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미국 네브라스카의 관개된 옥수수 농업생태계의 복사, 에너지 및 엔트로피의 교환

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Radiation, Energy, and Entropy Exchange in an Irrigated-Maize Agroecosystem in Nebraska, USA

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ABSTRACT

An irrigated-maize agroecosystem is viewed as an open thermodynamic system upon which solar radiation impresses a large gradient that moves the system away from equilibrium. Following the imperative of the second law of thermodynamics, such agroecosystem resists and reduces the externally applied gradient by using all means of this nature-human coupled system acting together as a nonequilibrium dissipative process. The ultimate purpose of our study is to test this hypothesis by examining the energetics of agroecosystem growth and development. As a first step toward this test, we employed the eddy covariance flux data from 2003 to 2014 at the AmeriFlux NE1 irrigated-maize site at Mead, Nebraska, USA, and analyzed the energetics of this agroecosystem by scrutinizing its radiation, energy and entropy exchange. Our results showed: (1) more energy capture during growing season than non-growing season, and increasing energy capture through growing season until senescence; (2) more energy flow activity within and through the system, providing greater potential for degradation; (3) higher efficiency in terms of carbon uptake and water use through growing season until senescence; and (4) the resulting energy degradation occurred at the expense of increasing net entropy accumulation within the system as well as net entropy transfer out to the surrounding

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environment. Under the drought conditions in 2012, the increased entropy production within the system was accompanied by the enhanced entropy transfer out of the system, resulting in insignificant net entropy change. Drought mitigation with more frequent irrigation shifted the main route of entropy transfer from sensible to latent heat fluxes, yielding the production and carbon uptake exceeding the 12-year mean values at the cost of less efficient use of water and light.

***Key words*: Radiation, Energy, Entropy, Thermodynamics, Irrigated-maize, Agroecosystem**

I. Introduction

The state of Nebraska is a part of the corn belt in north America, where the maize production is the third biggest in USA, accounting approximately 12% of the annual total maize production (USDA, 2019). The maize in Nebraska experienced a continental climate characterized as subhumid in the east and semiarid in the west (Wilhelmi and Wilhite, 2002). Generally, most of the precipitation (on average, 447 mm) occurred during the growing season from May to October (Rosenberg, 1987; Verma *et al.*, 2005).

The growing seasons at Mead in eastern Nebraska are characterized by high temperature, low humidity, and strong winds, resulting in high evaporative demand on the growing crops such as maize (i.e., Rosenberg, 1987). The opportune irrigation by farmer is essential during this period to maintain the maize production. In fact, irrigation land in Nebraska has increased and represents about 14% of the irrigated land in USA (Adegoke *et al.*, 2003; NASS, 2007). In Mead, to avoid yield reduction due to water stress, irrigation continues from May to September but mostly concentrated in July and August to replenish the soil moisture to approximately 90% of the field capacity (Kranz *et al.*, 2008; Irmak *et al.*, 2011; Suyker and Verma, 2012). In 2012, an exceptional and widespread drought occurred in the Great Plains including Nebraska (Grigg, 2014). The flash drought was the most severe with decreased precipitation from May to August (Force, 2013), resulting in quick depletion of the available soil water content in Mead, Nebraska (Yang *et al.*, 2018). Accordingly, farmers applied more frequent irrigations to alleviate the impact of the drought (Suyker and Verma, 2008; 2010; 2012).

Irrigation affects the surface energy exchange in agroecosystem. For example, irrigated water into the system under drought condition increases latent heat flux. The evaporative cooling of the canopy surface by irrigation leads to a reversal of the temperature gradient between the crop canopy and the overlying ambient air, resulting in sensible heat advection that provides an additional energy for evapotranspiration (*ET*) (Rosenberg *et al.*, 1983; Huber *et al.*, 2014).

Such changes in system temperature as well as the relative magnitudes of energy balance components have immediate consequences in entropy change (defined as $dS = dQ/T$, where dQ is change in a system's energy and T is the system temperature) (Clausius, 1867). Entropy exchange (i.e. entropy production within the system and entropy transfer in and out of the system) is an important thermodynamic indicator which can be used to measure the system's degradation or self-organizing capacity (associated with system's sustainability) (Steinborn and Svirezhev, 2000; Eulenstein *et al.*, 2003; Patzek, 2008). Recently, Cochran *et al.* (2016) reported that an irrigated maize site during the drought in 2012 maintained non-drought level carbon uptake and the production at the cost of increased entropy production. They interpreted this increase in entropy production as a sign of reduced sustainability of the maize agroecosystem. However, we argue that the thermodynamic assessment of a system's sustainability must take the evaluation of complete entropy balance (including not only the production term but also the transfer term) into account (e.g., Brunsell *et al.*, 2011).

The objective of our study is to ascertain and to document the radiation, energy, and entropy exchange in an irrigated-maize agroecosystem. The ultimate purpose is to better understand the thermodynamic imperative and to test the hypothesis that growth and development of agroecosystem increase energy degradation thus following the imperative of the 2nd law of thermodynamics. Here, ecological growth is the increase of energy throughflow and stored biomass and ecological development is the internal reorganization of energy and mass (i.e., information) (Fath *et al*., 2004). We analyzed the energetics using the eddy covariance flux data along with micrometeorological, soil and plant observation from 2003 to 2014 at the AmeriFlux NE1 irrigated-maize site at Mead, Nebraska, USA. Results and discussion are presented based on the 12-year time series with particular focus on 2012 when a prolonged severe drought was encountered and mitigated by more frequent irrigation management.

II. Materials and Methods

2.1. Study site

The study site is located at the experimental field of the University of Nebraska-Lincoln near Mead, Nebraska, USA. Among three sites in Mead, US-NE1 (NE1) site was managed with irrigation for maize monoculture (41.165°N, 96.477°W, 361 m above m.s.l.; 49 ha). Overall information on solar radiation (R_S), air temperature (T_{air}), precipitation (P = rainfall+irrigation) during the growing season and for the entire year and irrigation and rainfall during the growing season is shown in Table 1. The amount of irrigation was over 300 mm to compensate the least rainfall in 2012 and the irrigation times was the most frequent in 2012. In our study, a fixed period for the growing season (i.e., May to October) was used based on the averaged planting date (2 May) and harvest date (23 October) from 2003 to 2014 (Table 2).

Table 1. Growing season- and annually-integrated (given in parentheses) values of solar radiation (R_S), air temperature (T_{air}), precipitation (P = rainfall+irrigation) at NE1 site at Mead, Nebraska from 2003 to 2014

Year	R_S (MJ m^{-2})		T_{air} (degree C)		P (mm)		Irrigation (mm) / (times)	Rainfall (mm)
2003	3654	(5601)	19.4	(10.0)	732	(886)	348+/*	384
2004	3487	(5491)	19.1	(10.5)	632	(823)	226+/*	406
2005	3678	(5590)	20.4	(11.0)	672	(873)	332+/*	340
2006	3570	(5526)	19.5	(11.3)	703	(922)	273+/*	430
2007	3546	(5663)	20.6	(10.5)	867	(1074)	*	*
2008	3613	(5618)	19.1	(9.1)	754	(843)	224++ / 7	530
2009	3427	(5449)	18.0	(9.3)	572	(629)	191++ / 6	381
2010	3685	(5669)	19.5	(10.3)	743	(903)	137++ / 5	606
2011	3745	(5801)	19.2	(10.0)	698	(830)	117++/ 5	581
2012	4064	(6329)	19.7	(12.0)	593	(715)	315++/ 10	278
2013	3681	(5763)	18.9	(9.2)	763	(915)	*	*
2014	3689	(5800)	18.8	(9.4)	796	(920)	*	*
AVG	3653	(5692)	19.4	(10.2)	710	(861)	240 / 7	437
SD	153	(221)	0.7	(0.9)	82	(106)	78 / 2	105

+ Irrigation (mm) during growing season (Suyker and Verma, 2010)
++ Irrigation (mm) during growing season
* Irrigation data are not available during growing season
All irrigation was conducted during growing season.

Table 2. Tillage management, dates, growing season, and maize yield information at NE1 site from 2003 to 2014

Year	Tillage	Planting date	Emergence date	Harvest date	GSL (day)	Yield (Mg ha^{-1})
2003	No tillage	5/15	5/27	10/27	166	12.1
2004		5/5	5/15	10/17	166	12.2
2005	Tillage	5/4	5/17	10/13	163	12.0
2006		5/5	5/16	10/5	154	10.5
2007		5/1	5/10	11/5	189	12.8
2008		5/1	5/11	11/20	204	12.0
2009		4/20	5/5	11/9	204	13.4
2010		4/19	5/4	9/21	156	2.0*
2011		5/18	5/26	10/26	162	12.0
2012		4/26	5/4	10/11	170	13.0
2013		4/29	5/14	10/22	177	**
2014		4/21	5/7	10/28	191	**
AVG	-	5/1	5/13	10/22	173	11.2
SD	-	9 days	8 days	15 days	17	3.2
Source	2003-2012 (Nguy-Robertson *et al.*, 2015) 2013-2014 (Yang *et al.*, 2018)					

* Decrease in yield due to hail event in September 2010.
** Yield data are not available.

Information on tillage, growing season length (*GSL*), and yield are summarized in Table 2 (Nguy-Robertson *et al.*, 2015; Yang *et al.*, 2018). The study site was maintained as no-till from 2001 to the harvest of 2005. A conservation plow method was applied as tillage operation since fall in 2005. After the harvest, a conservation-plot tillage was operated. The field has been fertilized and treated with herbicide and pesticides following the best management practices for Eastern Nebraska (Suyker and Verma, 2008). Irrigation was conducted with center pivot system when the soil moisture content decreased below a certain point (~25%), mostly during the severe drought conditions in 2012. The maize grew up to 2.5 m during the harvest season in Autumn and one-third of the crop remained after harvest (Suyker, 2016).

2.2. Flux measurement and data processing

The hourly time series data of energy, water vapor and carbon exchange at the NE1 site were obtained from the eddy covariance tower flux measurement (3 m above the ground surface when the canopy was < 1 m; and later moved to 6 m above ground until harvest) (Suyker *et al.*, 2005). An omni-directional sonic anemometer (R3, Gill Instruments Ltd., Lymington, UK) was used to measure wind speed, wind direction, and temperature, and a closed-path infrared gas analyzer (LI 6262, Li-Cor Inc., Lincoln, NE) to measure the fluctuations of H_2O and CO_2 concentrations. An open path gas analyzer (LI7500, Li-CorInc., Lincoln, NE) was also used for monitoring CO_2. Flux corrections were applied for inadequate frequency response of fast-response sensors and the sensor separation (Moore and Knowles, 1989; Massman, 1991; Suyker and Verma, 1993). Flux data were obtained at 10 Hz. Data availability after quality control was provided in Appendix 1. The missing data were filled with combined measurement, interpolation, and empirical data synthesis (e.g., Kim *et al.*, 1992; Wofsy *et al.*, 1993; Verma *et al.*, 2005). Ecosystem respiration during daytime was estimated based on the relation between night CO_2 exchange and temperature with~

10% uncertainty (e.g., Flanagan *et al*., 2000; Desai *et al*., 2008). More details can be found in Suyker and Verma (2001), Suyker *et al.* (2005), and Verma *et al*. (2005).

2.3. Carbon and water use efficiency

Gross primary productivity (*GPP*) was used in this study as the indicator for productivity at ecosystem scale (e.g., Falge *et al*., 2002; Gitelson *et al*., 2006). *GPP* was also used to calculate carbon uptake efficiency (*CUE*) and water use efficiency (*WUE*).

Carbon uptake efficiency is defined as the ratio of *GPP* to ecosystem respiration (*RE*):

$$CUE = \frac{GPP}{RE} \quad \text{(Eq. 1)}$$

CUE describes how efficiently an ecosystem manages the carbon uptake for growth and development relative to the maintenance (Odum, 1969).

WUE at the ecosystem level (e.g., Reichstein *et al*., 2007; Kuglitsch *et al*., 2008) is defined as:

$$WUE = \frac{GPP}{ET} \quad \text{(Eq. 2)}$$

where *ET* is evapotranspiration which can be calculated from the measured water vapor flux. Both efficiencies were calculated by using the daily integrated flux values.

2.4. Radiation, Energy and Entropy Balances

To evaluate entropy balance, understanding of radiation and energy balance should be preceded. Let us consider a maize agricultural system undergoing state changes due to exchange of energy and matter with its surrounding environment. If this is done reversibly and thus the system is in balance, we can express the radiation balance [W m^{-2}] within the system as:

$$R_n = R_{S\downarrow} + R_{S\uparrow} + R_{l\downarrow} + R_{l\uparrow} \quad \text{(Eq. 3)}$$

where R_n is net radiation; $R_{S\downarrow}$ and $R_{S\uparrow}$ are incoming and outgoing shortwave radiation, respectively; and $R_{l\downarrow}$ and $R_{l\uparrow}$ are incoming and outgoing longwave radiation, respectively. Sign convention is such that flux going into (or away from) the system is positive (or negative). R_n is partitioned to various components of surface energy balance as:

$$R_n = H + LE + G + ST + M \quad \text{(Eq. 4)}$$

where *H* is sensible heat flux, *LE* is latent heat flux, *G* is soil heat flux, *ST* is heat storage (e.g., Wilson and Baldocchi, 2000), and *M* is metabolic energy associated with photosynthesis and respiration (e.g., McCaughey and Saxton, 1988). In our study, we assumed that *G*, *ST,* and *M* are negligibly small on a daily or greater time scale (e.g., Holdaway *et al.*, 2010).

In this system, the total change in entropy is $\triangle S = \int dQ/T$, where T is the temperature of the system and Q is the added energy. Here, $\int dQ/T$ is called the entropy flux from the environment into the system ($\triangle S_e$). For irreversible processes (Endres, 2017):

$$\triangle S - \triangle S_e = \triangle S_i \geq 0 \quad \text{(Eq. 5)}$$

where $\triangle S_i$ is the entropy production. After division by Δ, Eq. 5 becomes in the infinitesimal limit:

$$\frac{dS}{dt} = \frac{dS_i}{dt} + \frac{dS_e}{dt} = \sigma + J \quad \text{(Eq. 6)}$$

where $dS_i/dt\ (=\sigma) \geq 0$ is the non-negative entropy production rate and $dS_e/dt\ (= J)$ is the entropy transfer rate which can be positive or negative and have contributions from heat flow at temperature *T* and material flux (e.g., H_2O, CO_2). Hence, the time-averaged rate of entropy change [MJ m^{-2} K^{-1}] is:

$$\overline{\frac{dS}{dt}} = \overline{\sigma} + \overline{J} \quad \text{(Eq. 7)}$$

The σ consists of two entropy production terms:

$$\sigma = \sigma_{Rsn} + \sigma_{Rl\downarrow} \qquad \text{(Eq. 8)}$$

where σ_{Rsn} [MJ m^{-2} K^{-1}] is the entropy production rate by energy dissipation of the net shortwave radiation (i.e., $R_{sn} = R_{S\downarrow} + R_{S\uparrow}$) and $\sigma_{Rl\downarrow}$ [MJ m^{-2} K^{-1}] is the entropy production rate by absorbed incoming longwave radiation ($R_{l\downarrow}$). Here, σ_{Rsn} is calculated as:

$$\sigma_{Rsn} = R_{sn}\left(\frac{1}{T_{sfc}} - \frac{1}{T_{sun}}\right) \qquad \text{(Eq. 9)}$$

where T_{sfc} [K] is the surface temperature calculated by using the Stefan-Boltzmann law, $R = \varsigma\varepsilon T^4$(where R is the radiation (i.e., $R_{l\uparrow}$), ς is the Stefan- Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-1}), ε is the emissivity of maize canopy (0.98, see Humes *et al.*, 1994). T_{sun} is assumed as a constant (= 5780 K). The other term $\sigma_{Rl\downarrow}$ is given:

$$\sigma_{Rl\downarrow} = R_{l\downarrow}\left(\frac{1}{T_{sfc}} - \frac{1}{T_{atm}}\right) \qquad \text{(Eq. 10)}$$

where T_{atm} [K] is calculated using the Stefan-Boltzmann law and ε = 0.85 was used for the atmosphere (Campbell and Norman, 1998).

Entropy transfer rates (J) [MJ m^{-2} K^{-1}] have several contributors:

$$J = J_{Rsn} + J_{Rl\downarrow} + J_{Rl\uparrow} + J_H + J_{LE} \qquad \text{(Eq. 11)}$$

where J_{Rsn}, $J_{Rl\downarrow}$, $J_{Rl\uparrow}$, J_H, and J_{LE} are the entropy transfers rates associated with R_{sn}, $R_{l\downarrow}$, $R_{l\uparrow}$, H, and LE, respectively and are computed as:

$$J_{Rsn} = \frac{R_{sn}}{T_{sun}} \qquad \text{(Eq. 12)}$$

$$J_{Rl\downarrow} = \frac{R_{l\downarrow}}{T_{atm}} \qquad \text{(Eq. 13)}$$

$$J_{Rl\uparrow} = \frac{R_{l\uparrow}}{T_{sfc}} \qquad \text{(Eq. 14)}$$

$$J_H = \frac{H}{T_{air}} \qquad \text{(Eq. 15)}$$

where T_{air} is the air temperature [K] at the measurement height of eddy covariance system (3 m above the surface when the canopy < 1 m; and later moved to a 6 m above until harvest) (Suyker *et al.*, 2005); and

$$J_{LE} = J_{LEheat} + J_{LEmix} \qquad \text{(Eq. 16)}$$

$$J_{LEheat} = \frac{LE}{T_{air}} \qquad \text{(Eq. 17)}$$

$$J_{LEmix} = (E)(R_v)\ln(RH_{amb}) \qquad \text{(Eq. 18)}$$

where E (kg m^{-2}s^{-1}) is the evaporation, R_v is water vapor gas constant (= 461 J kg^{-1} K^{-1} for moist air) and RH_{amb} is the ambient relative humidity at the point at which the flux is occurring (Kleidon and Schymanski, 2008). In our study, we did not consider J_{LEmix} because the magnitude was less than 5% of J_{LEheat}.

III. Results

3.1. Radiation and energy exchange

Understanding of the characteristics of radiation and energy exchange at the study site is a prerequisite for an accurate assessment of the entropy production and transfer in the maize production system at NE1. Table 3 presents the integrated values of radiation balance, energey balance, and energy balance closure (*EBC*) for the growing seasons (from May to October) and those for the whole years (provided in parentheses) from 2003 to 2014.

Table 3. The growing season- and annually-integrated (given in parenthesis) values (in MJ m^{-2}) of the radiation balance, energy balance, and energy balance closure (*EBC*) at NE1 site at Mead, Nebraska, USA from 2003 to 2014

Year	$R_{S\downarrow}$ (MJ m^{-2})	$R_{S\uparrow}$ (MJ m^{-2})	$R_{l\downarrow}$ (MJ m^{-2})	$R_{l\uparrow}$ (MJ m^{-2})	R_n (MJ m^{-2})	G (MJ m^{-2})	H (MJ m^{-2})	LE (MJ m^{-2})	EBC
2003	3654 (5601)	671 (1288)	5582 (9789)	6466 (11389)	2097 (2694)	101 (86)	387 (658)	1379 (1640)	0.82 (0.84)
2004	3487 (5491)	674 (1344)	5672 (9944)	6476 (11501)	2000 (2578)	62 (46)	436 (708)	1259 (1489)	0.85 (0.86)
2005	3678 (5590)	708 (1269)	5728 (10029)	6602 (11612)	2095 (2732)	78 (42)	406 (675)	1317 (1603)	0.84 (0.85)
2006	3570 (5526)	601 (995)	5701 (10011)	6533 (11675)	2136 (2856)	55 (18)	329 (581)	1354 (1682)	0.80 (0.81)
2007	3546 (5663)	604 (1268)	5825 (10017)	6612 (11550)	2154 (2862)	42 (-16)	241 (447)	1490 (1892)	0.78 (0.80)
2008	3613 (5618)	606 (1095)	5624 (9717)	6413 (11266)	2215 (2971)	36 (-14)	287 (580)	1414 (1790)	0.75 (0.76)
2009	3427 (5449)	593 (1087)	5644 (9823)	6326 (11226)	2143 (2943)	25 (6)	342 (636)	1270 (1565)	0.77 (0.77)
2010	3685 (5669)	672 (1243)	5730 (9982)	6501 (11370)	2233 (3001)	40 (-2)	301 (476)	1410 (1752)	0.77 (0.79)
2011	3745 (5801)	632 (1189)	5611 (9745)	6483 (11357)	2235 (2975)	74 (45)	323 (504)	1432 (1789)	0.82 (0.82)
2012	4064 (6329)	698 (1222)	5543 (9847)	6527 (11717)	2373 (3209)	26 (15)	385 (717)	1464 (1779)	0.77 (0.79)
2013	3681 (5763)	657 (1204)	5638 (9682)	6453 (11250)	2198 (2977)	31 (9)	283 (535)	1323 (1676)	0.73 (0.73)
2014	3689 (5800)	627 (1066)	5621 (9705)	6449 (11317)	2229 (3108)	32 (-4)	428 (817)	1207 (1522)	0.72 (0.72)
AVG	3653 (5692)	645 (1189)	5660 (9858)	6487 (11436)	2176 (2909)	50 (19)	346 (611)	1360 (1682)	0.79 (0.80)
SD	153 (221)	38 (101)	73 (127)	75 (163)	90 (169)	23 (29)	60 (106)	84 (118)	0.04 (0.04)

The 12-year-mean growing seasons $R_{S\downarrow}$ was 3653± 153 MJ m^{-2} (equivalent to a daily mean of ~20 MJ m^{-2} d^{-1}), of which R_n was approximately 60%. However, the latter was only 36% during the non-growing seasons (from November to April). The energy capture, $R_n/R_{S\downarrow}$ (i.e., a thermodynamic indicator for system's self-organization; Lin *et al.*, 2009) was nearly 70% higher during the growing seasons. The more efficient energy capture during the growing seasons is demonstrated also in terms of the albedo ($R_{S\uparrow}/R_{S\downarrow}$) which was reduced to 18% compared to that during the non-growing seasons (36%). The two terrestrial radiation components (i.e., $R_{l\downarrow}$ and $R_{l\uparrow}$) consisted of the major portions of the radiation balance with little interannual variability (within ±1%). However, they cancelled out each other, resulting in the averaged net outgoing longwave radiation of 827 MJ m^{-2} (i.e., ~26% of $R_{S\downarrow}$) during the growing seasons and 751 MJ m^{-2} (~ 37% of $R_{S\downarrow}$) during the non-growing seasons. Both shortwave and longwave radiation components contributed to more efficient energy capture during the growing seasons.

The 12-year mean growing season R_n (a daily mean of ~12 MJ m^{-2} d^{-1}) was partitioned predominantly to *LE* (63%, equivalent to *ET* of ~3 mm d^{-1}) and much less to *H* (16%). During the non- growing seasons, as expected, relatively more energy was partitioned to *H* (36%) and less to *LE* (44%). The annually-integrated *G* averaged less than 1% of R_n but was 2% during the growing seasons. The energy balance closure ($EBC = \sum(H + LE + G) / \sum R_n$) of the daily integrated fluxes ranged from 0.72 to 0.86 with an average of ~0.80 during both the growing and the non-growing seasons. This circa 20% energy imbalance is rather typical in the literature and may be attributed to the uncertainties associated with potential errors in flux measurement, data processing, and mismatch of flux footprint between eddy covariance measurement (i.e., *H* and *LE*) and slow-response measurement (i.e., R_n and *G*).

It is worth noting that during the growing season of 2012 (i.e., the year with a prolonged drought), both $R_{S\downarrow}$ and $R_{S\uparrow}$ were the highest (11% and 8% higher than the 12-year means, respectively) whereas $R_{l\downarrow}$ and $R_{l\uparrow}$ were 2% lower and ~1% higher, respectively. Consequently, with more frequent irrigation, R_n was 9% higher, resulting in *LE* and *H* that were 8 % and 11% higher, respectively. Although *G* was 52% lower, it was two orders of magnitude smaller. The growing season $R_n/R_{S\downarrow}$ and *EBC* in 2012 were 0.58 and 0.77, respectively, which were slightly lower than the 12-year means.

3.2. Carbon, water, and light use efficiency

In Table 4, the growing season-integrated values of *GPP*, *RE*, and *ET* are summarized from 2003 to 2014. For the sake of completeness, the annually-integrated values are also given (in parentheses) although the contributions from the non-growing seasons were all < 20%. *GPP* applies only to the growing seasons because there was no photosynthetic activity during the non-growing seasons (i.e., *GPP* was nil). *GPP* ranged from 1618 to 1952 g C m^{-2} y^{-1}, whereas *RE* from 1077 to 1361 g C m^{-2} y^{-1}. The resultant *CUE* ranged from 1.25 to 1.62, and averaged 1.47 (±0.10), which was comparable to *CUE* reported for maize (1.51) and soybean (1.17) (Suyker *et al.*, 2005). *ET* ranged from 495 to 611 mm, yielding the *WUE* of 1.98 to 2.92 g C (kg H_2O)$^{-1}$ with an average of 2.35 (±0.26) g C (kg H_2O)$^{-1}$. This value was less than *WUE* reported for maize (2.60) but bigger than those reported for winter wheat (2.20), soybean (1.97), and paddy rice (1.66) (e.g., Wang *et al.*, 2018).

In 2012, the farmers' drought mitigation strategy (with frequent irrigation intervention to maintain soil moisture above 90% of the field capacity) resulted in *GPP*, *RE*, and *CUE* that were all comparable to those of the 12-year means. In terms of water use, however, the growing season *ET* increased to 600 mm (about 8% greater than the 12-year mean), resulting in the lowest *WUE* of 1.98 g C (kg H_2O)$^{-1}$ (~16% lower than the 12-year mean).

Considering the increased amount (by 12%) of the absored net solar radiation (i.e., $R_{sn} = R_{S\downarrow} + R_{S\uparrow}$; approximately half of this can be considered as a proxy for absorbed photosynthetically active radiation, *APAR*) (Table 3) and the slightly less normal amount (by −1%) of *GPP* in 2012 (Table 4), the light use efficiency (*LUE* = *GPP*/*APAR*) would have decreased also by ~12%. Therefore, more frequent irrigation during the drought period enabled farmers to accomplish above-normal yield and carbon sequestration at the expense of less efficient use of light and water in 2012.

Table 4. The growing-season and the annually-integrated (given in parentheses) values of *GPP*, *RE* and *ET*, and the growing-season averaged *CUE* and *WUE* at NE1 site at Mead, Nebraska, USA from 2003 to 2014

Year	*GPP* ($g\ C\ m^{-2}$)	*RE* ($g\ C\ m^{-2}$)		*ET* (mm)		*CUE* (-)	*WUE* ($g\ C\ (kg\ H_2O)^{-1}$)
2003	1676	1117	(1291)	565	(672)	1.50	2.11
2004	1664	1149	(1312)	516	(610)	1.45	2.43
2005	1618	1077	(1276)	540	(657)	1.50	2.09
2006	1622	1205	(1466)	555	(689)	1.35	2.12
2007	1900	1234	(1447)	611	(776)	1.54	2.47
2008	1781	1120	(1298)	579	(734)	1.59	2.47
2009	1952	1204	(1403)	520	(641)	1.62	2.92
2010	1787	1333	(1538)	578	(718)	1.34	2.24
2011	1708	1361	(1614)	587	(733)	1.25	2.26
2012	1703	1145	(1372)	600	(729)	1.49	1.98
2013	1692	1120	(1282)	542	(687)	1.51	2.43
2014	1632	1120	(1299)	495	(624)	1.46	2.65
AVG	1728	1182	(1383)	557	(689)	1.47	2.35
SD	103	86	(107)	34	(48)	0.10	0.26

Table 5. The growing season- and the annually-integrated (given in parentheses) entropy production terms in NE1 site at Mead, Nebraska, USA from 2003 to 2014

Year	σ_{Rsn} ($MJ\ m^{-2}\ K^{-1}$)		$\sigma_{Rl\downarrow}$ ($MJ\ m^{-2}\ K^{-1}$)		σ ($MJ\ m^{-2}\ K^{-1}$)	
2003	9.41	(13.87)	0.03	(0.08)	9.38	(13.79)
2004	8.94	(13.36)	0.04	(0.03)	8.98	(13.33)
2005	9.34	(13.83)	0.01	(0.04)	9.33	(13.78)
2006	9.39	(14.58)	0.02	(0.11)	9.41	(14.47)
2007	9.32	(14.20)	0.06	(0.01)	9.39	(14.19)
2008	9.55	(14.68)	0.05	(0.05)	9.60	(14.63)
2009	9.04	(14.16)	0.13	(0.07)	9.17	(14.23)
2010	9.56	(14.32)	0.07	(0.10)	9.63	(14.42)
2011	9.92	(14.94)	0.02	(0.09)	9.91	(14.85)
2012	10.63	(16.38)	0.11	(0.27)	10.53	(16.11)
2013	9.62	(14.83)	0.03	(0.08)	9.64	(14.76)
2014	9.72	(15.33)	0.01	(0.10)	9.73	(15.23)
AVG	9.54	(14.54)	0.02	(0.06)	9.56	(14.48)
SD	0.42	(0.76)	0.01	(0.09)	0.38	(0.70)

3.3. Entropy exchange

3.3.1. Entropy production

Table 5 shows the entropy production on a growing season basis as well as an annual basis (the latter given in parentheses). Entropy is produced through the energy dissipation of net shortwave radiation (σ_{Rsn}) and absorbed longwave radiation ($\sigma_{Rl\downarrow}$). The contribution of the latter was negligible (<< 1%) and that of the former prevailed.

The 12-year mean of net entropy production ($\sigma = \sigma_{Rsn} + \sigma_{Rl\downarrow}$) was 14.5±0.7 MJ m^{-2} K^{-1} of which two-thirds was produced during the growing seasons. Interannual variability of σ was relatively small (<4%) except the drought year 2012 when σ was highest (i.e., 10% greater than the 12-year mean).

3.3.2. Entropy transfer

Entropy is transferred into and out of the maize production system and the five radiation and surface energy flux terms are mainly involved in this process (see Eq. 11). Table 6 summarized the amount of entropy transferred by these terms for each growing season and for individual years (the latter given in parentheses). Positive/negative values indicate that the entropy is transferred into/out of the maize system.

The entropy transfer into the system by J_{Rsn} was persistent but small (on average, 0.8±0.0 MJ m^{-2} K^{-1}). In 2012, J_{Rsn} was the highest (12% higher than the 12-year mean) because of the highest R_{sn} under the less cloudy conditions during the drought period.

As expected from the above-mentioned results on the radiation exchange (in Sec. 3.1), the entropy transfers by the two terrestrial radiation components (i.e., $R_{l\downarrow}$ and $R_{l\uparrow}$) were predominant and persistent (with <1% interannual variability) in terms of magnitudes. With their signs being opposite, however, they cancelled out. The resulting net entropy transfer ($J_{Rln} = J_{Rl\downarrow} + J_{Rl\uparrow}$) averaged 2.8 MJ m^{-2} K^{-1} during the growing seasons, which consisted 52% of the annual J_{Rln}, the second largest entropy transfer out of the system next to J_{LE}. In 2012 with drought, the maximum J_{Rln} was observed as a result of the combined effect of reduced $J_{Rl\downarrow}$ and increased $J_{Rl\uparrow}$. The growing season- and the annually-integrated values of J_{Rln} were both 14% greater than the 12-year mean.

The growing season entropy transfer out of the system through LE was the largest contributor with the averaged J_{LE} of 4.9 MJ m^{-2} K^{-1}(i.e., 82% of the annual J_{LE}). In 2012, the growing season precipitation was extremely low due to drought, but J_{LE} was 5% higher than the 12-year mean owing to more frequent irrigation in July.

J_H was the third largest contributor with a growing season mean of 1.1±0.2 MJ m^{-2} K^{-1}. Typically, under drought conditions, more energy is dissipated to H than to LE so that the contribution of J_H would be greater than that of J_{LE}. However, the reverse was the case in 2012 due to frequent irrigation. The magnitude of J_H increased by 16% but still remained about one quarter of J_{LE}.

Overall, net entropy transfer (J) was 12.4±0.5 MJ m^{-2} K^{-1} with <5% inter-annual variability. The highest amount of entropy transfer occurred in 2012, which was 10% higher than the 12-year mean.

3.3.3. Net ecosystem exchange (*NEE*) of entropy

In Table 7, the growing season- and the annually-integrated (given in parentheses) values of σ, J, and dS/dt (i.e., *NEE*) are summarized. On average, two-thirds of the entropy production and the entropy transfer occurred during the growing seasons, and the remainder was the contribution from the non-growing seasons. Overall, the ratio of J to σ averaged 0.85 for both the annual and the growing season periods. This indicates that approximately 85% of σ was transferred out of the system, resulting in a net annual accumulation of entropy within the system (i.e., positive *NEE* of 2.1±0.5 MJ m^{-2} K^{-1}), of which three quarters were the contribution from the growing seasons. It is important to note that there was an increasing trend in *NEE* from 2003 to 2014 by a factor of almost 2. Furthermore, the relative contribution from the non-growing season to the annual entropy accumulation increased by a factor of 2.5 from 2003 to 2014.

Table 6. The growing season- and the annually-integrated (given in parentheses) entropy transfer terms at NE1 site at Mead, Nebraska, USA from 2003 to 2014

Year	J_{RSN} (MJ m^{-2} K^{-1})		$J_{RL\downarrow}$ (MJ m^{-2} K^{-1})		$J_{RL\uparrow}$ (MJ m^{-2} K^{-1})		J_{LE} (MJ m^{-2} K^{-1})		J_H (MJ m^{-2} K^{-1})		J (MJ m^{-2} K^{-1})	
2003	0.52	(0.75)	19.08	(34.42)	-22.05	(-39.93)	-4.60	(-5.52)	-1.27	(-2.20)	-8.33	(-12.48)
2004	0.49	(0.72)	19.31	(34.86)	-22.08	(-40.26)	-4.21	(-5.03)	-1.44	(-2.35)	-7.93	(-12.06)
2005	0.51	(0.75)	19.45	(35.05)	-22.39	(-40.51)	-4.37	(-5.38)	-1.33	(-2.24)	-8.13	(-12.33)
2006	0.51	(0.79)	19.38	(35.01)	-22.22	(-40.70)	-4.51	(-5.66)	-1.09	(-1.94)	-7.92	(-12.51)
2007	0.51	(0.76)	19.70	(35.00)	-22.43	(-40.35)	-4.97	(-6.38)	-0.79	(-1.50)	-7.99	(-12.47)
2008	0.52	(0.78)	19.18	(34.24)	-21.92	(-39.64)	-4.74	(-6.09)	-0.95	(-1.97)	-7.90	(-12.68)
2009	0.49	(0.76)	19.24	(34.51)	-21.69	(-39.51)	-4.27	(-5.31)	-1.13	(-2.15)	-7.36	(-11.70)
2010	0.52	(0.77)	19.45	(34.92)	-22.14	(-39.88)	-4.70	(-5.91)	-0.99	(-1.59)	-7.87	(-11.68)
2011	0.54	(0.80)	19.15	(34.29)	-22.10	(-39.84)	-4.80	(-6.06)	-1.08	(-1.68)	-8.29	(-12.49)
2012	0.58	(0.89)	18.97	(34.60)	-22.20	(-40.83)	-4.86	(-5.96)	-1.27	(-2.38)	-8.78	(-13.68)
2013	0.52	(0.79)	19.22	(34.12)	-22.02	(-39.56)	-4.42	(-5.69)	-0.93	(-1.82)	-7.63	(-12.16)
2014	0.53	(0.82)	19.18	(34.18)	-22.01	(-39.74)	-4.05	(-5.17)	-1.42	(-2.78)	-7.77	(-12.69)
AVG	0.52	(0.78)	19.28	(34.60)	-22.11	(-40.06)	-4.54	(-5.68)	-1.14	(-2.05)	-7.99	(-12.41)
SD	0.02	(0.04)	0.19	(0.34)	0.19	(0.43)	0.27	(0.40)	0.20	(0.36)	0.35	(0.50)

Table 7. The growing season- and the annually-integrated (given in parentheses) values of σ, *J*, and dS/dt at NE1 site at Mead, Nebraska, USA from 2003 to 2014

Year	σ (MJ m^{-2} K^{-1})		J (MJ m^{-2} K^{-1})		dS/dt (MJ m^{-2} K^{-1})	
2003	9.38	(13.79)	-8.33	(-12.48)	1.05	(1.30)
2004	8.98	(13.33)	-7.93	(-12.06)	1.05	(1.27)
2005	9.33	(13.78)	-8.13	(-12.33)	1.20	(1.46)
2006	9.41	(14.47)	-7.92	(-12.51)	1.48	(1.96)
2007	9.39	(14.19)	-7.99	(-12.47)	1.40	(1.71)
2008	9.60	(14.63)	-7.90	(-12.68)	1.69	(1.95)
2009	9.17	(14.23)	-7.36	(-11.70)	1.81	(2.53)
2010	9.63	(14.42)	-7.87	(-11.68)	1.76	(2.74)
2011	9.91	(14.85)	-8.29	(-12.49)	1.62	(2.37)
2012	10.53	(16.11)	-8.78	(-13.68)	1.75	(2.43)
2013	9.64	(14.76)	-7.63	(-12.16)	2.01	(2.60)
2014	9.73	(15.23)	-7.77	(-12.69)	1.96	(2.53)
AVG	9.56	(14.48)	7.99	(12.41)	1.57	(2.07)
SD	0.38	(0.70)	0.35	(0.50)	0.32	(0.51)

In 2012, as pointed out earlier, the magnitudes of both σ and *J* were the greatest (~10% greater than the 12-year mean). However, the resulting *NEE* was not much different from those of other years with no severe drought. Whether or not such an insignificant difference in *NEE* might have resulted from the drought mitigation with more frequent irrigation and/or from the maize ecosystem's self-organizing adaptability deserves further investigation, which is the subject of the sections below.

3.4. Monthly variations in 2012 with drought

3.4.1. Radiation, energy, and efficiency

Table 8 summarizes the monthly integrated values of radiation and energy balance components in 2012 along with their 12-year mean monthly values. The striking changes in the radiation and energy balance occurred during the first half of the growing season (particularly in June and July), which are characterized by (1)~15% increases in $R_{S\downarrow}$ and R_n, (2)~30% increase in *LE* (hence *ET* in Fig. 1), and (3) the advection of *H* (manifested as small positive or negative fluxes) via the oasis effect due to frequent irrigation under drought conditions (see Fig. 1).

Table 9 summarizes the monthly integrated values of *GPP*, *RE* and *ET*, and the monthly means of *CUE* and *WUE* in 2012. In comparison with the 12-year monthly mean, more rapid and greater accumulation of *GPP*, *RE* and *ET* from May to July was compensated by much lower accumulation after July, yielding comparable values to their 12-year growing

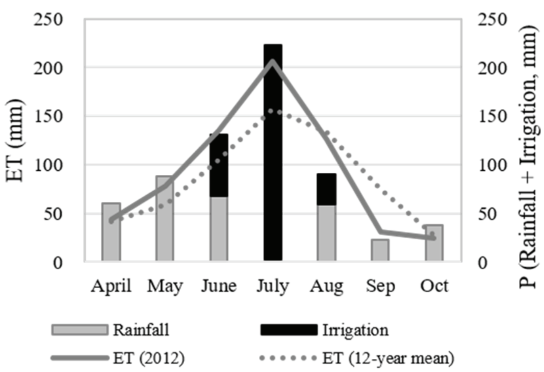

Fig. 1. Precipitation (*P* = rainfall + irrigation) and evapotranspiration (*ET*) during the growing season in 2012 at the NE1 site in Mead, Nebraska, USA. (Dotted line represents the 12-year monthly mean *ET*.)

Table 8. The monthly integrated values of $R_{S\downarrow}$, $R_{S\uparrow}$, $R_{l\downarrow}$, $R_{l\uparrow}$, R_n, *LE*, and *H* in 2012 along with their 12-year mean monthly values (mean) at the NE1 site at Mead, Nebraska, USA from 2003 to 2014

Month	$R_{S\downarrow}$ (MJ m^{-2})		$R_{S\uparrow}$ (MJ m^{-2})		$R_{l\downarrow}$ (MJ m^{-2})		$R_{l\uparrow}$ (MJ m^{-2})		R_n (MJ m^{-2})		*LE* (MJ m^{-2})		*H* (MJ m^{-2})	
	2012	Mean	2012	Mean	2012	Mean	2012	Mean	2012	Mean	2012	Mean	2012	Mean
Jan	268	253	54	109	655	654	803	763	64	34	23	25	43	14
Feb	355	329	150	123	635	608	751	717	77	94	52	42	2	26
Mar	509	450	80	90	823	751	999	889	252	220	72	75	94	75
Apr	617	541	96	90	811	797	994	955	337	291	108	103	149	114
May	775	673	135	116	919	909	1123	1083	435	382	190	144	131	140
June	780	700	134	118	959	962	1118	1108	486	435	328	256	19	66
July	867	748	149	135	1043	1039	1182	1155	578	496	502	385	-62	-10
Aug	701	644	119	113	974	1024	1124	1134	432	420	308	326	51	11
Sep	565	514	87	90	844	898	1033	1034	287	287	76	182	175	65
Oct	376	376	74	75	802	828	948	973	155	155	60	68	70	74
Nov	298	260	48	56	696	706	852	840	92	69	43	50	36	27
Dec	213	202	92	75	662	676	768	779	14	25	16	27	9	10
Annual	6324	5690	1219	1189	9842	9853	11693	11430	3209	2909	1779	1681	717	611

Table 9. Monthly integrated *GPP*, *RE*, and *ET*, and the averaged *CUE* and *WUE* in 2012 and the 12-year mean values (Mean) at NE1 site at Mead, Nebraska from 2003 to 2014

Month	*GPP* ($g\ C\ m^{-2}$)		*RE* ($g\ C\ m^{-2}$)		*ET* (mm)		*CUE* (-)		*WUE* ($g\ C\ (kg\ H_2O)^{-1}$)	
	2012	Mean	2012	Mean	2012	Mean	2012	Mean	2012	Mean
Jan	0	0	19	19	10	10	0.00	0.00	0.00	0.00
Feb	0	0	26	19	21	17	0.00	0.00	0.00	0.00
Mar	0	0	61	39	29	31	0.00	0.00	0.00	0.00
Apr	0	0	58	59	44	42	0.00	0.00	0.00	0.00
May	62	16	111	96	78	59	0.56	0.16	0.80	0.26
June	547	308	288	216	134	105	1.89	1.43	4.07	2.94
July	710	688	335	334	206	158	2.12	2.06	3.45	4.36
Aug	362	533	250	308	126	134	1.45	1.73	2.87	3.99
Sep	22	177	98	167	31	75	0.22	1.06	0.71	2.37
Oct	0	7	61	62	25	28	0.00	0.11	0.00	0.25
Nov	0	0	41	39	18	20	0.00	0.00	0.00	0.00
Dec	0	0	23	26	7	11	0.00	0.00	0.00	0.00
Annual	1703	1728	1372	1383	729	689	0.52	0.55	0.99	1.18

season means. Consequently, *CUE* and *WUE* also showed similar decreasing patterns - higher efficiency from May to July followed by much lower efficiency afterwards. The reduced efficiency can be attributed to the rapid reduction in *GPP* after July and also to the sustained *ET* in August, which was 40% greater than the sum of irrigation and rainfall (Fig. 1). The maize crops transpired more water from the deeper soil, which was replenished by the excessive amount of irrigation in the preceding month (i.e., July).

3.4.2. Entropy exchange

In Fig. 2, the monthly integrated values of σ_{Rsn}, $\sigma_{Rl\downarrow}$, and their anomalies at NE1 site in 2012 are presented. As expected, the seasonality of σ_{Rsn} followed that of R_{sn} and peaked in July. Positive

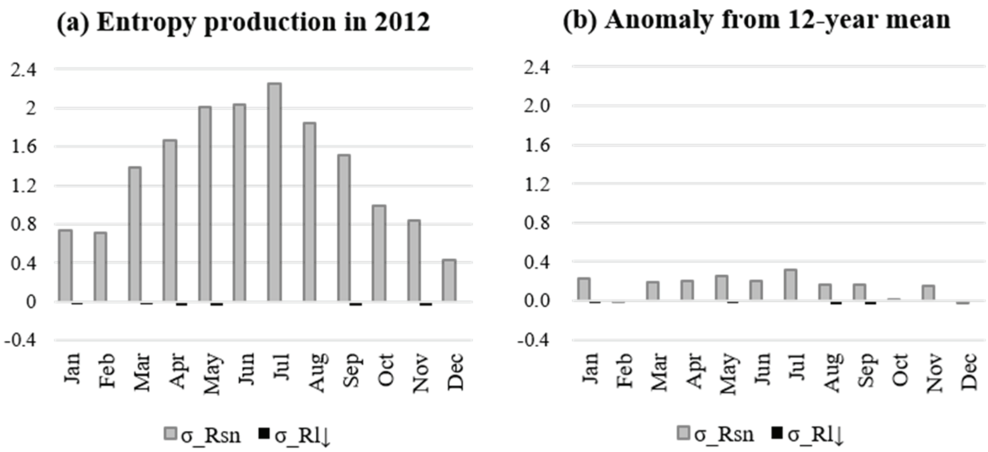

Fig. 2. Monthly integrated values of (a) σ_{Rsn} and $\sigma_{Rl\downarrow}$ and (b) anomalies from the 12-year monthly means at NE1 site at Mead, Nebraska, USA in 2012.

anomalies were observed before, during and after the growing season, indicating that the impact of drought was persistent throughout the year. The seasonality and the magnitude of $\sigma_{Rl\downarrow}$ were insignificantly small but the fluctuations of the sign of entropy production deserves further investigation regarding the estimation of the atmospheric temperature (T_{atm}).

In terms of monthly entropy transfer in 2012, J_{Rsn} showed a clear seasonality but small and positive (transfer into the system) with near zero anomalies, whereas J_{Rln} fluctuated around 0.5 MJ m^{-2} K^{-1} with small negative anomalies throughout the year (Fig. 3). Both J_{LE} and J_H showed noteworthy changes particularly in June, July and September. In June, large positive anomaly of J_H and much greater negative anomaly of J_{LE} were the manifestation of the frequent occurrence of strong sensible heat advection that provided an additional energy for the enhanced *ET*. This process was further amplified in July as a result of more frequent irrigation. However, the reduced irrigation in August and its termination in September produced the reversed anomalies between J_{LE} and J_H.

Overall, σ, *J*, and dS/dt all showed smooth seasonal variations without no abrupt changes throughout the year (Fig. 4). Their anomalies clearly demonstrated that (1) the prolonged drought conditions in 2012 produced more entropy within the maize

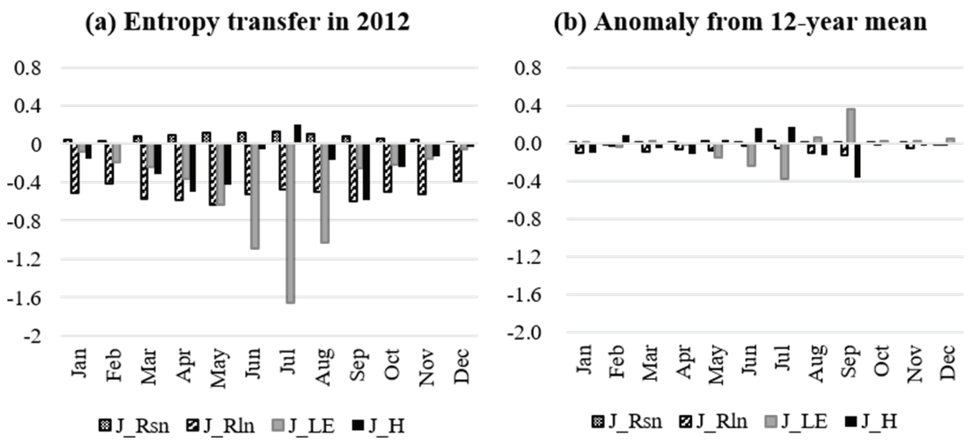

Fig. 3. Monthly integrated values of (a) J_{Rsn}, J_{Rln}, J_{LE}, and J_H and (b) the anomalies from the 12-year monthly means of entropy transfer terms at NE1 site at Mead, Nebraska, USA in 2012.

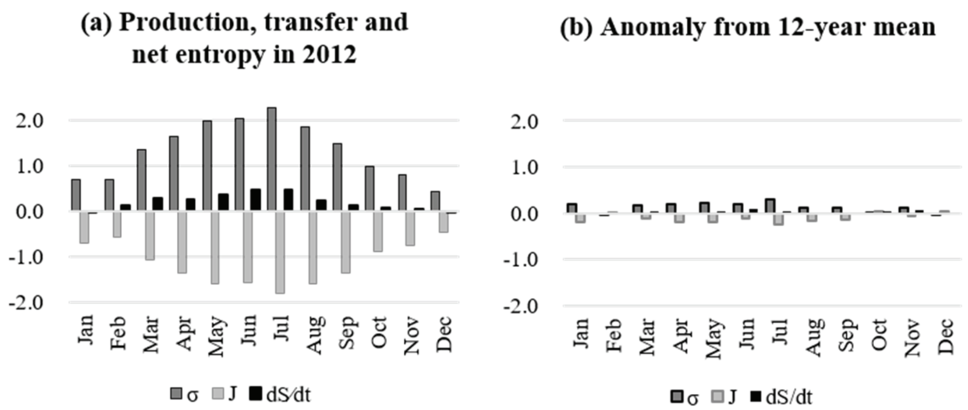

Fig. 4. Monthly values of (a) σ, *J*, and dS/dt in 2012 and (b) the anomalies from the 12-year monthly means at NE1 site at Mead, Nebraska, USA in 2012.

agroecosystem, (2) the increased energy dissipation resulted in concurrent enhancement of entropy transfer processes, and (3) therefore, the monthly anomalies of dS/dt were not notable, revealing that neither drought nor irrigation affected significantly the net entropy exchange in 2012.

IV. Discussion and Summary

Our objective was to evaluate and to document the energetics in the NE1 irrigated-maize site. From the thermodynamic perspective, we viewed this agroecosystem as an open thermodynamic system with a large gradient impressed upon it by the sun. As the system is moved away from equilibrium, thermodynamic imperative drives the system to resist and to reduce the externally applied gradient by using all biotic, physical, chemical, and human components of this ecological-social system (SES) acting together as a nonequilibrium dissipative process (e.g., Schneider and Kay, 1994). The NE1 SES is a highly ordered complex system emerged as a result of decades-long development and adaptation through diverse disturbances and adaptive management. Thus, the system would grow and develop in ways which systematically increase its ability to dissipate and to degrade the incoming solar radiation at the expense of increasing the disorder at higher levels in the system's hierarchy. Here, dissipation means to move energy through a system, which may or may not annihilate gradients; whereas degradation means to annihilate the ability of energy to set up gradients that can accomplish work (Kay, 1984).

Our results from the analyses of the energetics in this SES demonstrated: (1) more energy capture during growing season than non-growing season, and increasing energy capture through growing season until senescence (e.g., the $R_n/R_{S\downarrow}$ ratio increased from 0.56 in May to 0.62–0.66 in June to August and then decreased to 0.41 in October, whereas that of non-growing season averaged 0.30); (2) more energy flow activity within and through the system, providing greater potential for degradation (e.g., the LE/R_n ratio increased from 0.38 in May to 0.78 in July-August and then decreased to 0.44 in October); (3) higher efficiency in terms of CUE and WUE through growing season until senescence; and (4) the resulting energy degradation occurred at the expense of increasing net entropy accumulation (dS/dt at a rate of ~1.57 MJ m^{-2} K^{-1} per growing season and ~2.07 MJ m^{-2} K^{-1} annually) as well as net entropy transfer out to the surrounding environment (J at a rate of ~7.99 MJ m^{-2} K^{-1} per growing season and ~12.41 MJ m^{-2} K^{-1} annually). In comparison with the entropy balance reported in the literature for grassland ecosystems (σ = 15.5–16.0 MJ m^{-2} K^{-1}, dS/dt = 3.4~3.7 MJ m^{-2} K^{-1}; Brunsell *et al.*, 2011), the NE1 irrigated-maize agroecosystem was slightly lower in entropy production but pumped more entropy out to the environment, resulting in much lower annual entropy accumulation within the system.

The role of thermodynamics in the growth and development of ecosystems and their response to disturbance deserves more attention. Ecosystem ecology based on thermodynamic paradigm holds the promise of propelling ecosystem science from a descriptive to a predictive science (Schneider and Kay, 1994). Despite the insightful results from our study, caution must be exercised to draw any implication on the sustainability of the irrigated-maize agroecosystem based on entropy accounting only. The self-organization process serves to effectively reduce the impressed gradient between the system and its surrounding environment. Thus, using the flux time series data from measurement, modeling and remote sensing, information theory-based analyses such as spectral entropy (i.e., a measure of self-organizing capacity that ensures system's sustainability) or dynamic process network (that can delineate changes in the strength and direction of energy/material flows and the subsystems' structure) should be considered in tandem (e.g., Ruddell and Kumar, 2009; Yun *et al.*, 2014).

적 요

이 연구의 목표는 관개된 옥수수 밭에서의 복사, 에너지 및 엔트로피의 교환을 평가하고 문서화하는 것이다. 열역학적 관점에서, 우리는 이 농업생태계를 태양 복사로 인해 시스템 내부와 외부 사이에 큰 경도(gradient)가 부여되는 열린 열역학적 시스템으로 간주하였다. 따라서 시스템이 평형에서 멀어질 때, 열역학적 원칙에 따라 비평형 소산 과정(nonequilibrium dissipative process)인 이 생태-사회시스템이 모든 생물, 물리, 화학 및 인위적 구성 요소를 사용하여 태양으로부터 주어진 경도에 저항하여 이를 감소시키도록 움직인다고 가정하였다. 이 가설을 검증하기 위한 첫 단계로서 미국 네브라스카의 옥수수 밭에 위치한 AmeriFlux의 NE1 사이트에서 2003년부터 2014년까지 관측된 플럭스 및 미기상 자료를 사용하여 복사, 에너지 및 엔트로피의 교환을 정량화하였다. 12년 평균한 생장기간의 결과에 따르면, 시스템의 에너지 포획(순복사와 하향단파복사의 비, $R_n/R_{S\downarrow}$)은 옥수수의 생장과 함께 증가하였고, 생장기간이 비생장기간보다 약 80% 높았다. 생장기간 동안 시스템 내의 엔트로피 생성(σ)은 평균 9.56 MJ m^{-2} K^{-1}이었고, 주로 하향단파복사에 의해 결정되었다. 엔트로피 수송(J)은 잠열플럭스, 순장파복사, 현열플럭스의 순으로 기여하였고, 시스템 외부 환경으로 퍼낸 양은 σ의 ~84%에 해당하는 −7.99 MJ m^{-2} K^{-1}이었다. 따라서 매년 생장 기간 동안 시스템 내에 순 축적된 엔트로피(dS/dt)는 1.57 MJ m^{-2} K^{-1}이었다. 탄소 흡수 효율(CUE)은 1.25～1.62, 물 사용 효율(WUE)은 1.98～2.92 g C (kg H_2O)$^{-1}$이었고 모두 옥수수의 성장과 함께 증가하였다. 극심한 가뭄으로 관개가 더 빈번하게 행해진 2012년의 경우, σ와 J가 모두 평년보다 10% 많은 최대값을 보였고, 그 결과 서로 대부분 상쇄되어 dS/dt는 평년보다 조금 높은 수준에 머물렀다. 가뭄 중에도 빈번한 관개로 인해 엔트로피 수송의 주된 경로가 현열플럭스에서 잠열플럭스로 바뀌면서 생산량과 CUE는 평년값을 웃돌았으나 물과 빛의 사용 효율은 오히려 낮아졌다. 이러한 결과에 근거하여 관개된 옥수수 생태-사회시스템의 지속가능성의 변화를 평가하기에는 아직 여러가지 문제가 남아있다. 자기-조직화 과정은 시스템과 주변 간의 경도를 효과적으로 감소시키는 역할을 한다. 따라서 엔트로피 자료와 함께, 지속가능성의 척도가 되는 자기-조직화 역량을 나타내는 스펙트랄 엔트로피, 또는 하부시스템의 구조 및 에너지･물질의 흐름의 강도와 방향의 변화를 가늠할 수 있는 역학적 과정망(dynamic process network) 분석 등의 추가 연구가 병행되어야 한다.

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REFERENCES

Adegoke, J. O., R. A. P. Sr., J. Eastman, R. Mahmood, and K. G. Hubbard, 2003: Impact of irrigation on midsummer surface fluxes and temperature under dry synoptic conditions: A regional atmospheric model study of the U.S. high plains. *Monthly Weather Review* **131**(3), 556-564. https://doi.org/10.1175/1520-0493(2003)131<0556:Ioioms>2.0.Co;2

Brunsell, N., S. Schymanski, and A. Kleidon, 2011: Quantifying the thermodynamic entropy budget of the land surface: is this useful? *Earth System Dynamics Discussions* **2**(1), 57-103. 10.5194/esdd-2-71-2011

Campbell, G. S., and J. Norman, 1998: *An introduction to environmental biophysics*. Springer-Verlag New York.

Clausius, R., 1867: *The mechanical theory of heat: With its applications to the steam-engine and to the physical properties of bodies*. J. van Voorst., London.

Cochran, F. V., N. A. Brunsell, and A. E. Suyker, 2016: A thermodynamic approach for assessing agroecosystem sustainability. *Ecological Indicators* **67**, 204-214. https://doi.org/10.1016/j.ecolind.2016.01.045

Endres, R. G., 2017: Entropy production selects nonequilibrium states in multistable systems. *Scientific Reports* **7**(1), 14437. https://doi.org/10.1038/s41598-017-14485-8

Eulenstein, F., W. Haberstock, W. Steinborn, Y. U.

Svirezhev, J. Olejnik, S. Schlindwein, and V. Pomaz, 2003: Perspectives from energetic-thermodynamic analysis of land use systems: Perspektiven der energetisch-thermodynamischen analyse von landnutzungssystemen. *Archives of Agronomy and Soil Science* **49**, 663-676. https://doi.org/10.1080/03650340310001615138

Desai, A. R., A. D. Richardson, A. M. Moffat, J. Kattge, D. Y. Hollinger, A. Barr, E. Falge, A. Noormets, D. Papale, M. Reichstein, and V. J. Stauch, 2008: Cross-site evaluation of eddy covariance GPP and RE decomposition techniques **148**(6-7), 821-838. https://doi.org/10.1016/j.agrformet.2007.11.012

Falge, E., D. Baldocchi, J. Tenhunen, M. Aubinet, P. Bakwin, P. Berbigier, C. Bernhofer, G. Burba, R. Clement, K. J. Davis, J. A. Elbers, A. H. Goldstein, A. Grelle, A. Granier, J. Guðmundsson, D. Hollinger, A. S. Kowalski, G. Katul, B. E. Law, Y. Malhi, T. Meyers, R. K. Monson, J. W. Munger, W. Oechel, K. T. Paw U, K. Pilegaard, Ü. Rannik, C. Rebmann, A. Suyker, R. Valentini, K. Wilson, and S. Wofsy, 2002: Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. *Agricultural and Forest Meteorology* **113**(1), 53-74. https://doi.org/10.1016/S0168-1923(02)00102-8

Fath, B. D., S. E. Jørgensen, B. C. Patten, and M. Straškraba, 2004: Ecosystem growth and development. *BioSystems* **77**, 213-228. https://doi.org/10.1016/j.biosystems.2004.06.001

Flanagan, L. B., L. A. Wever, and P. J. Carson, 2002: Seasonal and interannual variation in carbon dioxide exchange and carbon balance in anorthern temperate grassland. *Global Change Biology* **8**, 599-615.

Force, D. T., 2013: *An interpretation of the origins of the 2012 central great plains drought.*

Gitelson, A. A., A. Viña, S. B. Verma, D. C. Rundquist, T. J. Arkebauer, G. Keydan, B. Leavitt, V. Ciganda, G. G. Burba, and A. E. Suyker, 2006: Relationship between gross primary production and chlorophyll content in crops: Implications for the synoptic monitoring of vegetation productivity. *Journal of Geophysical Research: Atmospheres* **111**(D8). https://doi.org/10.1029/2005jd006017

Grigg, N. S., 2014: The 2011–2012 drought in the United States: new lessons from a record event. *International Journal of Water Resources Development* **30**(2), 183-199. https://doi.org/10.1080/07900627.2013.847710

Holdaway, R. J., A. D. Sparrow, and D. A. Coomes, 2010: Trends in entropy production during ecosystem development in the Amazon Basin. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* **365**(1545), 1437-1447. https://doi.org/10.1098/rstb.2009.0298

Huber, D., D. Mechem, and N. Brunsell, 2014: The effects of great plains irrigation on the surface energy balance, regional circulation, and precipitation. *Climate* **2**, 103-128. https://doi.org/10.3390/cli2020103

Humes, K. S., W. P. Kustas, M. S. Moran, W. D. Nichols, and M. A. Weltz, 1994: Variability of emissivity and surface temperature over a sparsely vegetated surface. *Water Resources Research* **30**(5), 1299-1310. https://doi.org/10.1029/93wr03065

Irmak, A., K. Singh, R., A. Walter-Shea, E., B. Verma, S., E. Suyker, A., 2011: Comparison and analysis of empirical equations for soil heat flux for different cropping systems and irrigation methods. *Transactions of the ASABE* **54**(1), 67-80. https://doi.org/10.13031/2013.36261

Kay, J., 1984: Self-organization in living systems. University of Waterloo, Waterloo, Ontario, Canada.

Kim, J., S. B. Verma, and R. J. Clement, 1992: Carbon dioxide budget in a temperate grassland ecosystem. *Journal of Geophysical Research: Atmospheres* **97**(D5), 6057-6063.

Kleidon, A., and S. Schymanski, 2008: Thermodynamics and optimality of the water budget on land: A review. *Geophysical Research Letters* **35**(20). https://doi.org/10.1029/2008gl035393

Kranz, W. L., S. Irmak, S. J. Van Donk, C. D. Yonts, and D. L. Martin, 2008: Irrigation management for corn. *Neb Guide, University of Nebraska, Lincoln* **10**(5), 1-8.

Kuglitsch, F. G., M. Reichstein, C. Beer, A. Carrara, R. Ceulemans, A. Granier, I. A. Janssens, B. Koestner, A. Lindroth, D. Loustau, G. Matteucci, L. Montagnani, E. J. Moors, D. Papale, K. Pilegaard, S. Rambal, C. Rebmann, E. D. Schulze, G. Seufert, H. Verbeeck, T. Vesala, M. Aubinet, C. Bernhofer, T. Foken, T. Grünwald, B. Heinesch, W. Kutsch, T. Laurila, B. Longdoz, F. Miglietta, M. J. Sanz, R. and Valentini, 2008: Characterisation of ecosystem water-use efficiency of european forests from eddy covariance measurements. *Biogeosciences Discuss* **2008**, 4481-4519. https://doi.org/10.5194/bgd-5-4481-2008

Lin, H., M. Cao, P. Stoy, and Y. Zhang, 2009: Assessing self-organization of plant communities-A thermodynamic approach. *Ecological Modelling* **220**, 784-790. https://doi.org/10.1016/j.ecolmodel.2009.01.003

Massman, W. J., 1991: The attenuation of concentration fluctuations in turbulent flow through a tube. *Journal* *of Geophysical Research: Atmospheres* **96**(D8), 15269-15273. https://doi.org/10.1029/91jd01514

McCaughey, J. H., and W. L. Saxton, 1988: Energy balance storage terms in a mixed forest. *Agricultural and Forest Meteorology* **44**(1), 1-18. https://doi.org/10.1016/0168-1923(88)90029-9

Moore, T. R., and R. Knowles, 1989: The influence of water table levels on methane and carbon dioxide emissions from peatland soils. *Canadian Journal of Soil Science* **69**(1), 33-38. https://doi.org/10.4141/cjss89-004

NASS, 2007: *Census of Agriculture: Farm and Ranch Irrigation Survey*. *in* U. N. A. S. Service, editor., Washington, D.C.

Nguy-Robertson, A., A. Suyker, and X. Xiao, 2015: Modeling gross primary production of maize and soybean croplands using light quality, temperature, water stress, and phenology. *Agricultural and Forest Meteorology* **213**, 160-172. https://doi.org/10.1016/j.agrformet.2015.04.008

Odum, E. P., 1969: The strategy of ecosystem development. *Science* **164**(3877), 262-270. https://doi.org/10.1126/science.164.3877.262

Patzek, T. W., 2008: Thermodynamics of Agricultural Sustainability: The case of US maize agriculture. *Critical Reviews in Plant Sciences* **27**(4), 272-293. https://doi.org/10.1080/07352680802247971

Rosenberg, N. J., 1987: Climate of the great plains region of the United States. *Great Plains Quarterly* **7**(1), 22-32.

Rosenberg, N. J., B. L. Blad, and S. B. Verma, 1983: *Microclimate: The Biological Environment, 2nd Edition*. Wiley, USA.

Ruddell, B. L., and P. Kumar, 2009: Ecohydrologic process networks: 1. Identification. **45**(3), https://doi.org/10.1029/2008WR007279

Schneider, E. D., and J. J. Kay, 1994: Life as a manifestation of the second law of thermodynamics. *Mathematical and Computer Modelling* **19**(6), 25-48. https://doi.org/10.1016/0895-7177(94)90188-0

Steinborn, W., and Y. Svirezhev, 2000: Entropy as an indicator of sustainability in agro-ecosystems: North Germany case study. *Ecological Modelling* **133**(3), 247-257. https://doi.org/10.1016/S0304-3800(00)00323-9

Suyker, A., 2016: AmeriFlux US-Ne1 Mead - irrigated continuous maize site.

Suyker, A. E., and S. B. Verma, 1993: Eddy correlation measurement of CO_2 flux using a closed-path sensor: Theory and field tests against an open-path sensor. *Boundary-Layer Meteorology* **64**(4), 391-407. https://doi.org/10.1007/bf00711707

Suyker, A. E., and S. B. Verma, 2001: Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie. *Global Change Biology* **7**(3), 279-289. https://doi.org/10.1046/j.1365-2486.2001.00407.x

Suyker, A. E., and S. B. Verma, 2008: Interannual water vapor and energy exchange in an irrigated maize-based agroecosystem. *Agricultural and Forest Meteorology* **148**(3), 417-427. https://doi.org/10.1016/j.agrformet.2007.10.005

Suyker, A. E., and S. B. Verma, 2010: Coupling of carbon dioxide and water vapor exchanges of irrigated and rainfed maize-soybean cropping systems and water productivity. *Agricultural and Forest Meteorology* **150**(4), 553-563. https://doi.org/10.1016/j.agrformet.2010.01.020

Suyker, A. E., and S. B. Verma, 2012: Gross primary production and ecosystem respiration of irrigated and rainfed maize-soybean cropping systems over 8 years. *Agricultural and Forest Meteorology* **165**, 12-24. https://doi.org/10.1016/j.agrformet.2012.05.021

Suyker, A. E., S. B. Verma, G. G. Burba, and T. J. Arkebauer, 2005: Gross primary production and ecosystem respiration of irrigated maize and irrigated soybean during a growing season. *Agricultural and Forest Meteorology* **131**(3), 180-190. https://doi.org/10.1016/j.agrformet.2005.05.007

USDA, 2019: *Crop Production 2018 Summary*. *in* U. S. D. o. Agriculture, editor.

Verma, S. B., A. Dobermann, K. G. Cassman, D. T. Walters, J. M. Knops, T. J. Arkebauer, A. E. Suyker, G. G. Burba, B. Amos, H. Yang, D. Ginting, K. G. Hubbard, A. A. Gitelson, and E. A. Walter-Shea, 2005: Annual carbon dioxide exchange in irrigated and rainfed maize-based agroecosystems. *Agricultural and Forest Meteorology* **131**(1), 77-96. https://doi.org/10.1016/j.agrformet.2005.05.003

Wang, T., X. Tang, C. Zheng, Q. Gu, J. Wei, and M. Ma, 2018: Differences in ecosystem water-use efficiency among the typical croplands. *Agricultural Water Management* 209, 142-150. https://doi.org/10.1016/j.agwat.2018.07.030

Wilhelmi, O. V., and D. A. Wilhite, 2002: Assessing vulnerability to agricultural drought: A Nebraska case study. *Natural Hazards* **25**(1), 37-58. https://doi.org/10.1023/a:1013388814894

Wilson, K., and D. Baldocchi, 2000: Seasonal and interannual variability of energy fluxes over a broadleaved temperate deciduous forest in North America. *Agricultural and Forest Meteorology* **100**, 1-18. https://doi.org/10.1016/S0168-1923(99)00088-X

Wofsy, S. C., M. L. Goulden, J. W. Munger, S. M. Fan, P. S. Bakwin, B. C. Daube, S. L. Bassow, and F. A. Bazzaz, 1993: Net exchange of CO_2 in a midlatitude forest. *Science* **260**, 1314−1317.

Yang, Y., M. C. Anderson, F. Gao, B. Wardlow, C. R. Hain, J. A. Otkin, J. Alfieri, Y. Yang, L. Sun, and W. Dulaney, 2018: Field-scale mapping of evaporative stress indicators of crop yield: An application over Mead, NE, USA. *Remote Sensing of Environment* **210**, 387-402. https://doi.org/10.1016/j.rse.2018.02.020

Yun, J., M. Kang, S. Kim, J. Hwa Chun, C.-H. Cho, and J. Kim, 2014: How is the process network organized and when does it show emergent properties in a forest ecosystem? In: Sanayei, A., I. Zelinka, and O. E. Rössler, (Eds) ISCS 2013: *Interdisciplinary Symposium on Complex Systems*. Berlin, Heidelberg: Springer Berlin Heidelberg, 307-317.

Appendix 1. Data availability (%) after quality control (QC) of meteorological variables and eddy covariance flux data. Metrological variables include incoming shortwave radiation ($R_{s\downarrow}$), outgoing shortwave radiation ($R_{s\uparrow}$), incoming longwave radiation ($R_{l\downarrow}$), outgoing longwave radiation ($R_{l\uparrow}$), net radiation (R_n), wind speed (*WS*), wind direction (*WD*), air temperature (T_{air}), and precipitation (*P*). Eddy covariance flux data include CO_2 flux(Fco_2), latent heat flux (*LE*), sensible heat flux (*H*), and friction velocity (*U**) from 2003 to 2014

Year	$R_{s\downarrow}$	$R_{s\uparrow}$	$R_{l\downarrow}$	$R_{l\uparrow}$	R_n	*WS*	*WD*	T_{air}	*P*	Fco_2	*LE*	*H*	*U**
2003	97	98	97	97	96	31	97	100	100	94	87	96	88
2004	100	100	100	100	100	30	99	100	100	94	87	96	88
2005	100	100	100	100	100	31	100	100	100	94	89	98	93
2006	97	95	90	90	88	27	99	100	100	96	90	98	90
2007	97	100	100	100	97	42	100	99	100	94	87	97	90
2008	98	100	100	100	98	41	100	99	100	95	87	97	91
2009	99	100	100	100	99	40	98	100	100	91	89	96	91
2010	97	100	98	100	95	26	98	100	100	92	86	96	89
2011	97	100	100	100	97	30	99	100	100	96	86	98	90
2012	98	100	100	100	98	31	99	100	100	96	86	98	89
2013	98	100	100	100	98	33	98	100	100	95	91	97	90
2014	100	100	100	100	99	31	98	100	100	96	90	97	92