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Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges

The Differential Response of Surface Fluxes from Agro-Ecosystems in Response to Local Environmental Conditions

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Abstract

Meeting the competing demands for freshwater of the urban, industrial, and agricultural communities is increasingly challenging as the global population continues to grow and the need for potable water, food, fiber, and fuel grows with it. One of the keys to meeting these demands is maximizing the efficiency of water use in agricultural applications. Toward this end, a thorough understanding of the factors driving evapotranspiration and their response to spatiotemporal variations in local environmental conditions is needed for the development and validation of numerical and remote sensing-based models. Moreover, because these exchange processes are strongly nonlinear, scaling measurements collected at one scale to another remains a nontrivial task. In an effort to identify the key environmental drivers controlling the latent heat flux (λE) from agro-ecosystems and their potential impacts on upscaling in-situ flux measurements, eddy covariance and micrometeorological data collected over maize and soy at three distinct sites located in Maryland, Iowa, and Minnesota, respectively were evaluated for the years between 2007 and 2011. The magnitudes of the evaporative fluxes were comparable for measurements collected during clear-sky days with similar environmental conditions; on average, the measurements of λE agreed to within 50 W m^{-2}, or approximately 10%. When considered in terms of evaporative fraction (f_e), however, there were marked differences among the sites. For example, while the magnitude and diurnal pattern of f_e for mature maize at the Minnesota site was nearly constant (f_e = 0.66) during the day, f_e at both the Maryland and Iowa site increased steadily during the day from a minimum value near 0.68 at midmorning to peak value of 0.87 in the afternoon. These differences appear to be primarily linked to differences in soil moisture and vegetation density at the various sites. As such, this research underscores the impact of local environmental conditions in controlling land-atmosphere exchange processes. It also underscores the importance accurately describing local environmental conditions when modeling surface fluxes.

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1. Introduction

Water scarcity is one of the most important issues emerging today. Ensuring there is sufficient fresh water to satisfy the competing needs of urban, rural, and agricultural communities is already a significant issue in many parts of the world. It is estimated that nearly one-third of the global population live in regions characterized by severe and chronic water shortages [1-3]. Moreover, it is projected that nearly two-thirds of the population will be impacted by water shortages by 2050 due to population growth, increased energy needs and changing dietary preferences [4-5].

The largest consumer of fresh water is agriculture. On average, agriculture accounts for 75% of global fresh water use annually; in arid regions this percentage can exceed 80% [4, 6]. Most of this water is used for irrigation. For example, the 7.5% (23 million hectares) of irrigated cropland in the United States for 80% to 90% of consumptive water use. It also accounted for nearly 40% ($118.5.3 billion) of the value of US agricultural production [7].

Clearly, maximizing the efficiency of irrigation is critical to ensuring there is sufficient fresh water to meet growing demand. To achieve this, detailed information regarding water loss and plant stress, both current and projected, is needed on both field and regional scales. In turn, this requires detailed information regarding the drivers of land-atmosphere exchange processes. The exchange of moisture between the land surface and the atmosphere is a single mechanism in a complex network of interactions and feedbacks linking both biogeophysical and biogeochemical cycles; as a result evapotranspiration can vary substantially and nonlinearly in response to changing environmental conditions [8].

In an effort to characterize the impact of surface and atmospheric conditions on the moisture flux, as well as the other turbulent fluxes, flux measurements collected at three agricultural sites were compared. Additionally, the relative roles of local environmental factors, such as soil moisture and leaf area index, were explored.

2. Methods

2.1. Site Description

The data used in this study was collected over maize (*Zea mays*) at three agricultural sites located in Minnesota, Iowa, and Maryland respectively (Figure 1). The first of these sites was located at the Rosemount Research and Outreach Center (RROC), a long-term agricultural research site operated by the University of Minnesota. The site consists of a pair of 17 ha fields managed using conventional tillage and management practices typical of the upper Midwest; crops of maize were rotated annually with soyean (*Glycine max*). The surface carbon and energy fluxes, as well as the meteorological and soil properties data, were collected over each of the fields using an eddy covariance micrometeorological system. Further information about this site is reported by Baker and Griffis [9]. The second site (SF) was located central Iowa within the watershed of the South Fork of the Iowa River. The watershed is dominated by cropland planted almost exclusively with maize and soybean in annual rotation. As with the RROC site, the measurements were collected over a pair of adjacent fields using an eddy covariance micrometeorological stations.

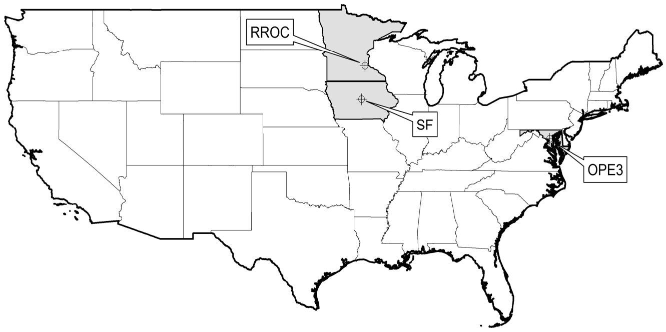

Figure 1. The locations where the data used in this study were collected.

The final site was in the" Optimizing Production Inputs for Economic and Environmental Enhancement" (OPE3) experimental watershed located near Beltsville, Maryland and operated by the USDA Agricultural Research Service. The data at this site was collected over maize again using the eddy covariance technique. Additional information about this site is reported by Gish and co-authors [10].

2.2. Data Analysis

The data analysis was conducted in two phases. The first phase of these utilized multiple regression analysis with a full factorial design to characterize the response of the turbulent fluxes to changing environmental conditions. The analysis was conducted for each site using the half-hourly data collected over maize during the summer growing season (May through August) during the years from 2007 to 2011) while focusing on the unstable daytime (defined here as the period when the incident solar radiation exceeded 100 W m^{-2}) conditions. Additionally, following Alfieri et al. [11], the analysis was conducted using standardized data so that the relative influence of each environmental factor could be quantified according to:

$$I = 100 \times |\delta_i| / \sum |\delta| \tag{1}$$

where I is the relative influence expressed as a percentage, δ represents the regression coefficient, and i is an index indicating the environmental factor.

The factorial design focused on three environmental factors: wind speed (U), air temperature (T), and specific humidity (q). Each factor was parsed into one of three subsets to generate three by three factorial design with a total of 27 treatments (Table 1). The criteria for each subset were based on the median (Q_2) and first (Q_1) and third (Q_3) quartile of each factor at each site. Specifically, the first subset was defined as $Q_1 \pm 0.10Q_2$; the second subset was defined as $Q_2 \pm 0.10Q_2$; the third subset was defined as $Q_3 \pm Q_2$. For example, the three subsets associated with U at SF were bounded as 3.4 ± 0.5 m s^{-1}, 4.6 ± 0.5 m s^{-1}, and 6.2 ± 0.5 m s^{-1} for subset 1, subset 2, and subset 3, respectively.

Table 1. The treatments used in the factorial analysis are shown. The minus sign (-) denotes the subset defined as $Q_1 \pm 0.10Q_2$; the zero (o) denotes the subset defined as $Q_2 \pm 0.10Q_2$; the plus sign (+) denotes the subset defined as $Q_3 \pm 0.10Q_2$.

Treatment	*U*	*T*	*q*	Treatment	*U*	*T*	*q*	Treatment	*U*	*T*	*q*
1	-	-	-	**10**	o	-	-	**19**	+	-	-
2	-	-	o	**11**	o	-	o	**20**	+	-	o
3	-	-	+	**12**	o	-	+	**21**	+	-	+
4	-	o	-	**13**	o	o	-	**22**	+	o	-
5	-	o	o	**14**	o	o	o	**23**	+	o	o
6	-	o	+	**15**	o	o	+	**24**	+	o	+
7	-	+	-	**16**	o	+	-	**25**	+	+	-
8	-	+	o	**17**	o	+	o	**26**	+	+	o
9	-	+	+	**18**	o	+	+	**27**	+	+	+

The second phase of the analysis compared the partitioning of the surface energy budget among the turbulent and non-turbulent fluxes at each of the sites under similar environmental conditions. To accomplish this, five to ten clear-sky days conforming to the following criteria were identified each site:

1. The median daytime *U* was between 1.5 m s^{-1} and 3.0 m s^{-1}.
2. The median daytime *T* was between 25°C and 32 °C.
3. The median daytime *q* was between 15 g kg^{-1} and 19 g kg^{-1}.
4. The total growing degree units was between 1100 C d^{-1} and 1400 °C d^{-1}.

The data from these days was averaged to create composite curves describing the typical daily pattern in the environmental factors *U*, *T*, and *q* along with each of the components of the surface energy budget: net radiation (R_n), soil heat flux (*G*), *H* and λE. To facilitate the generation of these composite curves, closure of the energy budget was forced while maintaining a constant ratio between the turbulent fluxes. The partitioning of the energy budget in terms of the fraction of R_n, the Bowen ratio (β) and the evaporative fraction (f_e) was then compared for each site.

3. Results and Discussion

The results of the regression analysis demonstrated similar results at all three sites. All showed a tendency for the sensible (*H*) and latent heat (λE) flux to increase with increasing *T* and decreasing *q*. The carbon dioxide flux (F_c) tended to decrease as both of these factors increased. The impact of *U*, in contrast, was mixed. The turbulent fluxes tended to increase with *U* at SF but variations in *U* had little impact on the fluxes measured at OPE3 and RROC. This is likely due to the relatively calmer winds at OPE3 and RROC compared to SF; *U* ranged between approximately 1.5 m s^{-1} and 9.8 m s^{-1} with a median value of 4.6 m s^{-1} at SF while it ranged between 0.7 m s^{-1} and 4.0 m s^{-1} with a median value of 1.7 m s^{-1} at OPE3 and it ranged between 0.6 m s^{-1} and 5.3 m s^{-1} with a median value of 2.0 m s^{-1} at RROC.

The analysis also showed that the relationships between the environmental factors and the turbulent fluxes were strongly nonlinear and unique for each site. For example, as can be seen in Figure 2, *H* exhibited an exponential relationship with *T* at each of the study sites, but the exact form of that relationship differed from site-to-site. More dramatically, the relationship between *H* and *q* appeared to be linear at SF and OPE3 but followed a power law relationship at RROC. Given that *q* was typically much higher at RROC than the other sites, this would suggest that the influence of *q* tends to plateau as the humidity approaches a threshold value.

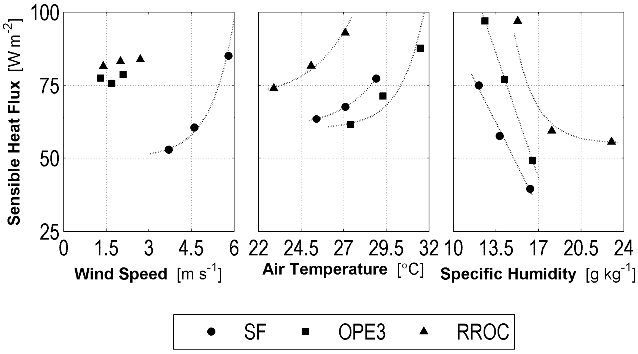

Figure 2. The relationship between the each of the environmental factors and the sensible heat flux is shown for each of the study sites.

The unique response of the turbulent fluxes to changing environmental conditions can also be seen in the relative influence of each environmental factor on the magnitude of the flux. For *H*, the relative influence of *U* was 40.6%, 1.1%, and 10.8%, respectively, for SF, OPE3, and RROC. Note that this result again suggests that U has little impact on the flux at RROC and especially OPE3 due to the lower wind speeds at those sites. The main factor controlling *H* at both OPE3 and RROC was *q* which had *I* values of 63.5% and 60.1%, respectively. In the case of λE, *I* for *U*, *T*, and *q* were 19.2%, 33.4%, and 47.4%, respectively, at SF and averaged 5.0%, 36.2%, and 58.6%, respectively, for OPE3 and RROC. In the case of F_c, the relative influence of each of the factors was similar for all of the sites; the average *I* for *U*, *T*, and *q* were 2.3%, 43.4%, and 51.6%, respectively.

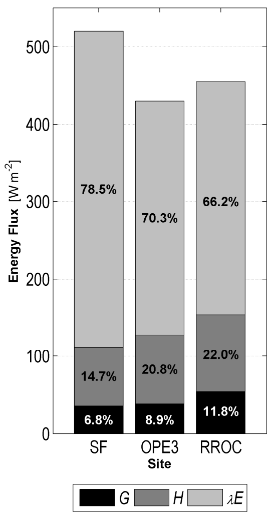

Figure 3. The partitioning of net radiation among the other components of the surface energy budget is shown for each site.

The intercomparison of the flux partitioning at each of the sites also indicated an unique response to differences in surface conditions, specifically vegetation density as measured via leaf area index (LAI) and near-surface, i.e. 5 cm, soil moisture content (θ). As can be seen in Figure 3, the partition of daytime R_n among the other components of the energy budget is unique for each site. The mean daytime β at each of the sites was approximately 0.18, 0.30, and 0.28, respectively, for SF, OPE3, and RROC, respectively. The associated f_e are 0.84, 0.77, and 0.78, respectively. A comparison of the diurnal patterns in f_e also showed that it was nearly constant at OPE3, but varied substantially over the course of the day at the other two sites. At SF and RROC, f_e was lowest in morning but increased steadily throughout the day to reach peak values in the late afternoon.

Regression analyses indicated that these differences are largely linked to differences in LAI and θ (Fig. 4). Not unexpectedly, the analysis showed that G degreased with decreasing θ and increasing LAI with LAI being the dominant controlling factor. The low percentage of R_n converted to G at SF can then be explained in terms of relatively high LAI (3.9 m^2 m^{-2}) compared to that of RROC; the site in Minnesota had the highest θ (0.23 m^3 m^{-3}) and lowest LAI (1.71 m^2 m^{-2}) of the 3 study sites. Similarly, the large percentage of R_n converted to λE at SF can be explained in terms of its moist soil conditions and high LAI. In this case too, LAI, which had an I of 65.9%, was the main controlling factor.

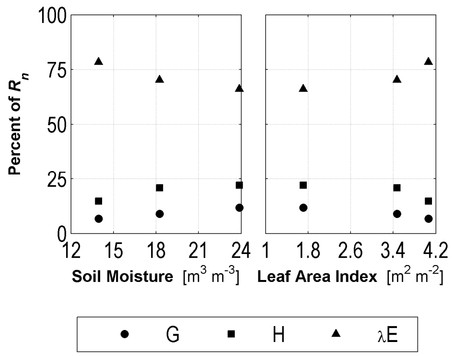

Figure 4. The fraction of net radiation partitioned into each of the surface flux is shown as a function of soil moisture and leaf area.

4. Conclusions

While general trends that are similar at all of the sites are evident, this analysis shows that the specific response of the surface fluxes are unique for each of the three study sites. It also shows that these responses are closely tied to local surface conditions such as soil moisture and vegetation density. As such, this research underscores the impact of local environmental conditions in controlling land-atmosphere exchange processes. It also underscores the importance accurately describing local environmental conditions when modeling surface fluxes.

Acknowledgements

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References

[1] Postel SL, Daily GC, Ehlrich PR. Human appropriation of renewable fresh water. *Science* 1996;**271**:785-788.
[2] Vörösmarty CJ, Green P, Salisbury J, Lammers RB. Global water resources: vulnerability from climate change and population growth. *Science* 2000;**289**:284-8.
[3] Mukheirbir P. Water access, water scarcity, and climate change. *Environ Manag* 2010;**45**:1027-1039.
[4] Wallace JS. Increasing agricultural water use efficiency to meet future food production. *Agric Ecosyst Environ* 2000;**82**:105-119.
[5] de Fraiture C, Wichelns D. Satisfying future water demands for agriculture. *Agric Water Manag* 2010;**97**:502-511.
[6] Fereres E, Soriano MA. Deficit irrigation for reducing agricultural water use. *J Expt Bot* 2007;**58**:147-159.
[7] Schaible GD, Aillery MP. *Water conservation in Irrigated agriculture: trends and challenges in the face of emerging demands*. USDA ERS Economic Information Bulletin No. 99; 2012.
[8] Brubaker KL, Entekhabi D. Analysis of feedback mechanisms in land-atmosphere interaction. *Water Resour Res* 1996;**32**:1343-1357.
[9] Baker JM, Griffis TJ. Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques. *Agric For Meteorol* 2005;**128**:163-177.
[10] Gish TJ, Prueger JH, Daughtry CST, Kustas WP, McKee LG, Russ AL, Hatfield JL. Comparison of field-scale herbicide runoff and volatilization losses: an eight-year field investigation. *J Environ Qual* 2011;**40**:1432-1442.
[11] Alfieri JG, Blanken PD, Yates DN, Steffen K. Variability in the environmental factors driving evapotranspiration from a grazed rangeland during severe drought conditions. *J Hydrometeorol* 2007;**8**:207-220.