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The Bowen ratio-energy balance method for estimating latent heat flux of irrigated alfalfa evaluated in a semi-arid, advective environment

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Abstract

The Bowen ratio-energy balance (BREB) is a micrometeorological method often used to estimate latent heat flux because of its simplicity, robustness, and cost. Estimates of latent heat flux have compared favorably with other methods in several studies, but other studies have been less certain, especially when there was sensible heat advection. We compared the latent heat flux of irrigated alfalfa (*Medicago sativa*, L.) estimated by the BREB method with that measured by lysimeters over a growing season in the semi-arid, advective environment of the southern High Plains. Difference statistics from the comparison and indicators of sensible heat advection were used to analyze the performance of the BREB method relative to lysimeters. Latent heat flux was calculated from mass change measured by two precision weighing lysimeters and from two BREB systems that used interchanging temperature and humidity sensors. Net radiation (R_n), soil heat flux (G), and other meteorological variables were also measured. Difference statistics included the root mean square difference (RMSD) and relative RMSD (normalized by mean lysimeter latent heat flux). Differences between lysimeters averaged 5–15% during the day, and 25–45% at night. Estimates of latent heat flux by the two BREB systems agreed closely (relative RMSD=8%) when they were at the same location with sensors at the same height. Differences increased when the location was the same but sensors were at different heights, or when the sensor height was the same but location in the field different, and probably was related to limited fetch and the influence of different source areas beyond the field. Relative RMSD between lysimeter and BREB latent heat fluxes averaged by cutting was 25–29% during the first two cuttings and decreased to 16–19% during the last three cuttings. Relative RMSD between the methods varied from 17 to 28% during morning hours with no pattern based on cutting. Afternoon relative RMSD was 25% during the first two cuttings and decreased to 15% during subsequent cuttings. Greatest differences between the two methods were measured when the Bowen ratios were less than 0, on days that were hot, dry and windy, or when the latent heat flux exceeded the available energy ($R_n - G$). These conditions were likely to be encountered throughout the growing season, but were more common earlier in the season. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Advection; Alfalfa; Bowen ratio; Energy balance; Latent heat flux; Lysimeter

Abbreviations: BREB, Bowen ratio-energy balance; PRTD, platinum resistance temperature device; DOY, day of year; RMSD, root mean square difference; IA, index of agreement

1. Introduction

The Bowen ratio-energy balance (BREB) method has been used to quantify water use (Fritschen, 1966; Malek et al., 1990; Wight et al., 1993; Cargnel et al., 1996), calculate crop coefficients (Malek and Bingham, 1993b), investigate plant–water relations (Grant and Meinzer, 1991; Malek et al., 1992; Alves et al., 1996) and evaluate crop water use models (Ortega-Farias et al., 1993; Farahani and Bausch, 1995; Todd et al., 1996). It is considered to be a fairly robust method,

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and has compared favorably with other methods such as weighing lysimeters (Grant, 1975; Asktorab et al., 1989; Bausch and Bernard, 1992; Prueger et al., 1997), eddy covariance (Cellier and Olioso, 1993) or water balance (Malek and Bingham, 1993a). Most of the studies that showed agreement were conducted when Bowen ratios were mostly positive and sensible heat advection absent. Others showed less certain agreement (Blad and Rosenberg, 1974; Dugas et al., 1991; Xianqun, 1996).

The BREB method estimates latent heat flux from a surface using measurements of air temperature and humidity gradients, net radiation, and soil heat flux (Fritschen and Simpson, 1989). It is an indirect method, compared to methods such as eddy covariance, which directly measures turbulent fluxes, or weighing lysimeters, which measure the mass change of an isolated soil volume and the plants growing in it. Its advantages include straight-forward, simple measurements; it requires no information about the aerodynamic characteristics of the surface of interest; it can integrate latent heat fluxes over large areas (hundreds to thousands of square meters); it can estimate fluxes on fine time scales (less than an hour); and it can provide continuous, unattended measurements. Disadvantages include sensitivity to the biases of instruments which measure gradients and energy balance terms; the possibility of discontinuous data when the Bowen ratio approaches −1, and the requirement, common to micrometeorological methods, of adequate fetch to ensure adherence to the assumptions of the method.

The BREB method relies on several assumptions (Fritschen and Simpson, 1989). Transport is assumed to be one-dimensional, with no horizontal gradients. Sensors which measure gradients are assumed to be located within the equilibrium sublayer where fluxes are assumed to be constant with height. The surface is assumed to be homogeneous with respect to sources and sinks of heat, water vapor and momentum. The ratio of turbulent exchange coefficients for heat and water vapor is assumed to be 1. The first two assumptions are usually met if adequate upwind fetch is available. A fetch to height-above-surface ratio of 100:1 is often considered a rule of thumb (Rosenberg et al., 1983), although a ratio as low as 20:1 was considered adequate when Bowen ratios were small and positive (Heilman et al., 1989). Sensors at different heights respond to different upwind source areas (Schuepp et al., 1990; Schmid, 1997), so that all sensors must have adequate fetch.

Blad and Rosenberg (1974) observed underestimation of latent heat flux of alfalfa by the BREB method compared to lysimeters in eastern Nebraska under sensible heat advection. Subsequently, Verma et al. (1978) and Motha et al. (1979) showed that the exchange coefficient for heat was greater than that for water vapor during sensible heat advection. Lang et al. (1983) studied latent heat and sensible heat fluxes over an Australian rice paddy located in an extensive dry region and found the converse when there was sensible heat advection. Based on these studies, the behavior of exchange coefficients in the presence of sensible heat advection is uncertain.

The semi-arid environment of the southern High Plains provided an opportunity to evaluate the BREB method for estimating water use of an irrigated crop under conditions of local and regional sensible heat advection. A mosaic of rangeland and dryland crops mixed with irrigated areas, and the presence of regional-scale, dry, downslope winds contribute to the advective environment experienced over much of the growing season. Our objective was to investigate the performance of the BREB method in the advective environment of the southern High Plains. We compared the latent heat flux estimated by the BREB method with the latent heat flux measured by precision weighing lysimeters. Then, we used difference statistics from the comparison and indicators of sensible heat advection to analyze the performance of the BREB method relative to lysimeters under a range of conditions encountered over a growing season.

2. Materials and methods

2.1. Study location

Research was conducted in 1998 from day of year (DOY) 111 to DOY 271 at the USDA-ARS Conservation and Production Research Laboratory near Bushland, TX (35°N, 102°W, elevation 1169 m), where the soil is a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll, 30% clay, 53% silt). The experimental field was 450 m long from north to south and 210 m long from east to west, and was irrigated by a lateral-move sprinkler system on a schedule that met the water use demands of the crop. Dryland sorghum bordered the experimental field for 210 m to the west and a variety of dryland crops extended from the south border for more than 500 m. Irrigated wheat, sorghum and corn grew for 200 m to the north, and irrigated corn, grass or soybean grew for 90–235 m along the east border of the alfalfa field, with dryland crops beyond that for more than 700 m. Alfalfa, planted in the autumn of 1995, was harvested five times in 1998 with a mean yield of 3.3 Mg ha^{-1} dry hay per cutting.

2.2. Weighing lysimeters

Two precision weighing lysimeters (Marek et al., 1988), 3 m×3 m×2.3 m deep were used to directly measure alfalfa evapotranspiration. They were located at the centers of the north and south halves of the experimental field. Voltages from lysimeter load cells were sampled every 6 s by a data logger (CR7, Campbell Scientific Inc., Logan, UT[1]) and 5 min averages were calculated. The evapotranspiration rate was determined by using the method of least squares (James et al., 1993) to find the slope of the straight line fitted to the six 5 min means for each half-hour period. Calibration coefficients for each lysimeter and an area correction to account for the area between the inner and outer walls of the lysimeter were applied to the slopes of each half-hour period to convert the rate of change of voltage to depth of water. We assumed that the performance of the lysimeters was consistent over the range of conditions encountered, and that they only responded to changes in mass due to water loss or gain.

2.3. The BREB method

Two identical BREB systems were used. Each consisted of two integrated temperature–humidity probes (THP-1, Radiation and Energy Balance Systems, Seattle, WA) inside radiation-shielded, fan-aspirated housings that were mounted on a chain-driven automatic exchange mechanism (AEM-1, Radiation and Energy Balance Systems, Seattle, WA). Two calibrated thin film platinum resistance temperature devices (PRTDs) were incorporated in each temperature–humidity probe. One PRTD measured air temperature used to calculate the air temperature gradient and the other measured the air temperature of the humidity sensor cavity of the probe, which was used to calculate the saturation vapor pressure of water. A capacitive humidity sensor measured relative humidity. Temperature resolution of the PRTDs was 0.0056°C, and resolution of the humidity sensor was 0.033% relative humidity. The exchange mechanism automatically switched the position of the sensors every 5 min. After each exchange, sensors were allowed to equilibrate with the new aerial environment for 2 min before a 3 min measurement period. Distance between the sensors was 1 m. The height of sensors was periodically adjusted as alfalfa grew so that the bottom sensors were at least 1.2 times the canopy height. Maximum height of the top sensors during the study was 2 m. System 1 (SYS1) was initially installed 15 m east of the north lysimeter on DOY 111. System 2 (SYS2) was installed at the same location and sensor height on DOY 124. SYS2 subsequently remained at the north lysimeter location throughout the experiment, but the location of SYS 1 was alternated between the north and south lysimeters. Deployment of the BREB systems is detailed in Table 1.

Fetch for the BREB system installed near the north lysimeter ranged from a minimum of 90 m to the east to 360 m to the south–southwest. Prevailing winds during the growing season were southerly, with 48% of the mean half-hour wind directions between 140 and 220°. Fifty percent of the half-hour BREB measurements at the north location had more than 170 m of fetch; maximum fetch-to-height ratio of the top sensors ranged from about 200:1 to 250:1. Half-hour measurements used to calculate the Bowen ratio were screened for validity using the methods of Ohmura (1982), which test for indications of counter-gradient fluxes or for a Bowen ratio near −1, a condition that gives very unstable latent heat flux estimates. Calculations of the temperature and vapor pressure gradients, Bowen ratio, and BREB latent heat flux followed Bausch and Bernard (1992).

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[1] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-ARS.

Table 1
Deployment of BREB systems over irrigated alfalfa[a]

DOY		SYS1		SYS2[d]		Mean canopy height (m)
Start	End	Location[b]	Height[c] (m)	Location	Height (m)	
111	124	N	0.5	–	–	0.37
125	137	N	0.7	N	0.7	0.57
139	146	N	0.7	N	0.7	0.12
147	160	N	1.0	N	0.5	0.28
161	174	N	1.0	N	0.75	0.52
175	194	S	0.75	N	0.75	0.3
195	202	S	0.85	N	0.85	0.63
204	219	S	0.5	N	0.5	0.25
220	226	S	0.65	N	0.65	0.52
227	237	N	0.75	N	0.75	0.63
243	261	S	0.5	N	0.5	0.36
262	271	S	0.75	N	0.75	0.56

[a] Sensor arms were 1 m apart.
[b] Location indicates whether the BREB system was located near the north or the south lysimeter.
[c] Height indicates the height of the lower sensors.
[d] SYS2 was deployed on DOY 124.

2.4. Meteorological and energy balance measurements

Identically instrumented meteorological masts were centered on the north side of each weighing lysimeter and they held a cup anemometer (014A, Met One, Grants Pass, OR) and a temperature–humidity probe (HT225R, Rotronics, Huntington, New York) mounted 2 m above the soil surface, and a net radiometer (Q*5.5, Radiation and Energy Balance Systems, Seattle, WA), mounted at 1 m height that extended 1 m over the lysimeter. The radius of the source area that contributed 90% of the radiation sensed by the lower surface of the net radiometer was 1.5 m when the alfalfa was 0.5 m tall (Schmid, 1997). The radiation source area increases with shorter alfalfa and decreases with taller alfalfa. In a concurrent study, net radiation measured by a Q*5.5 net radiometer compared well with net radiation calculated from independent measurements of the shortwave (C14 albedometer, Kipp and Zonen, Delft, The Netherlands) and longwave (CG1/2, Kipp and Zonen, Delft, The Netherlands) components of the radiation balance (K. Copeland, personal communication; $R_{\mathrm{n,Q5}}=-6.55+1.03R_{\mathrm{n,KZ}}$, $r^2=0.99$, root mean square difference (RMSD)=18.8 W m^{-2}, mean $R_{\mathrm{n,Q5}}=138.8$ W m^{-2}, mean $R_{\mathrm{n,KZ}}=135.9$ W m^{-2}, $n=3117$). Net radiation is important to the BREB latent heat flux estimates, and the net radiation measured by similar instruments can vary considerably (Kustas et al., 1998). The absolute accuracy of net radiation was not critical to our analysis because we were interested in the relationship between BREB and lysimeter latent heat fluxes, expressed by statistical difference measures of the comparison, under conditions with and without evidence of sensible heat advection.

Soil heat flux (G) within each lysimeter was measured with four heat flux transducers (HFT-1, Radiation and Energy Balance Systems, Seattle, WA) buried at a depth of 50 mm. Surface soil heat flux was calculated by correcting the heat flux at 50 mm for heat storage above the transducers, determined by change in soil temperature of the soil volume above the heat flux transducers and an assumed volumetric soil water content of 0.32 m^3 m^{-3}. A sensitivity analysis showed that when the soil water content was varied from 0.32 m^3 m^{-3} by ±25%, 88% of the half-hour measurements of soil heat flux changed by less than 5 W m^{-2}, and 98% of them changed by less than 10 W m^{-2}. A change in soil heat flux of 5 W m^{-2} changed the BREB latent heat flux (λE_{B}) by 1% for a typical case of high net radiation ($R_{\mathrm{n}}=600$ W m^{-2}, $G=60\pm5$ W m^{-2}), by 5% for a typical case of low net radiation ($R_{\mathrm{n}}=100$ W m^{-2}, $G=0\pm5$ W m^{-2}), and by 17% for a typical night-time case ($R_{\mathrm{n}}=-60$ W m^{-2},

$G=-30\pm5$ W m^{-2}. The soil water content did not vary much because of the high irrigation frequency, so that the error contributed to λE_B by assuming constant soil water content was considered negligible during the day, although potentially significant at night. Soil temperature above the soil heat flux plates was measured with four pairs of copper–constantan thermocouples (304SS, Omega Engineering, Stamford, CT). Each pair had one thermocouple installed at 10 mm depth and one at 40 mm depth and they were wired in parallel to integrate the soil temperature. The same data logger that sampled the lysimeter load cells also sampled other sensors every 6 s and calculated 15 min means which were later processed as half-hour means. Net radiation and soil heat flux were averaged from measurements at the north and south lysimeter instrument locations to account for spatial variability between the two locations.

2.5. Comparison statistics and indicators of sensible heat advection

Latent heat fluxes were compared using univariate, regression, and mean difference statistics given by Willmott (1982, 1984). The RMSD was calculated with

$$\mathrm{RMSD}=\left[n^{-1}\sum_{i=1}^{n}(P_i-O_i)^2\right]^{1/2} \tag{1}$$

where n is the number of half-hour observations, and P_i and O_i are half-hour observations of the two variables being compared. The RMSD is a conservative absolute difference measurement because it is more sensitive to extreme differences (Willmott, 1984) and can be considered a high estimate of the actual average difference (Willmott, 1982). The RMSD expressed as a percentage of either the mean of the two lysimeters, λE_L, or the mean of the two BREB systems, λE_B, was used as a measure of relative difference. The index of agreement (IA) is a relative difference measure calculated with

$$\mathrm{IA}=1-\left[\frac{\sum_{i=1}^{n}(P_i-O_i)^2}{\sum_{i=1}^{n}(|P_i-\bar{O}|+|O_i-\bar{O}|)^2}\right] \tag{2}$$

where $\bar{O}$ is the mean of variable O (Willmott, 1982). Perfect agreement between P and O would be expressed by IA=1.

We used the definition of Rosenberg et al. (1983), where advection is the “transport of energy or mass in the horizontal plane in the downwind direction.” Sensible heat advection was not directly measured, but was inferred when the ratio of mean lysimeter latent heat flux to available energy (R_n-G) was greater than 1, and when sensible heat was consumed rather than generated by the alfalfa field. An index that measures the combined effects of temperature, vapor pressure deficit, available energy and wind speed is the ratio of the climatological resistance r_i to the aerodynamic

Table 2
Comparison of means of half-hourly latent heat flux measured by the north (λE_N) and south (λE_S) lysimeters

Cutting	Time	n	Mean λE_N (W m^{-2})	Mean λE_S (W m^{-2})	RMSD[a] (W m^{-2})	RMSD/λE_L	1-Ia[b]
1	Day	341	412	425	45	0.11	0.05
	Night	314	29	32	18	0.59	0.22
2	Day	445	455	454	35	0.08	0.02
	Night	343	57	62	17	0.29	0.10
3	Day	372	440	477	78	0.17	0.14
	Night	225	39	47	22	0.51	0.44
4	Day	330	366	384	38	0.10	0.04
	Night	229	20	27	12	0.51	0.26
5	Day	369	373	385	27	0.07	0.02
	Night	350	28	32	11	0.37	0.28

[a] Root mean square difference.

[b] Index of disagreement.

resistance r_a. Thom (1975) pointed out that this ratio will be very large if there is a strong, dry air flow over vegetation, which he called an 'oasis situation'. The ratio was calculated from meteorological measurements at the north lysimeter using expressions given by Thom (1975) for the climatological resistance and the aerodynamic resistance uncorrected for thermal stability:

$$\frac{r_i}{r_a}=\frac{\rho_a c_p D[\gamma(R_n-G)]^{-1}}{[\ln((z-d)/z_0)]^2(k^2u)^{-1}} \tag{3}$$

where the saturation vapor pressure deficit D (kPa), was calculated from the temperature and humidity measured at z=2 m, d is the zero plane displacement height (m), estimated as $0.63z_c$ (z_c is the canopy height), z_0, estimated as $0.13z_c$, is the roughness length (m), k=0.41 is von Karmen's constant, and u is the wind speed at a height of 2 m (m s^{-1}). The ratio becomes very large when aerial conditions are warm, dry, and windy, as were encountered on days with evidence of sensible heat advection.

3. Results and discussion

3.1. Weighing lysimeter variability

Factors that contribute to the variability between lysimeter measurements include environmental differences due to field position or differences in crop density, development or leaf area. We examined the variability about the mean of the latent heat flux measurements of the two weighing lysimeters by calculating the RMSD where $\lambda E_{N,i}$ and $\lambda E_{S,i}$ were half-hour observations of latent heat flux at the north and south lysimeters, respectively. Relative difference was calculated by normalizing the RMSD by the mean latent heat flux of the two lysimeters. During the daytime (0700–1900 h), mean relative RMSD by cutting ranged from 7 to 17% (Table 2). At night (1900–0700 h), relative RMSD ranged from 29 to 59% (Table 2). Variability was greater at night because 52% of the night-time half-hour observations were less than the 0.05 mm h^{-1} resolution of the lysimeters. Index of disagreement (1-IA) was less, ranging from 2 to 14% during the daytime and from 10 to 44% at night. Based on this analysis, a reasonable estimate of variability about λE_L during the day was from 5 to 15%, while at night, the variability increased to about 25–45%. Mean latent heat flux of the south lysimeter was greater than that of the north lysimeter except during the daytime of the second cutting, when they were similar (Table 2).

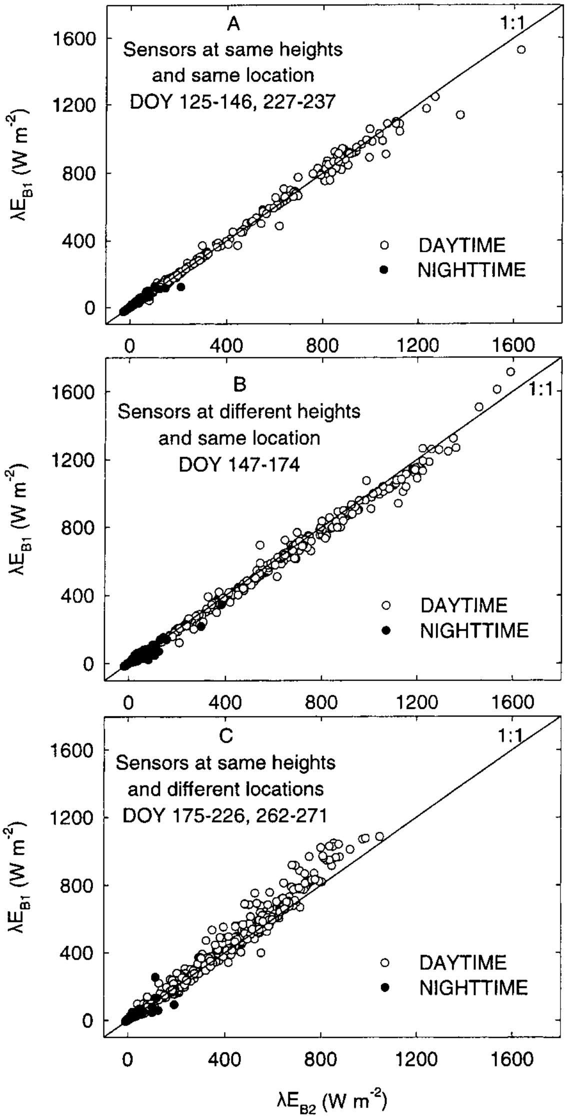

Fig. 1. Comparisons of latent heat flux estimated by two BREB systems, with three deployments. SYS1 (λE_{B1}) was near the north lysimeter (A, B) or near the south lysimeter (C). SYS2 (λE_{B2}) was always near the north lysimeter. Other details are given in Table 1.

3.2. Comparison of BREB systems

The tests of Ohmura (1982) indicated counter-gradient fluxes usually during the early morning hours. Bowen ratios near −1 were most likely between 1730 and 1930 h on days when the sensible heat flux towards the canopy was a significant component of the energy balance. Retention of data ranged from 85 to 94% of the daytime half-hour observations of the five cuttings. Over the season, 91% of daytime observations were valid. At night, 71% of the half-hour observations were valid. The BREB estimates of latent heat flux behaved erratically on the days when alfalfa was irrigated. As the temperature and humidity measured by the BREB sensors were integrated over a large area of the alfalfa field, they were often affected by irrigation even after the irrigation system passed over the sensors. The magnitude of this effect depended on wind direction. Also, when the irrigation system passed over the BREB systems, drop nozzles wetted the lower sensor arm, while the upper sensor arm remained dry. Lysimeter measurements during irrigation or precipitation, recorded as mass gains, were also uncertain. Therefore, days with irrigation or significant precipitation were excluded from analysis.

The two BREB systems, with sensor pairs at the same heights and positioned near the north lysimeter, had similar estimates of latent heat flux (Fig. 1A). Daytime RMSD between the two systems was 8% of the mean latent heat flux of the two systems, and 1-IA was 1% (Table 3). Relative difference measures between lysimeters during this deployment were 16 and 6% for the normalized RMSD and 1-IA, respectively. Less variability between the BREB systems compared to that between lysimeters was probably because the BREB systems spatially integrated the same area, while the lysimeter measurements each represented a discrete 9 m^2 area. During night-time hours, the two BREB systems also agreed closely, although the relative difference between them increased compared to the daytime case (Table 3).

When the systems were located near the north lysimeter but at different heights (SYS1 sensors were 0.25 or 0.5 m higher, Table 1), λE_{B2} was consistently greater than λE_{B1} (Fig. 1B). Relative difference of the latent heat flux between the two systems was slightly different compared to when the systems were at the same height, with a relative RMSD of 6% and a 1-IA of 2% (Table 3). Most of the time, with the sensors of the two systems separated by up to 0.5 m, latent heat flux decreased with height. Two factors, both related to fetch, may explain this. First, sensors at different heights experienced different upwind source footprints. For example, cumulative relative flux, the fraction of flux that originated from the alfalfa field (Schuepp et al., 1990), was always less for the higher sensors of SYS1. Mean cumulative relative flux for the top sensor of SYS1 during this deployment was 0.78, compared to mean cumulative relative flux for the top sensor of SYS2 of 0.83. Higher sensors were more affected by areas beyond the alfalfa field. Second, under the commonly encountered conditions of warmer, drier air moving horizontally over the cooler, moister air above the alfalfa field, and high wind speeds, latent heat may have been diverted from the vertical flow into the horizontal flow, so the assumption that flux was constant with height was invalid.

Most of the time, the two BREB systems had sensors at the same height, but one was located at the north

Table 3
Comparison of means of half-hourly latent heat flux estimated by BREB SYS1 (λE_{B1}) and SYS2 (λE_{B2})

Deploy	Time	n	Mean λE_{B1} ($W m^{-2}$)	Mean λE_{B2} ($W m^{-2}$)	RMSD[a]	RMSD/λE_B	1-Ia[b]
Same	Day	210	426	427	33	0.08	0.01
	Night	179	18	19	9	0.49	0.07
Different height	Day	311	588	608	38	0.06	0.02
	Night	172	37	39	15	0.39	0.10
Different location	Day	411	443	417	57	0.13	0.07
	Night	316	11	9	12	1.20	0.32

[a] Root mean square difference.

[b] Index of disagreement.

Table 4
A comparison of two days which showed disagreement (DOY 219) or agreement (DOY 224) between the BREB systems deployed at the same heights and located near the south lysimeter (SYS1) or the north lysimeter (SYS2)[a]

DOY	Wind direction	$\lambda E_L/(R_n-G)$	South lysimeter				North lysimeter			
			Air temperature, T (°C)	D (kPa)	u ($\mathrm{m\,s^{-1}}$)	λE_{B1} ($\mathrm{W\,m^{-2}}$)	Air temperature, T (°C)	D (kPa)	u ($\mathrm{m\,s^{-1}}$)	λE_{B2} ($\mathrm{W\,m^{-2}}$)
219	S to SW	1.32	27.6	2.08	4.6	553	27.0	1.91	4.1	492
224	W to NW	1.02	24.8	0.99	2.7	357	25.0	1.14	2.7	361

[a] Air temperature, saturation vapor pressure deficit (D) and wind speed (u) were measured at 2 m above each lysimeter. All means are for the daytime (0700–1900 h).

lysimeter and the other at the south lysimeter, separated by 225 m (Table 1). For this deployment, λE_{B1}, located near the south lysimeter, was usually greater than λE_{B2}, located near the north lysimeter (Fig. 1C). Variability between the two systems increased compared to the previously discussed deployments. Normalized RMSD was 13% and 1-IA was 7% (Table 3).

Part of the greater variability observed between the two BREB systems during this deployment was because the systems usually had different fetch and experienced different upwind footprints. Two days which illustrate this are contrasted in Table 4 and Fig. 2. On DOY 219, winds were predominantly from the south to southwest and λE_L exceeded R_n-G by 32%. On DOY 224, winds blew from the west to northwest and there was little evidence of sensible heat advection. Air temperature, vapor pressure deficit and wind speed were greater on DOY 219, and λE_{B1} (near the south lysimeter) was greater than λE_{B2} (near the north lysimeter) throughout the daytime hours (Fig. 2A), while on DOY 224, λE_{B1} and λE_{B2} agreed very closely (Fig. 2B).

3.3. Comparison of lysimeter and BREB latent heat fluxes

We assumed that lysimeters only responded to change in mass from water loss or gain, so that they provided a baseline latent heat flux that responded consistently over a wide range of conditions. Latent heat flux estimated by SYS2 (λE_{B2}) located near the north lysimeter was compared with the mean latent heat flux measured by the two lysimeters, because it usually experienced the greatest fetch. Disagreement between the BREB and lysimeter daytime latent heat fluxes was greatest during the first and the second cutting, when the relative RMSD was 24 and 29%, respectively (Table 5). Daytime relative RMSD decreased during subsequent cuttings, and ranged from

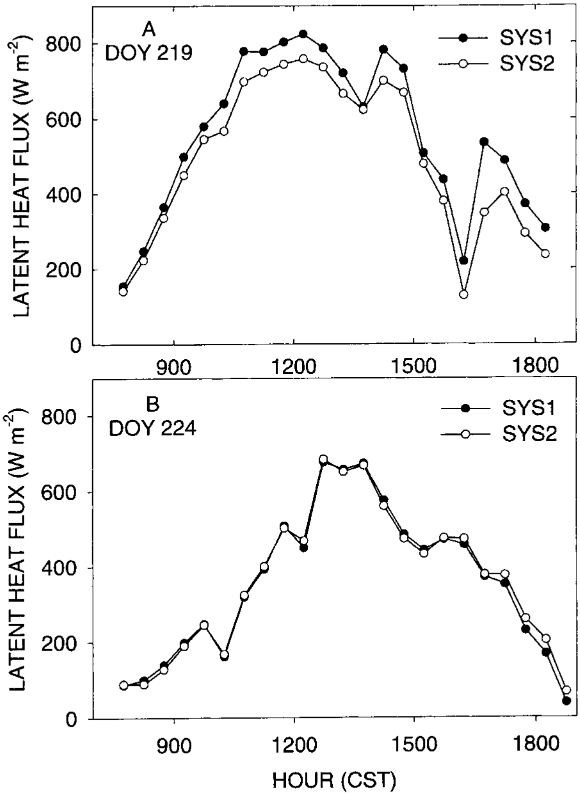

Fig. 2. Latent heat flux estimated by the two BREB systems deployed with sensors at the same height but located near the south (SYS1) or north (SYS2) lysimeters. DOY 219 (A) was characterized by southerly winds, with evidence of sensible heat advection. DOY 224 (B) was characterized by westerly winds and no evidence of sensible heat advection.

Table 5
Univariate, regression and mean difference comparisons of half-hour measurements of mean latent heat flux (λE_L) and latent heat flux estimated by the BREB system located near the north lysimeter (λE_{B2})

When	n	Mean latent heat flux ($W\,m^{-2}$)		RMSD[a] ($W\,m^{-2}$)	RMSD/λE_L	IA[b]	Regression	
		λE_L	λE_{B2}				Intercept ($W\,m^{-2}$)	Slope
Cutting 1, DOY 112–137								
Day	341	418	471	99	0.24	0.76	25.2[c]	1.19[c]
Night	314	30	18	36	1.18	0.15	3.5	0.47[c]
Cutting 2, DOY 140–173								
Day	445	455	529	131	0.29	0.77	41.6[c]	1.26[c]
Night	343	60	36	52	0.87	0.10	7.0[d]	0.48[c]
Cutting 3, DOY 175–201								
Day	372	458	484	82	0.19	0.85	−5.8	1.07[c]
Night	225	43	17	37	0.86	−0.13	−1.0	0.43[c]
Cuffing 4, DOY 203–234								
Day	330	375	404	61	0.16	0.90	11.7[d]	1.11[c]
Night	229	24	8	24	1.00	−0.02	4.1[c]	0.52[c]
Cutting 5, DOY 245–271								
Day	369	379	418	71	0.19	0.85	3.4	1.09[c]
Night	350	30	8	29	0.97	−1.03	44[c]	0.41[c]

[a] Root mean square difference.
[b] Index of agreement.
[c] Intercept was significantly different from 0 or slope was significantly different from 1 at the $p<0.01$ level.
[d] Intercept was significantly different from 0 or slope was significantly different from 1 at the $p<0.05$ level.

16 to 19%. IA and regression statistics also indicated greater disagreement between the two methods during the first two cuttings compared to the later cuttings (Table 5). Greatest disagreement was when the latent heat flux densities were greater than 400 $W\,m^{-2}$ (Fig. 3). Night-time latent heat flux of the two methods disagreed more than the daytime fluxes. Relative RMSD, by cutting, ranged from 86 to 118%, and no pattern related to cutting was detected (Table 5).

Mean half-hour latent heat fluxes were calculated for each cutting and plotted as diel courses of λE_{B2} and λE_L (Fig. 4). During the first two cuttings, λE_{B2}

Table 6
Mean latent heat flux estimated by the BREB system located near the north lysimeter (λE_{B2}) and measured by lysimeters, and the difference measures of BREB estimates compared with lysimeter-measured latent heat flux, by morning and afternoon within cutting

Cutting	Morning[a]						Afternoon[b]					
	n	λE_L ($W\,m^{-2}$)	λE_{B2} ($W\,m^{-2}$)	RMSD[c] ($W\,m^{-2}$)	RMSD/ λE_L	IA[d]	n	λE_L ($W\,m^{-2}$)	λE_{B2} ($W\,m^{-2}$)	RMSD) ($W\,m^{-2}$)	RMSD/ λE_L	IA
1	159	419	470	85	0.20	0.78	147	476	535	115	0.24	0.63
2	191	436	517	122	0.28	0.77	198	546	623	145	0.26	0.71
3	164	463	506	78	0.17	0.85	162	519	529	89	0.17	0.78
4	145	386	429	66	0.17	0.87	148	418	441	57	0.14	0.90
5	173	368	434	79	0.21	0.79	162	453	478	64	0.14	0.83

[a] Morning hours were from 0800 to 1300 h.
[b] Afternoon hours were from 1300 to 1800 h.
[c] Root mean square difference.
[d] Index of agreement.

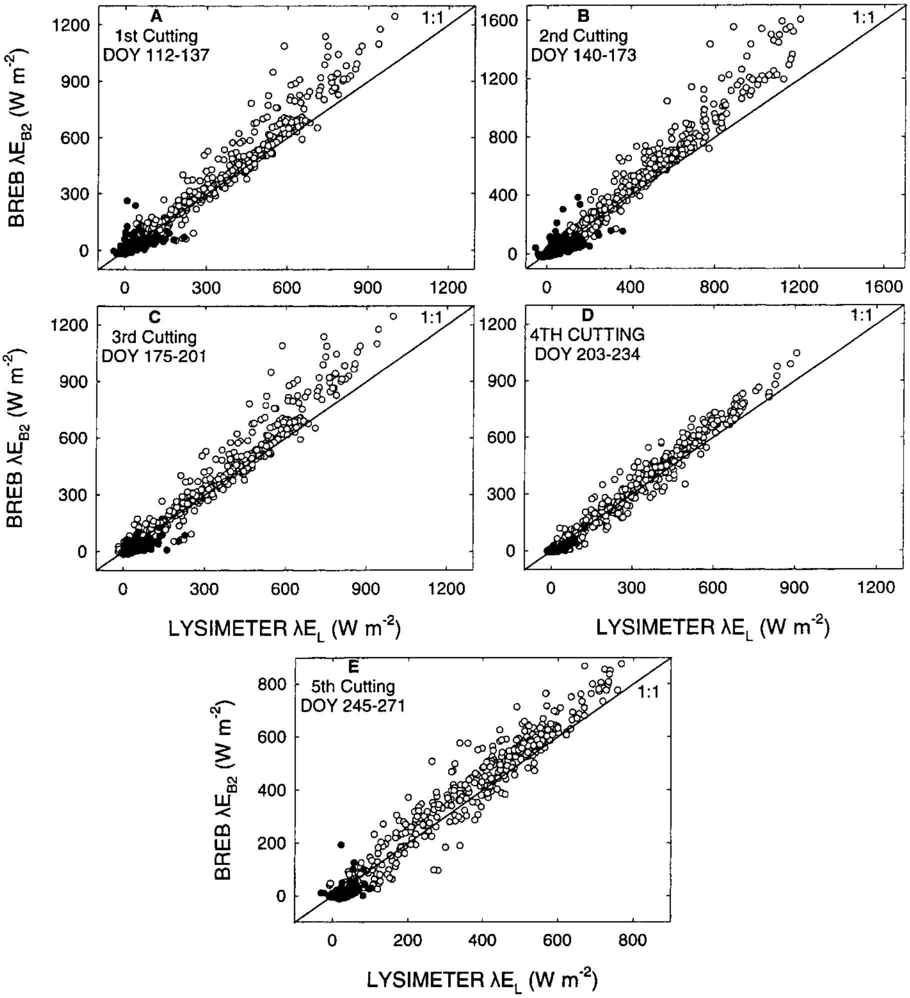

Fig. 3. Comparisons of half-hour latent heat flux estimated by the BREB method (λE_{B2}) with mean half-hour latent heat flux measured by lysimeters (λE_L), by alfalfa cutting. Open circles are daytime measurements (0700–1900 h) and closed circles are night-time measurements.

exceeded λE_L during the daytime hours. The only exceptions were during late afternoon when there were few BREB measurements in a half-hour mean because of invalid data. During subsequent cuttings, λE_{B2} was greater than λE_L during the daytime morning and early afternoon hours, but agreed more closely later in the afternoon. Mean half-hour λE_{B2} was consistently less than λE_L during the night-time hours. Disagreement of the BREB method with lysimeters appeared to have two components. There was a consistent disagreement during the morning hours which was common from one cutting to another. This morning (0800–1300 h) disagreement showed no pattern based on cutting; RMSD ranged from 17 to 28% of λE_L (Table 6). Afternoon (1300–1800 h) RMSD averaged 25% of λE_L during the first two cuttings, and decreased to about 15% of λE_L during the last three cuttings. There were also several days when the BREB method strongly disagreed with λE_L. Notable examples of this were on DOYs 115, 133, 134 and 137 during the first cutting, and DOYs 150, 164, 167 and 171 during the second cutting, when daily λE_{B2} exceeded λE_L by 13–35%.

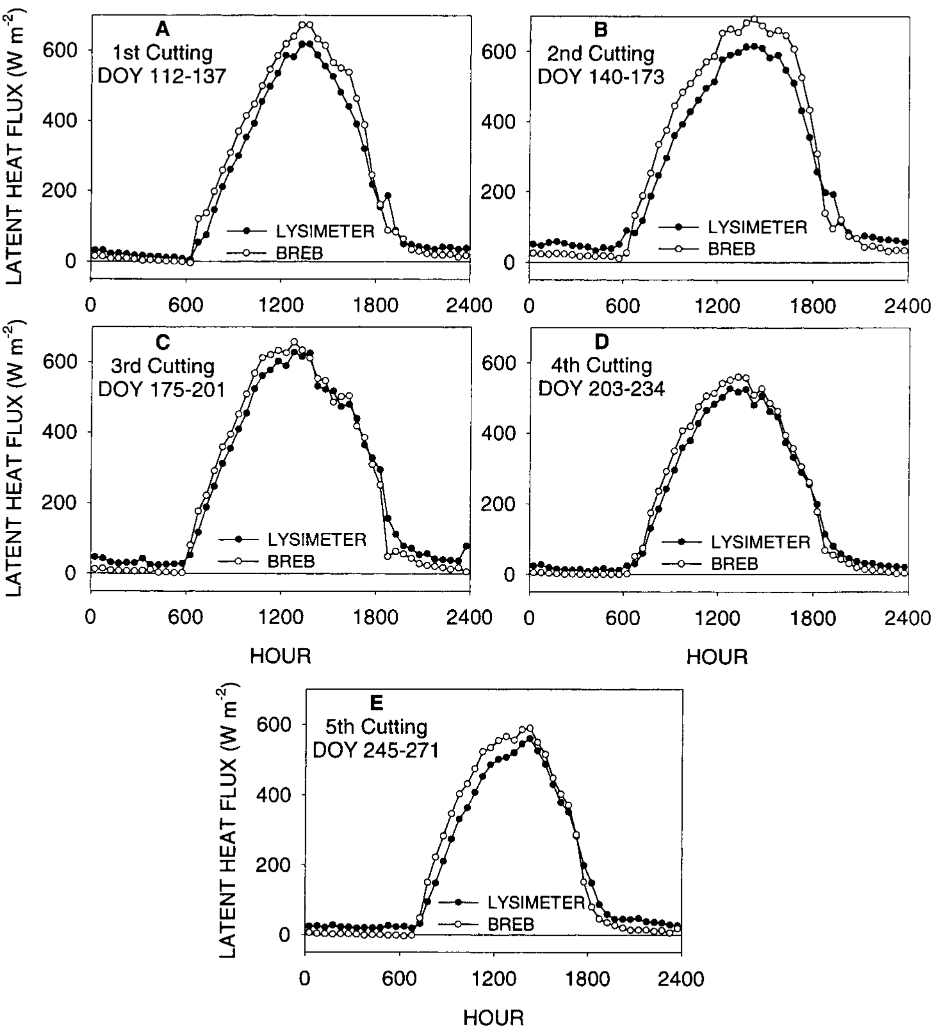

Fig. 4. Mean diel latent heat flux measured by lysimeters (λE_{L}) and estimated by the BREB method (λE_{B2}), by cutting.

3.4. The Bowen ratio versus relative difference between BREB and lysimeter latent heat fluxes

Half-hour daytime λE_{B2} and λE_{L} were compared for each day and the RMSD of each day normalized by mean daytime λE_{L}. We then calculated a mean daytime Bowen ratio with $\beta_{\mathrm{EB}}=H_{\mathrm{R}}/\lambda E_{\mathrm{L}}$, where R_{n}, G and λE_{L} were measured and sensible heat flux, H_{R}, was the residual term of the energy balance. The BREB method estimated the latent heat flux best when β_{EB} was between 0 and 0.3 (Fig. 5). Relative RMSD was within the relative RMSD observed between lysimeters during the daytime on 17 out of 86 days. The relative difference increased both as β_{EB} decreased from 0 and as β_{EB} increased from 0.3. On 9 out of 10 of the days when $\beta_{\mathrm{EB}}>0.3$, the leaf area index was less than 0.1, the canopy height was small, and the bottom sensors were located more than half a meter above the canopy. Best performance of the BREB method was on days with low, positive Bowen ratios and a more fully developed alfalfa canopy.

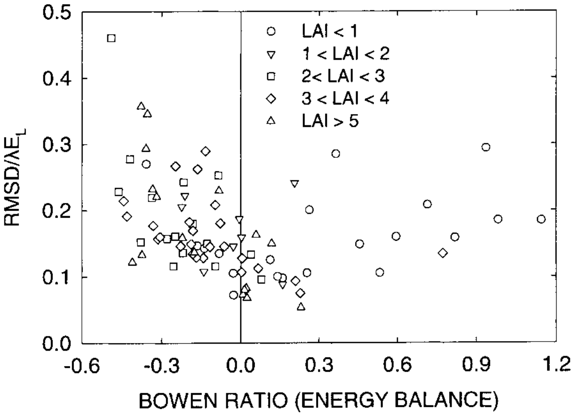

Fig. 5. Relative root mean square difference (RMSD/λE_L) of the daytime BREB and lysimeter latent heat flux comparison correlated with the energy balance Bowen ratio, by days within leaf area index (LAI) class.

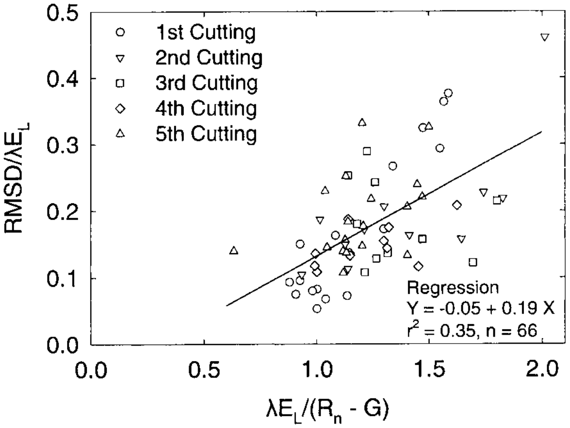

Fig. 7. Relative root mean square difference (RMSD/λE_L) of the daytime BREB and lysimeter latent heat flux comparison correlated with the ratio of latent heat flux to available energy, by days within cutting.

3.5. Indicators of sensible heat advection versus relative difference between BREB and lysimeter latent heat fluxes

Relative RMSD of daytime latent heat flux increased linearly as r_i/r_a increased and was evident for all cuttings (Fig. 6). Days during the first two cuttings showed the greatest relative difference and the greatest r_i/r_a. Greatest difference between lysimeter measurements and the BREB estimate of latent heat flux occurred on days that were hot, dry, and windy. The mean daytime BREB and lysimeter latent heat fluxes agreed most closely when the ratio of latent heat flux to available energy (R_n-G) was around 1.0 (Fig. 7). Relative RMSD increased to values greater than 0.3 as the ratio increased to more than 1.5.

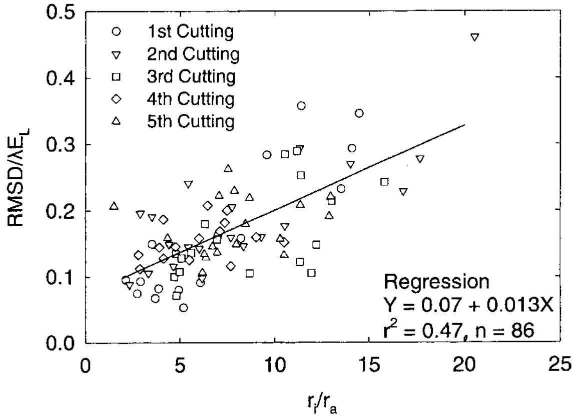

Fig. 6. Relative root mean square difference (RMSD/λE_L) of the daytime BREB and lysimeter latent heat flux comparison correlated with the ratio of climatological resistance (r_i) to aerodynamic resistance (r_a), by days within cutting.

4. Summary and conclusions

Variability about the mean latent heat flux measured by the two precision weighing lysimeters during the daytime was generally within 5–15%. Night-time variability was greater, on the order of 25–45%. On an average, 91% of half-hour daytime observations and 71% of night-time observations of latent heat flux by the BREB method were valid. Estimates of latent heat flux by the two BREB systems agreed closely when they were at the same location with sensors at the same height. Differences increased when the location was the same but the sensors were at different heights, or when the sensor height was the same but location in the field different, and probably was related to limited fetch and the influence of different source areas beyond the field.

Relative RMSD between lysimeter and BREB latent heat fluxes averaged by cutting was greatest during the first two cuttings and decreased during the last three cuttings. Relative RMSD between the methods varied during morning hours with no pattern based on cutting. Afternoon relative RMSD was 25% during the first two cuttings and decreased to 15% during subsequent cuttings. Greatest differences between the two methods were measured when the Bowen ratios were less than 0, on days that were hot, dry and windy, or when the latent heat flux exceeded the available energy ($R_n - G$). These conditions were likely to be encountered throughout the growing season, but were more common during the first two cuttings.

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