}.

The LE was more in crop growing season (381.38 W m^{-2}) compared to the fallow period (23.89 W m^{-2}); while, the H component showed an opposite trend compared to LE. The mean value of H recorded during the growing period (38.42 W m^{-2}) was much lower than for the fallow periods (281.35 W m^{-2}).

In the case of energy partition during the growth period, the LE accounted for 80-85 % of the net radiation for alfalfa crop and 83-87 % for the corn crop. The H component accounted for 5 to 8 % (alfalfa) and 5-13% (corn) of the R_n during the growing season on the daily scale. For the fallow periods, the recorded partitions of LE and H were in the range of 6.9 to 8.2 % and 77 to 84 %, respectively. On the monthly time scale, H and LE fluxes varied throughout the cropping periods (Fig. 3). The recorded LE

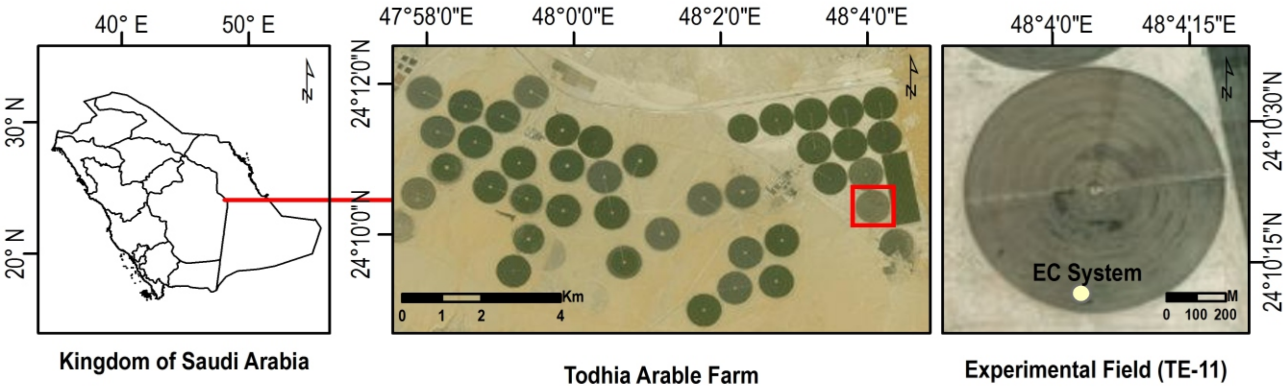


Fig. 1 : Location map of the experimental field

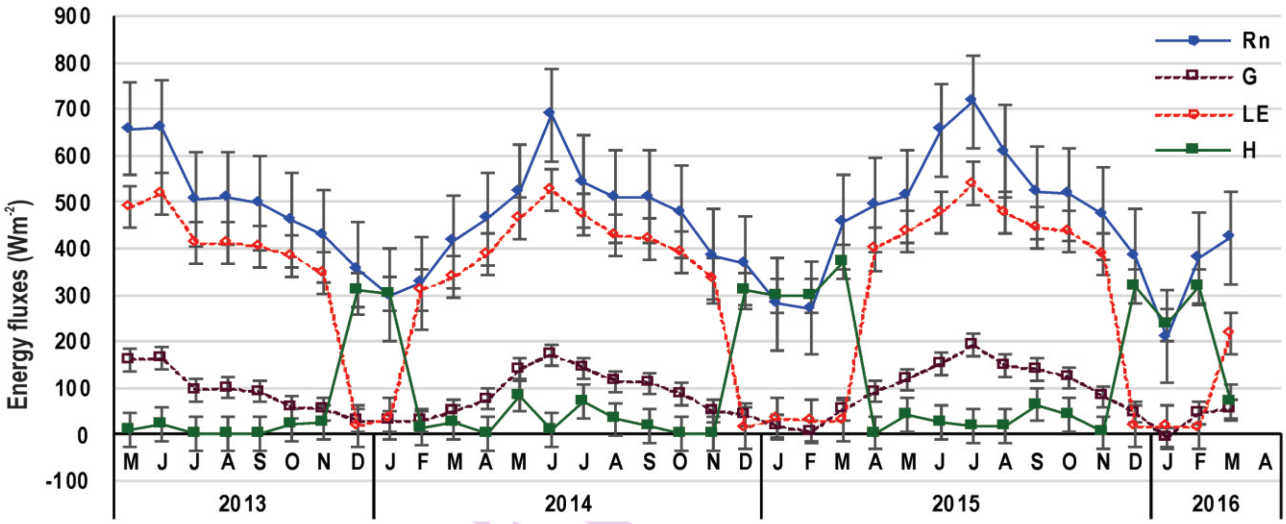


Fig. 2 : Seasonal dynamics of the recorded energy balance components over experimental field

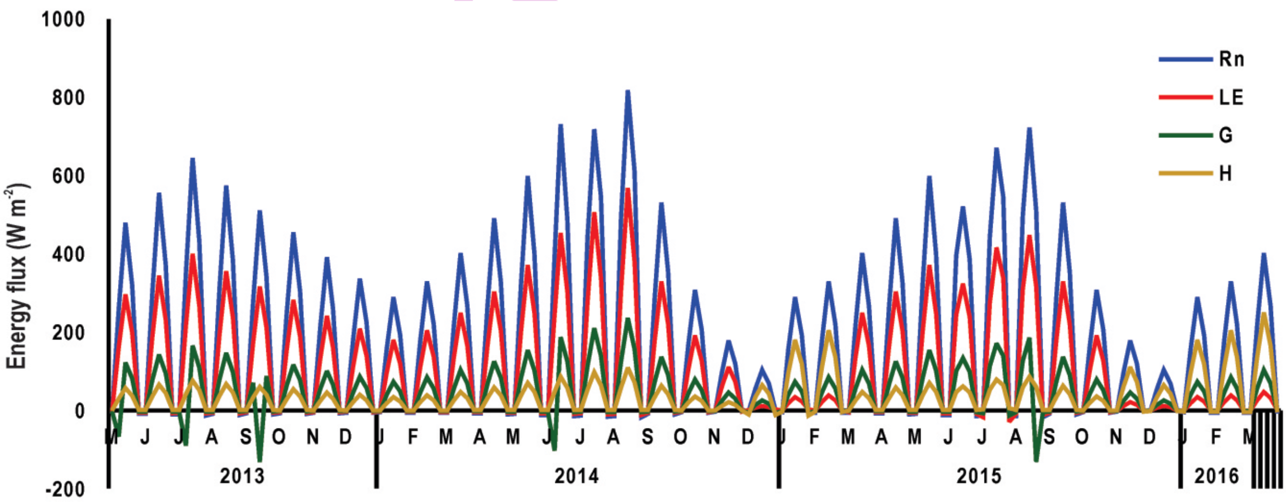


Fig. 3 : Monthly mean diurnal average of energy balance components over experimental field

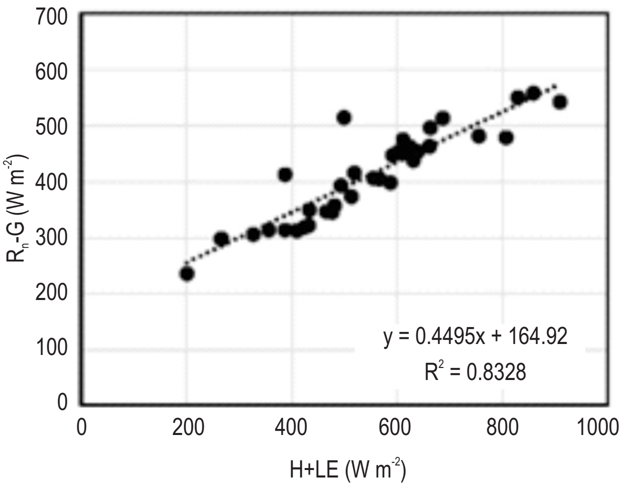


Fig. 4 : Monthly mean energy balance closure fo rthe cropping periods (June 2013 to March 2016)

was high (381.38 W m^{-2}) during summer months (July and August) and was equivalent to more than half of the available energy consumption. In the fallow period, H became the dominant component after harvesting both alfalfa and silage corn. During the early stages of silage corn, the proportions of partitioned energy into H (12.4%) and LE (18%) were higher than alfalfa. However, during the alfalfa post-harvest practices, the LE flux was always less as most of the available energy partitioned as H rather than LE flux.

On the daily timescale, the partitioned terrestrial energy components (R_n, G, H and LE) gradually increased after sunrise and typically reached their peak values at midday during the cropping season (Fig. 3). On the other hand, this type of variability in energy fluxes is expected since more energy reaches the soil surface at early stages of crop growth. Immediately the following irrigation, energy is dissipated primarily as LE. However, as the soil dries out, losses in LE rapidly decrease; but they increase in G and LE fluxes. During the early stages of corn (establishment to tillering), 12 to 16% of net radiation is stored in soil during the daylight hours. After full coverage of the crop (vegetative and flowering stages), G values decreased to 7%; while at the ripening/maturity stage it increased to about 9%. It is due to the slowdown of physiological activities in vegetative parts (especially, the expansion of leaf area) resulted in reduced canopy cover and subsequently, amoderate amount of radiation energy reached the soil surface. The seasonal dynamics of G was more or less similar to silage corn, but LE and H be have differently. The negative values for H flux indicated the temperature inversions and the advection over the experimental field.

To understand the pattern of terrestrial energy fluxes over the experimental field, energy balance closure analysis was performed. Since there was a significant portion of H and LE data eliminated due to instrumental error, higher temperatures and anomalies in time scale analysis, the gaps were filled using u (e_s-e_a) and u (T_s-T_a) functions described by McGloin *et al.* (2015). As depicted in Fig. 4, the overall mean value of the recorded Energy Balance Rato (EBR) for the entire cropping seasons was 0.83. However, the mean EBR of 0.73 was observed for the fallow periods. The average values of the EBR of cropped period was 0.83%, 0.79%, 0.80% and 0.90% for 2013, 2014, 2015 and 2016, respectively. However, the mean EBR of corn growth period was relatively high (0.86) when compared to alfalfa (0.81). Huizhi and Jianwu (2012) reported the lack of energy balance closure is common with EC measurement systems and the primary sources of energy imbalance could be due to the instrument bias, neglected energy sinks and high- or low-frequency loss and advection. A recent overview of past studies (Leuning *et al.*, 2012; Rosa and Tanny, 2015) pointed out a variety of factors affecting energy balance closure including instrument alignment, there liability of the measurements of the radiation and heat storage and the advective flux divergence.

The peak values of ET (2.8±1.2 mm h^{-1}) were observed during summer months. The recorded annual mean values of ET for the year 2013, 2014 and 2015 were 1.44, 1.32, 1.37 and 0.95 mm h^{-1}, respectively (Table 2). The maximum ET was observed in July/August across the entire study period as a result of high temperature, wind speed and VPD. Moreover, there was a variation in daily ET of alfalfa and silage corn with respect their phenology and pattern of energy partitioning across the growth period.

In the case of fallow periods (Mid-November through December 2014 and end of November through March 2016), the ET ranged between 0.1 and 0.5 mm h^{-1}; in which, the T_a, VPD and wind speed increased rapidly. The wind speed (U) exhibited in consistent seasonal variations with T_a, VPD and ET. The increase in wind speed generally occurred during spring through summer seasons, with a monthly mean wind speed of 6.2 m s^{-1} in July, 6.1 m s^{-1} in September and 6.8 m s^{-1} in August for the year 2013, 2014 and 2015, respectively. The recorded mean wind speed for winter months varied from 1.92 m s^{-1} (January) to 4.2 m s^{-1} (November).

As depicted in Fig. 5, the irrigation patterns varied across the growth period depending on the weather parameters (especially evapotranspiration) for each cultivated crop. In t case of alfalfa crop cultivated during May 2013 to March 2015, the total applied irrigation water was 6087 mm. The annual mean irrigation water for alfalfa was estimated at 3044±15 mm. While for silage corn, the irrigation water varied between 1192 mm (spring season) and 1381 mm (summer season). Corresponding to

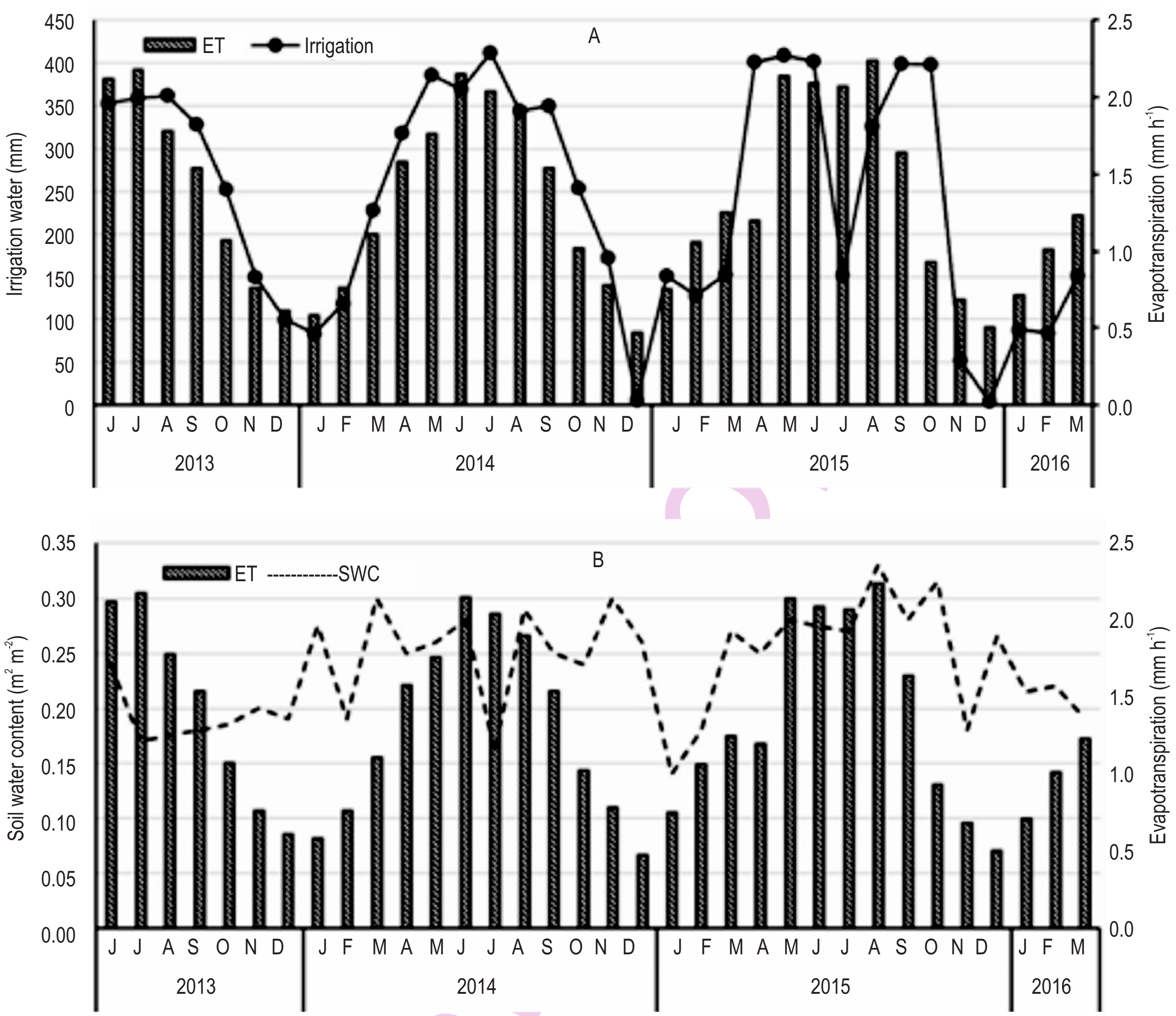


Fig. 5 : Seasonal variation evapotranspiration vs. (A) applied irrigation water and (B) soil water content of the experimental field

irrigation, the mean values of soil water content (SWC) determined at a depth of 0 to 30 cm were maintained at steady level of 0.19±0.02, 0.20±0.04, 0.25±0.03 and 0.23±0.04 $m^3 m^{-2}$ in 2013, 2014, 2015 and 2016, respectively. However, the SWC decreased to 0.14 (at 0 to 15 cm) and 0.09 (at 15 to 30 cm), especially when the field was at fallow or post-harvest period.

With respect to LE, crop water requirement was estimated and subsequently irrigation schedules were prepared for both alfalfa and silage corn. As LE increased from early vegetative stage as a result of rapid plant growth until the reproductive (silage corn) or the early blooming stage (alfalfa), thereafter, a rapid decrease in LE occurred during the harvest of alfalfa and initiation of leaf senescence in silage corn. The study attempted to understand the variation in the amount of applied irrigated water and ET of a crop. The mean seasonal ET of silage corn was 1368±176 mm; while, the annual cumulative ET during alfalfa growing season was 2086±150 mm, accounting for 68% (2013) and 79% (2014) of water consumption compared to the applied amounts of irrigation water. The amount of ET for silage corn growing season (1522±131 mm) was 11.2% higher than the corresponding cumulative applied irrigation water (1368±176 mm). Although there was a sufficient supply of irrigation water, the crops experienced temporary drought conditions due to the advection, with increased wind speed and high temperatures in summer months. The dry season in the Eastern-Region of Saudi Arabia begins in late April and continuous through September. July and August are the windiest and hot months of the year. During these windiest months, significant advection over the irrigated fields under the hyper-arid conditions of the experimental farm can be expected, because the heat generated from the surrounding dry land could easily be transferred to the

irrigated fields, especially during the hottest and windiest hours of the day (DeBruin *et al.,* 2005; Tolk *et al.,* 2006). During the study period, extreme ET events were noticed and were associated with large influxes of sensible heat, where *H* contributed with more than 55% of used energy.

Eddy Covariance measurements (May 2013 to March 2016) over a center-pivot irrigated field in the hyper-arid climates of Saudi Arabia revealed that the majority of R_n were partitioned into H and LE, varied across the growth stages of corn and alfalfa. The LE was high during mid-summer (July or August) for both the crops, irrespective of their growth stages. Three environmental factors including atmospheric water demand, humidity and wind speed during the growing season have a high impact on the seasonal and inter-annual variation of ET and triggered the quantities of applied irrigation water and their schedule of irrigation (Mamadou *et al*., 2014). Moreover, in the fallow period, H became the dominant component of partitioned energy after the harvest of both alfalfa and silage corn. Advection in dry months appear to be a regional event, needs to be focused in further studies for estimating crop water requirements on a regional and long-term basis.

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References

Alzahrani, K.H., S.E. Muneer, A.S. Taha and M.B. Baig: Appropriate cropping patterns an approach to enhancing irrigation water efficiency in the Kingdom of Saudi Arabia. *J. Animal Plant Sci.,* **22**, 224-232 (2012).

Bezerra, B.G., J.R.C. Bezerra, B.B. da Silva and C.A.C. dos Santos: Surface energy exchange and evapotranspiration from cotton crop under full irrigation conditions in the Rio Grande do Norte State, Brazilian Semi-Arid. *Bragantia,***74**, 120-128 (2015).

Chen, F. and Z. Xie: Effects of crop growth and development on regional climate: A case study over East Asian monsoon area. *Climate Dyn.,* **38**, 2291-2305 (2012).

Chi, J., S. Waldo, S.N. Pressley, P. O'Keeffe, W.L. Pan, E.S. Brooks, D.R. Huggins, C.O. Stockle and B.K. Lamb: Assessing carbon dynamics at high and low rainfall agricultural sites in the inland Pacific Northwest US using eddy covariance method. *Agric. Forest Meteorol.,* **218-219**, 25-36 (2016).

Clifton-Brown, J.C. and M.B. Jones: Alteration of transpiration rate, by changing air vapor pressure deficit, influences leaf extension rate transiently in Miscanthus. *J. Exp. Bot.,* **50**, 1393-1401 (1999).

DeBruin, H.A.R., O.K. Hartogensis, R.G. Allen and J.W.J.L. Kramer: Regional advection perturbations in an irrigated desert (RAPID) experiment. *Theor. Appl. Climatol.,* **80**, 143-152 (2005).

Evrendilek, F., J.B. Asher and M. Ayden: Dirunal photosynthesis, water use efficiency and light use efficiency of wheat under Mediterrean field conditions. *J. Environ. Biol.,* **29**, 397-406 (2008).

Gondim, P.S.S., J.R.S. Lima, A.C.D. Antonino, C. Hammecker, R.A.B. Silva and C.A. Gomes: Environmental control on water vapor and energy exchanges over grasslands in semiarid region of Brazil. *Rev. Bras. Eng. Agric. Ambient.,***19**, 1807-1929 (2015).

Huizhi, L. and F. Jianwu: Seasonal and inter annual variations of evapotranspiration and energy exchange over different land surfaces in a semiarid area of China. *J. Appl. Meteorol. Climatol.,* **51**, 1875-1888 (2012).

Imukova, K., J. Ingwersen, M. Hevart and T. Streck: Energy balance closure on a winter wheat stand: Comparing eddy covariance technique with the soil water balance method. *Biogeoscience,* **13**, 63-75 (2016).

IPCC: Climate change 2007: The Physical Science Basis. The Contribution of Working Group I to the Fourth Assessment Report to the Intergovernmental Panel on Climate Change (Eds.: S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 996 (2007).

Irmak, S., J.O. Payero, A. Kilic, L.O. Odhiambo, D. Rudnick, V. Sharma and D. Billesbach: On the magnitude and dynamics of eddy covariance system residual energy (energy balance closure error) in subsurface drip irrigated maize field during growing and non-growing (dormant) seasons. *Irrig. Sci.,***32**, 471-483 (2014).

Jing, C. and L. Li: Simulating energy and water fluxes from two alkaline desert ecosystems over Central Asia. *Adv. Meteorol.,* Article ID 4849525, 1-13 (2016).

Leuning, R., E. van Gorsela, W.J. Massman and P.R. Isaac: Reflections on the surface energy imbalance problem. *Agric. Forest Meteorol.,***156**, 65–74 (2012).

Licor: Eddypro software Instruction manual, LI-COR biosciences, Lincoln, Nebtaska, USA (2015). Accessed from https://www.licor.com/documents/1ium2zmwm6hl36yz9bu4.

Mamadou, O., J.M. Cohard, S. Galle, C.N. Awanou, A. Diedhiou, B. Kounouhewa and C. Peugeot: Energy fluxes and surface characteristics over a cultivated area in Benin: Daily and seasonal dynamics. *Hydrol. Earth Sys. Sci.,* **18**, 893-914 (2014).

McGloin, R., H. McGowan and D. McJannet: Effects of diurnal, intra-seasonal and seasonal climate variability on the energy balance of a small subtropical reservoir. *Int. J. Climatol.,* **35**, 2308–2325 (2015).

Moncrieff, J.B., J.M. Massheder, H. DeBruin, J. Elbers, T. Friborg, B. Heusinkveld, P. Kabat, S. Scott, H. Sogaard and A. Verhoef: A system to measure surface fluxes of momentum, sensible heat, water vapor and carbon dioxide. *J. Hydrol.,* **188–189**, 589–611 (1997).

Pihlatie, M., U. Rannik, S. Haapanala, O. Peltola, N. Shurpali, P.J. Martikainen, S. Lind, N. Hyvonen, P. Virkajarvi, M. Zahniser and I. Mammarella: Seasonal and diurnal variation in CO fluxes from an agricultural bioenergy crop. *Biogeosci. Discuss.,* doi: 10.5194/bg-2015-622 (2015).

Rodrigues, T.R., S.R. de Paulo, J.W.Z. Novais, L.F.A. Curado, J.S. Nogueira, R.G. de Oliveira, F.A. Lobo and G.L. Vourlitis: Temporal patterns of energy balance for a Brazilian Tropical Savanna under contrasting seasonal conditions. *Int. J. Atmos. Sci.,* Article ID 326010, 1-9 (2013).

Rosa, R. and J. Tanny: Surface renewal and eddy covariance measurements of sensible and latent heat fluxes of cotton during

two growing seasons. *Biosys. Eng.,* **136**, 149-161 (2015).

Rosenberg, N., B.L. Blad and S.B. Verma: Microclimate: The Biological Environment. 2nd Edn., Johny Wiley and Sons (1983).

Santanello, J.A., C. Peters-Lidard, A. Kennedy and S.V. Kumar: Diagnosing the nature of land-atmosphere coupling: A case study of Dry/Wet Extremes in the U.S. Southern Great Plains. *J. Hydrometeorol.,* **14**, 3-24 (2013).

Tolk, J.A., S.R. Evett and T.A. Howell: Advection influences on evapotranspiration of alfalfa in a semiarid climate. *Agronomy J.,* **98**, 1646-1654 (2006).

Wilczak, J.M., S.P. Oncley and S.A. Stage: Sonic anemometer tilt correction algorithms. *Bound Layer Meteorol.,* **99**, 127–150 (2001).

Wizemann, H.D., J. Ingwersen, P. Hogy, K. Warrach-Sagi, T. Streck and V. Wulfmeyer: Three year observations of water vapor and energy fluxes over agricultural crops in two regional climates of Southwest Germany. *Meteorologische Zeitschrift,* **24**, 39-59 (2015).

Zhang, X., Q. Tang, J. Zhang and Q. Ge: Warming/cooling effects of cropland greenness changes during 1982-2006 in the North China Plain. *Environ. Res. Lett.,* **8**, 024038, doi:10.1088/1748-9326/8/2/024038 (2013).