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LATENT HEAT FLUX OF IRRIGATED ALFALFA MEASURED BY WEIGHING LYSIMETER AND BOWEN RATIO-ENERGY BALANCE

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Summary:

Latent heat flux of irrigated alfalfa estimated by the Bowen ratio-energy balance (BREB) method was compared and contrasted with latent heat flux from measurements of two weighing lysimeters. The study was conducted between the third and fourth cutting of alfalfa in 1997 and before the first cutting in 1998, on the southern High Plains near Bushland, Texas. Latent heat flux often exceeded the sum of net radiation and soil heat flux, and there was significant sensible heat advection on 14 out of 22 days. Daily evapotranspiration (ET) estimated by the BREB method agreed with lysimeter ET in 1997, but the BREB method overestimated daily ET in 1998, especially when ET rates were greater than 6 mm d^{-1}. Half-hourly estimates of BREB ET also overestimated lysimeter ET, with slopes of regression comparisons usually greater than one. The BREB method usually overestimated lysimeter latent heat flux during the morning whether or not there was sensible heat advection, agreed within 10% between 1000 h and 1600 h, and either underestimated (1997) or overestimated (1998) during the afternoon when sensible heat advection was most likely to occur.

Keywords:

Bowen ratio, energy balance, latent heat flux, evapotranspiration, advection, alfalfa

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LATENT HEAT FLUX OF IRRIGATED ALFALFA MEASURED BY WEIGHING LYSIMETER AND BOWEN RATIO-ENERGY BALANCE[1]

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ABSTRACT

The Bowen ratio-energy balance (BREB) method is used to estimate latent heat flux to quantify crop water use, evaluate water use models, or investigate aspects of plant-water relations. Few studies have tested the BREB method in an environment where significant sensible heat advection occurs. We compared and contrasted daily and half-hourly BREB estimates of irrigated alfalfa latent heat flux with precision weighing lysimeter measurements in a semi-arid, advective environment. The research was conducted near Bushland, TX, between the third and fourth cutting of alfalfa in 1997 and before the first cutting in 1998. The BREB method used vertically-exchanged temperature and humidity sensors to measure gradients. Net radiation and soil heat flux were measured with instruments installed over or within two 3- x 3- x 2.3-m, monolithic, continuously weighed lysimeters located in the centers of adjacent 4.7 ha fields. Latent heat flux often exceeded the sum of net radiation and soil heat flux, and there was significant sensible heat advection on 14 out of 22 days. Daily ET estimated by the BREB method agreed within 3% of lysimeter ET in 1997, but overestimated ET in 1998, especially when rates were greater than 6 mm d^{-1}. The BREB method also tended to overestimate half-hourly measurements of ET. The BREB method overestimated diurnal latent heat flux during the morning hours regardless of whether there was sensible heat advection, agreed within 10% during mid-day, and either overestimated (in 1998) or underestimated (in 1997) latent heat flux during the afternoon when sensible heat advection was most likely to occur.

Keywords: Bowen ratio, energy balance, latent heat flux, evapotranspiration, advection, alfalfa

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INTRODUCTION

The Bowen ratio-energy balance (BREB) method has been used to quantify water use (Fritschen, 1966; Malek et al. 1990; Wight et al. 1994; Cargnel et al. 1996), calculate crop coefficients (Malek and Bingham, 1993b), investigate plant-water relations (Grantz and Meinzer, 1991, Malek et al., 1991; Alves et al., 1996) and evaluate crop water use models (Ortega-Farias et al., 1993, Farahani and Bausch, 1995; Todd, 1996). It is considered a fairly robust method, 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 correlation (Cellier and Olioso, 1993) or water balance (Malek and Bingham, 1993a). Most of the studies which showed agreement were conducted when Bowen ratios were mostly positive and sensible heat advection absent. Others have shown 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 with methods such as eddy correlation, 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); and it can estimate fluxes on fine time scales (less than an hour). Disadvantages include sensitivity to the biases of instruments which measure gradients and energy balance terms; and the requirement, common to micrometeorological methods, of adequate fetch.

The BREB method relies on several assumptions (Fritschen and Simpson, 1989). Transport is assumed to be one-dimensional, with no horizontal gradients, and sensors which measure gradients are located within the equilibrium sublayer, where fluxes are assumed 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, K_H/K_W, is assumed to be one. The first two assumptions are usually met if adequate upwind fetch is available. A fetch to height 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).

It is generally accepted that the equality of exchange coefficients holds during neutral or unstable atmospheric conditions . This may not be the case during stable conditions or when sensible heat is advected to a surface. Blad and Rosenberg (1974) observed underestimation of latent heat flux of alfalfa by the BREB method in eastern Nebraska under sensible heat advection. Subsequently, Verma et al. (1978) and Motha et al. (1979) showed that $K_H>K_W$ during sensible heat advection. Lang et al. (1983) studied latent heat and sensible heat fluxes over a rice paddy located in an extensive dry region and found that $K_H<K_W$ when there was sensible heat advection. K_H/K_W was close to one near neutral conditions and decreased to a minimum of about 0.6 as stability increased. Based on these studies, the behavior of the exchange coefficients in the presence of sensible heat advection is uncertain.

The semi-arid environment of the southern High Plains provides an opportunity to evaluate the ability of the BREB method to estimate water use of an irrigated crop under conditions of thermal stability 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 contributes to the advective environment experienced over most of the growing season. Our objective was to compare BREB estimates of alfalfa latent heat flux with latent heat flux measured by precision weighing lysimeters under advective and non-advective conditions. We wanted to not only investigate daily estimates of latent heat flux, but also to explore the diurnal dynamics of the Bowen ratio-energy balance.

METHODS AND MATERIALS

The gradient equations for latent and sensible heat flux densities are

$$H = \rho C_p \; K_H \; \frac{\partial T}{\partial z} \qquad (1)$$

$$\lambda E = \frac{\lambda \epsilon \rho}{P} \; K_W \; \frac{\partial e}{\partial z} \qquad (2)$$

where H and λE are sensible and latent heat flux densities (W m^{-2}), K_H and K_W are the turbulent exchange coefficients for heat and water vapor (m^2 s^{-1}), ρ is the density of air (kg m^{-3}), C_p is the specific heat of air at constant pressure (J kg^{-1} °C^{-1}), λ is the latent heat of vaporization of water (J kg^{-1}), $\epsilon = 0.622$ is the ratio of the molecular weights of water vapor and dry air, P is the atmospheric pressure (kPa), T is air temperature (°C), e is the water vapor pressure of the air (kPa), and the derivatives represent the respective temperature and vapor pressure gradients. When Eq.[1] and [2] are substituted into the Bowen ratio, $\beta = H/\lambda E$, then

$$\beta = \frac{P C_p \; K_H \; \frac{\partial T}{\partial z}}{\lambda \epsilon \; K_W \; \frac{\partial e}{\partial z}} \qquad (3)$$

Letting the psychrometric constant $\gamma = PC_P/\lambda\epsilon$ (kPa °C^{-1}), expressing the derivatives in finite difference form, and assuming equality of exchange coefficients, the Bowen ratio becomes

$$\beta = \gamma \frac{\Delta T}{\Delta e} \qquad (4)$$

where ΔT and Δe express the differences in temperature and vapor pressure between two measurement heights above the canopy. The energy balance (neglecting energy used in photosynthesis or stored in vegetation) is

$$R_n + G + H + \lambda E = 0 \tag{5}$$

where R_n is net radiation (W m^{-2}) and G is soil heat flux (W m^{-2}). All fluxes to the surface are positive. When H = β λE is substituted into Eq.[5], which is then solved for λE, an expression for latent heat flux results which combines the Bowen ratio and energy balance,

$$\lambda E_B = \frac{-(R_n + G)}{1 + \beta} \tag{6}$$

Research was conducted in 1997 and 1998 at the USDA-ARS Conservation and Production Research Laboratory near Bushland, Texas (35° 11′ N, 102° 2′ W, elevation 1169 m), where the soil is a Pullman silty clay loam (fine, mixed, thermic Torrertic Paleustoll). Alfalfa (*Medicago sativa L.*) was planted in the autumn of 1995. The experiment in 1997 was conducted from day of year (DOY) 247 to 271 (fourth cutting of alfalfa). In 1998, data were collected from DOY 111 to 138 (first cutting of alfalfa). Two precision weighing lysimeters (Marek et al., 1988), 3-m by 3-m by 2.3-m deep were used to measure alfalfa ET. They were located in the north and south halves of a sprinkler-irrigated field 434 meters long from north to south and 217 meters long from east to west. Voltages from lysimeter load cells were sampled every six seconds by data logger (CR7, Campbell Scientific, Inc. Logan, UT[3]) and five-minute averages calculated. Evapotranspiration 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 five-minute 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 ($ET_{L,}$ in mm/0.5 h). ET_L was converted to latent heat flux for each lysimeter with

$$\lambda E_L = \frac{ET_L \lambda}{1800} \tag{7}$$

where the latent heat of vaporization was calculated with $\lambda = 2501000 - 2361 T_a$, with T_a the air temperature measured above each lysimeter, and 1800 equals the seconds in a half-hour. Identically instrumented meteorological masts were located at each weighing lysimeter and held a net radiometer (Q*5.5, Radiation and Energy Balance Systems, Seattle, WA), cup anemometer (014A, Met One, Grants Pass, OR), and temperature-humidity probe (HT225R, Rotronics, Huntington, New York). Aerial sensors were mounted at 2 m above the soil surface, except for the net radiometer, which was at 1 m height. Soil heat flux within each lysimeter was measured with four heat flux transducers (HFT-1, Radiation and Energy Balance Systems, Seattle, WA)

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

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}. 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 soil temperature. The same data logger that sampled lysimeter load cells also sampled other sensors every 6 s and calculated 15-minute means which were later processed as half-hour means.

The Bowen ratio was calculated from measurements of air temperature and relative humidity at two heights by sensors in radiation-shielded, aspirated housings mounted on a chain-driven automatic exchange mechanism (AEM-1, Radiation and Energy Balance Systems, Seattle, WA) located 15 m east of the north weighing lysimeter. The exchange mechanism was the same, but a different sensor system was used each year. In 1997, air temperature at each height was measured with a copper-chromel thermocouple and relative humidity was measured with a temperature-humidity probe (HMP-35, Vaisala, Wolburn, MA). In 1998, two integrated temperature-humidity probes (THP-1, Radiation and Energy Balance Systems, Seattle, WA) were used. Two calibrated thin film platinum resistance temperature devices (PRTD) were incorporated in each THP-1. 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. The manufacturer gives a temperature resolution of the PRTDs of 0.0056 °C, and the accuracy of the humidity sensor is ±2% relative humidity. The exchange mechanism switched the position of the sensors every five minutes. After each exchange, sensors were allowed to equilibrate with the new aerial environment for two minutes before a three minute measurement period. Distance between sensors was 1 m. The height of sensors was periodically adjusted as alfalfa grew so that the bottom sensors were at least 0.2 m above the crop. Maximum height of the top sensors during the study was 1.7 m.

Fetch ranged from a minimum of 90 m to the east to 360 m to the south-southwest. In 1997, dryland sorghum bordered the irrigated alfalfa field to the west and south, irrigated sorghum to the north, and irrigated corn, grass or soybean to the east. In 1998, the east border was the same as 1997, but the border west and south was not planted (bare soil and residue), and irrigated wheat was to the north.

Days with no irrigation, precipitation or lysimeter maintenance were accepted for analysis. BREB estimates of ET can be unreasonable when temperature or vapor pressure gradients are very small or when the Bowen ratio approaches -1. These possibilities were reduced by only accepting observations between 0800 and 1800 h CST. In 1997 and 1998, 98% and 91% of the 24-h ET occurred during those hours, respectively. Ten days near the end of the fourth cutting of alfalfa in 1997 were analyzed. Leaf area index during that time varied from 2.0 to 3.8 m^2 m^{-2} and plant height ranged from about 0.3 to 0.5 m. Twelve days near the end of the first cutting of alfalfa in 1998 were analyzed; leaf area index ranged from 2.7 to 5.2 m^2 m^{-2} and plant height ranged from about 0.3 to 0.6 m.

RESULTS AND DISCUSSION

The daily energy balances show that latent heat flux was often augmented by positive sensible heat flux, and exceeded R_n+G on 8 out of 10 days in 1997 and 6 out of 12 days in 1998 (Table 1). The presence of sensible heat advection was usually associated with strong, southerly winds, and on those days latent heat flux from the south lysimeter was usually greater than that from the north lysimeter. For example, on DOY 261 in 1997, latent heat flux from the south lysimeter was -22.4 MJ m^{-2}, compared with -21.4 MJ m^{-2} for the north lysimeter. On DOY 133 in 1998, latent heat fluxes from the south and north lysimeters were -23.7 and -21.9 MJ m^{-2}, respectively. A diurnal composite of all days shows that sensible heat advection was likely to be a significant part of latent heat flux at any time of the day in 1997, and was especially strong in the afternoon (Fig. 1A). In 1998, sensible heat advection was more likely to be encountered during the afternoon (Fig. 1B).

Daily daytime lysimeter ET (ET_L) ranged from 1.3 to 9.0 mm d^{-1} in 1997 and from 3.9 to 9.4 mm d^{-1} in 1998 (Fig. 2). BREB ET (ET_B) agreed well with ET_L in 1997, when ET_B averaged 6.15 mm d^{-1} over 10 days, compared with ET_L of 5.98 mm d^{-1} (Table 2). In 1998, ET_B and ET_L averaged 6.48 and 6.11 mm d^{-1}, respectively, over 12 days, but the intercept (-0.984 mm d^{-1}) and slope (1.221) of the regression line describing the relationship between ET_L and ET_B were significantly different from zero and one, respectively. The BREB method overestimated ET_L at rates greater than 6 mm d^{-1}. When years were combined, mean daily ET_B averaged about 5% greater than mean daily ET_L, with a slope of 1.131 significantly greater than one.

Half-hour observations of each method were also compared (Fig. 3). Observations with or without sensible heat advection (SHA, inferred when $-\lambda EB > R_n + G$) were identified and methods were compared for those cases. In 1997, ET_B tended to overestimate ET_L in the presence or absence of sensible heat advection (Fig. 3A), and the intercept and slope of the regression line describing the relationship between the methods were significantly different from zero and one, respectively, when there was sensible heat advection (Table 3). When observations were combined, however, ET_B agreed well with ET_L. ET_B also overestimated ET_L in 1998 (Fig. 3B), especially when there was sensible heat advection and ET rates were greater than 0.3 mm/0.5 h. The BREB method overestimated ET_L, on average, by about 3% when there was no sensible heat advection, and by about 8% when there was sensible heat advection. Slopes were significantly different from one for all three comparisons in 1998 and ranged from 1.072, when there was no sensible heat advection, to 1.112 for all observations (Table 3).

Diurnal trends were inspected by calculating means for each half-hour for the 10 days in 1997 and the 12 days in 1998. Mean diurnal Bowen ratios were mostly negative in 1997, indicating inverted temperature profiles and sensible heat transfer to the canopy (Fig. 4A). In 1998, Bowen ratios usually were positive in the morning and decreased during the day, becoming negative near early afternoon (Fig. 4B). Lysimeter-energy balance and gradient Bowen ratios agreed better in 1997, compared with 1998, but both years showed the largest discrepancies during the morning hours. These differences in Bowen ratio were reflected in the mean diurnal latent heat flux. In 1997, λE_B overestimated $\lambda E_{L,N}$ (north lysimeter) and $\lambda E_{L,S}$ (south lysimeter) during the morning and underestimated lysimeter latent heat flux in the afternoon (Fig. 5A). The pattern in 1998 was similar to that observed in 1997 during the morning, but the BREB method slightly overestimated latent heat flux during the afternoon (Fig. 5B). The north and south lysimeters generally agreed with each other in 1997, but the south lysimeter showed slightly greater latent heat flux compared with the north lysimeter throughout the day in 1998.

The error of the BREB estimate of latent heat flux with respect to lysimeter latent heat flux was calculated with ERROR = $(\lambda E_B - \lambda E_L)/\lambda E_L$ for each half-hour observation. The diurnal course of BREB error was then found by calculating the mean error for each half-hour. In 1997, error was positive in the morning and negative in the afternoon (Fig. 6). Midday error was very close to zero, and BREB latent heat flux between 1000 h and 1600 h, on average, was within 10% of lysimeter latent heat flux. The diurnal pattern in 1998 was similar to 1997 for the morning and midday, but error remained positive in the afternoon. This positive afternoon error was mostly contributed by three days with strong sensible heat advection (DOY 115, 133, and 136). If those days are removed, the afternoon error tends to become negative, as in 1997.

Overestimation of latent heat flux by the BREB method occurred whether sensible heat flux was positive or negative, or whether or not there was sensible heat advected to the surface. When sensible heat advection was large, the BREB method often underestimated λE_L in 1997, while in 1998 the BREB method overestimated λE_L . While it is unclear whether or not the equality of exchange coefficients was valid, these conflicting results suggest other factors contributed to the observed differences.

Accurately measured net radiation is important to the accuracy of the BREB method. Error in the measurement of net radiation would probably introduce a systematic bias which would be expressed whether or not there was sensible heat advection. If this potential source of error was temperature dependent, however, it would help account for the overestimation of latent heat flux by the BREB method. Discrepancy in latent heat flux measured by the two methods could also result if the latent heat flux from the lysimeters was not representative of latent heat flux from the field. Leaf area index (LAI) of alfalfa inside the lysimeters was consistently less than the leaf area index of samples collected in the surrounding field. The field LAI was 12% greater than lysimeter LAI at the time of the fourth cutting in 1997, and 36% greater than lysimeter LAI at the first cutting in 1998. But greater LAI did not necessarily mean greater latent heat flux. For example, the south lysimeter had a 16% greater LAI than the north lysimeter at the first cutting in 1998, yet total ET for 12 days prior to the fourth cutting was 74.5 mm for the south lysimeter and 72.0 mm for the north lysimeter, a difference less than 3%. Uncertainty in the determination of LAI or in the effect of LAI on ET do not allow clear interpretation of the possible effect of LAI differences on ET.

Footprint analysis (Gash, 1986; Schuepp et al., 1990) indicated that the sensors at the two heights were influenced by different upwind areas. Cumulative relative flux, the fraction of flux contributed by the area of interest, was usually greater than 0.95 for the lower sensors, but averaged around 0.85 for the upper sensors. Areas beyond the field border which influenced the upper sensors, but not the lower sensors, may have increased the temperature at the upper height and increased the air temperature gradient. This would decrease the Bowen ratio and increase the latent heat flux estimate. The vapor pressure gradient would also be affected, however, becoming more negative. The magnitude of these possible effects is uncertain and difficult to determine.

Horizontal temperature gradients developed across the alfalfa field when there was sensible heat advection. For example, in 1998, DOY 112 had little or no sensible heat advection, with winds that blew from southeast to west at an average wind speed of 2.2 $m\ s^{-1}$, and the daytime temperature gradient between the south and north lysimeter averaged 0.0008$^\circ\ m^{-1}$

(measured at 2 m height). When sensible heat advection was moderate on DOY 130, with southerly winds which averaged 4.9 m s^{-1}, the air temperature gradient between the south and north lysimeter was 0.0024° m^{-1}. When sensible heat advection was strong on DOY 133, with southerly winds which averaged 7.3 m s^{-1}, the air temperature between the south and north lysimeter was 0.0044° m^{-1}. These temperature gradients indicate a violation of the assumption of no horizontal gradients and the presence of horizontal flux divergence.

SUMMARY AND CONCLUSIONS

Alfalfa latent heat flux estimated by the Bowen ratio-energy balance method was compared with latent heat flux from measurements by two precision weighing lysimeters over 22 days in 1997 and 1998. Fourteen days experienced sensible heat advection, so that latent heat flux often exceeded the sum of net radiation and soil heat flux. Daily evapotranspiration estimated by the BREB method agreed well with that of the lysimeters in 1997, but overestimated ET compared with lysimeters in 1998, especially at rates greater than 6 mm d^{-1}. Half-hourly observations were segregated by observations with or without sensible heat advection. The BREB method tended to overestimate lysimeter ET whether or not sensible heat advection was present, although the overestimation was greater in 1998, when there was sensible heat advection and ET rates exceeded 0.3 mm/0.5 h.

Bowen ratios generally decreased over the course of a day, and were mostly negative in 1997, but were often positive in the morning in 1998, becoming negative during early afternoon. The BREB method overestimated latent heat flux in the morning, but agreed well with lysimeter latent heat flux during mid-day. The BREB method underestimated latent heat flux during the afternoon in 1997, but overestimated latent heat flux in 1998. Latent heat flux was overestimated by the BREB method when sensible heat flux was negative or positive, and whether or not there was sensible heat advection. Possible factors which may have contributed to error in the BREB estimate include measurement of net radiation, the representativeness of the lysimetric measurements, violation of the assumptions of one-dimensional transport and no horizontal gradients, and different upwind footprints experienced by sensors at different heights.

The BREB method gave reasonably good estimates of daily ET, but closer analysis showed that compensating errors in the morning and afternoon were responsible for the good fit. If the BREB method is used at time scales of an hour or less, care should be taken to ensure that the assumptions of the method are not violated. These assumptions especially may not hold under the conditions encountered when there is sensible heat advection. Even when the fetch to height ratio is large, latent heat flux estimated by the BREB method may show an oasis effect because of the different sensor heights and the different upwind areas that sensors experience.

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Table 1. Daily (0800 h to 1800 h) energy balance and Bowen ratio (β) for irrigated alfalfa in 1997 and 1998. The mean sensible heat flux from lysimeters (H_L) was calculated as the unknown term in the energy balance equation. The sensible heat flux from the BREB method was calculated with $H_B = \beta\lambda E_B$. $\lambda E_{L,N}$ and $\lambda E_{L,S}$ are latent heat fluxes from the north and south weighing lysimeters. Fluxes to the crop-soil surface are positive.

DOY	R_n	G	$\lambda E_{L,N}$	$\lambda E_{L,S}$	λE_B	H_L	H_B	β
1997	------------------------------------ MJ m^{-2} ------------------------------------							
248	14.0	-1.0	-14.1	-14.2	-14.1	1.2	1.1	-0.09
249	14.6	-0.96	-17.0	-17.3	-17.2	3.5	3.5	-0.23
250	14.2	-0.87	-16.9	-17.4	-17.4	3.8	4.0	-0.26
252	9.3	-0.33	-11.2	-11.1	-11.5	2.3	2.6	-0.26
257	13.2	-0.70	-14.6	-15.6	14.9	2.6	2.4	-0.20
259	13.9	-0.64	-17.6	-17.5	-18.6	4.3	5.3	-0.31
261	13.4	-0.63	-21.4	-22.4	-22.8	9.1	10.0	-0.50
263	3.2	1.1	-3.4	-3.1	-2.8	-1.1	-1.5	0.52
268	13.3	-0.82	-11.4	-11.0	-12.9	-1.2	0.42	-0.08
269	12.5	-0.72	-16.6	-17.5	-17.7	5.3	5.9	-0.45
1998								
112	15.0	-1.6	-11.5	-12.0	-10.5	-1.6	-2.9	0.05
115	15.9	-1.0	-18.4	-18.9	-21.6	3.8	6.7	-0.34
118	13.3	-0.32	-10.2	-9.9	-9.9	-2.9	-3.1	0.24
119	14.4	-1.2	-10.3	-10.5	-10.9	-2.8	-2.3	0.19
122	16.4	-1.1	-14.3	-15.0	-15.5	-0.42	0.38	-0.03
123	16.1	-1.2	-15.2	-16.0	-16.3	0.73	1.4	-0.07
125	13.9	-1.0	-9.8	-9.6	-10.7	-3.1	-2.2	0.18
126	16.1	-0.91	-16.5	-16.4	-18.0	1.3	2.8	-0.07
129	13.8	-0.48	-12.3	-12.4	-12.2	-1.0	-1.1	0.05
130	15.7	-1.0	-14.2	-14.6	-14.2	-0.30	-0.51	0.10
133	16.0	-0.99	-21.9	-23.7	-26.1	7.8	2.0	-0.43
136	15.6	-0.81	-21.9	-23.6	-24.8	7.9	0.76	-0.41

Table 2. Univariate and regression statistics which compare daily observations of evapotranspiration estimated by the BREB method (ET_B) with evapotranspiration measured by weighing lysimeters (ET_L) in 1997, 1998, and for both years combined. RMSE is the root mean square error.

Year	Method	n	Mean	SD	Intercept	Slope	r^2	RMSE
			---------- mm d^{-1}	----------				mm d^{-1}
1997	ET_L	10	5.98	2.11				
	ET_B	10	6.15	2.21	-0.067	1.039	0.988	0.296
1998	ET_L	12	6.11	1.89				
	ET_B	12	6.48	2.23	-0.984*	1.221**	0.979	0.632
Both	ET_L	22	6.05	1.95				
	ET_B	22	6.33	2.23	-0.515	1.131**	0.975	0.508

* Intercept was significantly different from zero or the slope was significantly different from one at the 0.05 probability level.

** Intercept was significantly different from zero or the slope was significantly different from one at the 0.01 probability level.

Table 3. Univariate and regression statistics which compare half-hour observations of evapotranspiration estimated by the BREB method (ET_B) with evapotranspiration measured by weighing lysimeters (ET_L) in 1997 and 1998, for observations with or without sensible heat advection (SHA), and combined observations. RMSE is the root mean square error.

Year	Advection	Method	n	Mean	SD	Intercept	Slope	r^2	RMSE
				---------- mm/0.5 h ----------					mm d^{-1}
1997	No SHA	ET_L	51	0.185	0.119				
	No SHA	ET_B	51	0.209	0.135	0.011	1.071	0.900	0.049
	SHA	ET_L	149	0.338	0.125				
	SHA	ET_B	149	0.341	0.141	-0.022*	1.073**	0.912	0.043
	All	ET_L	200	0.299	0.140				
	All	ET_B	200	0.307	0.150	0.001	1.025	0.915	0.044
1998	No SHA	ET_L	125	0.250	0.093				
	No SHA	ET_B	125	0.258	0.109	-0.009	1.072*	0.831	0.046
	SHA	ET_L	115	0.366	0.142				
	SHA	ET_B	115	0.395	0.162	-0.010	1.108**	0.946	0.050
	All	ET_L	240	0.305	0.132				
	All	ET_B	240	0.324	0.153	-0.016*	1.112**	0.926	0.048

* Intercept was significantly different from zero or the slope was significantly different from one at the 0.05 probability level.

** Intercept was significantly different from zero or the slope was significantly different from one at the 0.01 probability level.

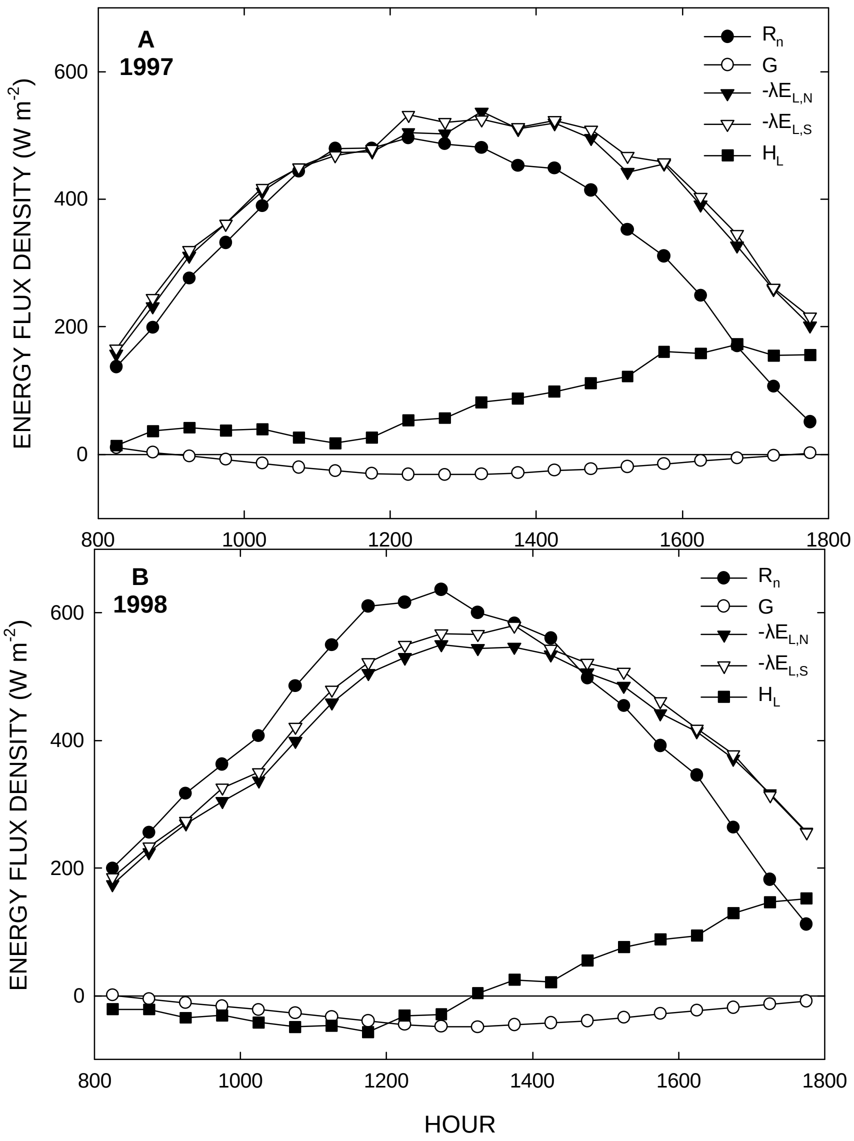

Figure 1. Mean diurnal energy balances in 1997 and 1998. H_L was calculated as the unknown term in the energy balance. $\lambda E_{L,N}$ and $\lambda E_{L,S}$ are latent heat fluxes from the north and south lysimeters.

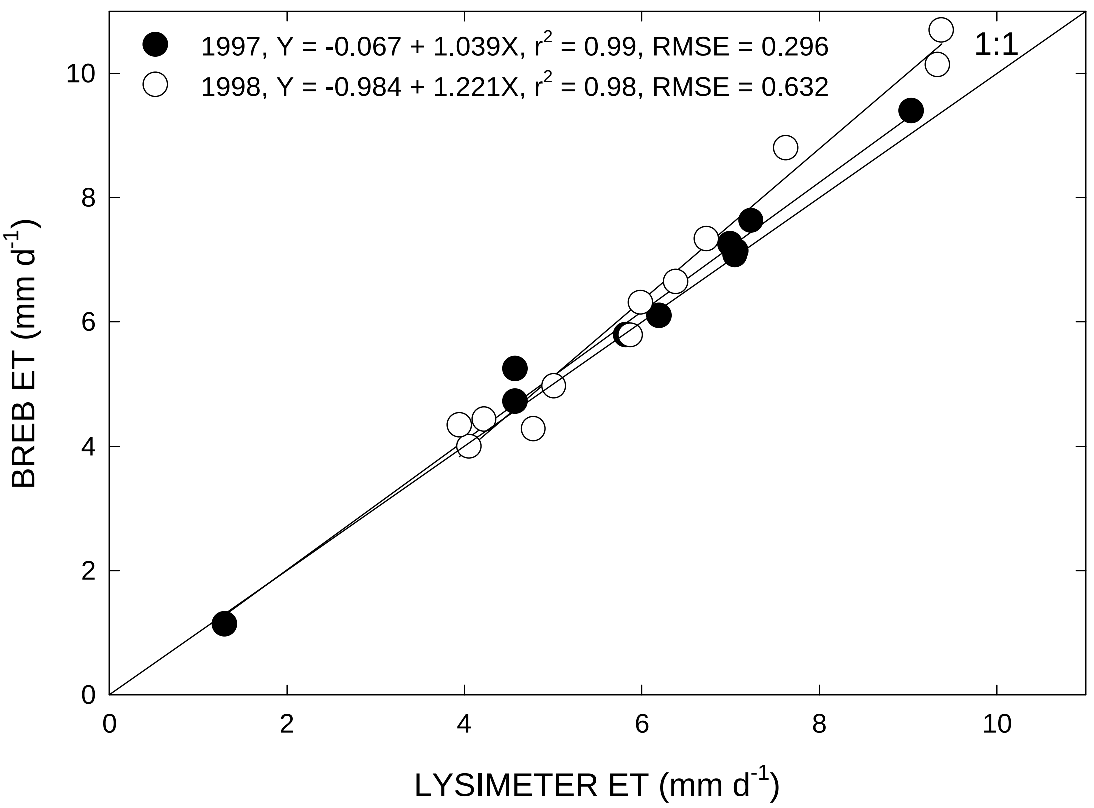

Figure 2. Daily alfalfa evapotranspiration estimated by Bowen ratio-energy balance compared with evapotranspiration measured by lysimeter, 1997 and 1998.

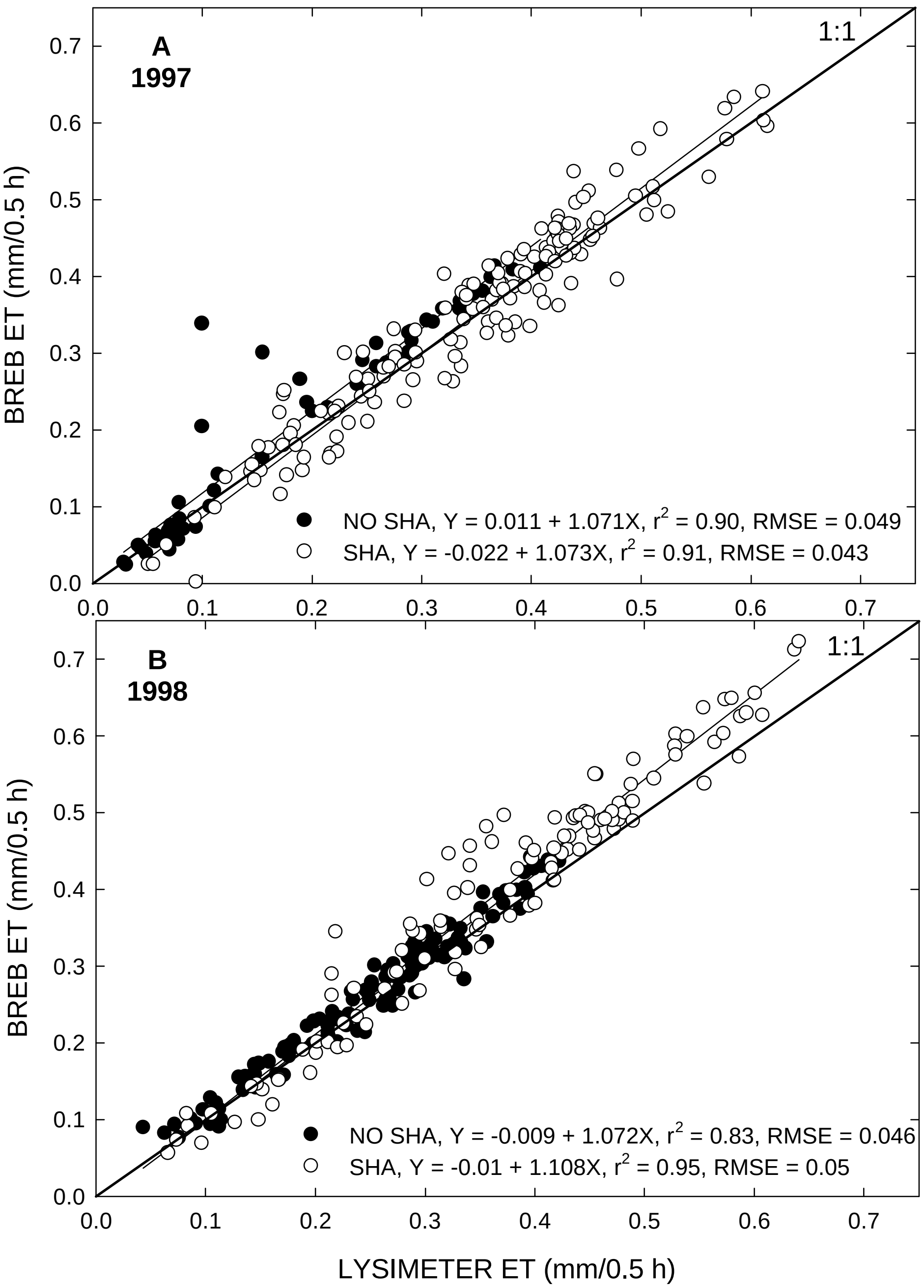

Figure 3. Bowen ratio-energy balance and lysimeter evapotranspiration compared in 1997 (A) and 1998 (B). Observations are divided into those with sensible heat advection (SHA) and no sensible heat advection.

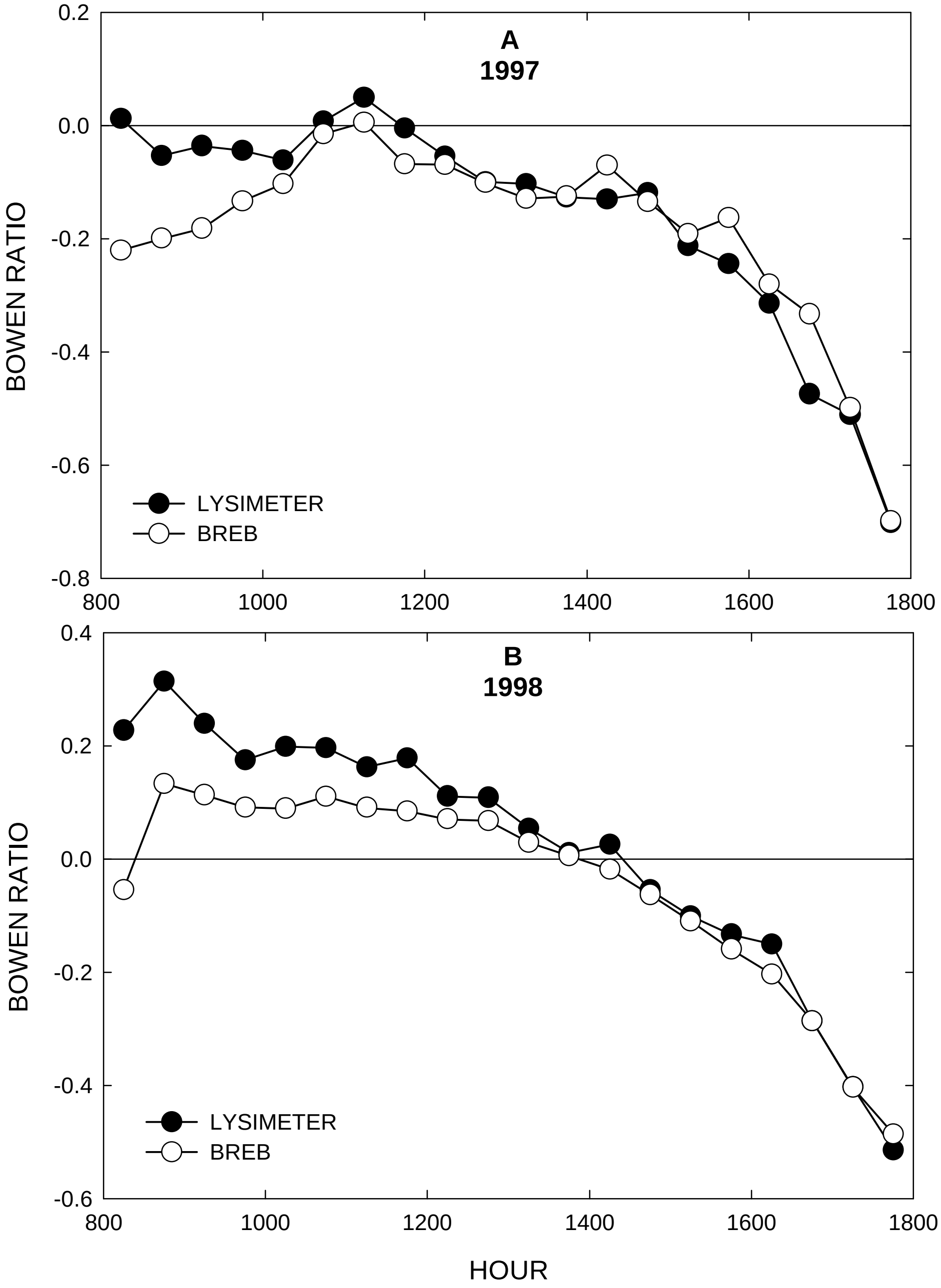

Figure 4. Mean diurnal Bowen ratios for 10 days in 1997 (A) and 12 days in 1998 (B). The lysimeter Bowen ratio was calculated from measured lysimeter latent heat flux and lysimeter sensible heat flux, which was calculated as the residual of the energy balance equation. The BREB Bowen ratio was calculated from air temperature and vapor pressure gradients.

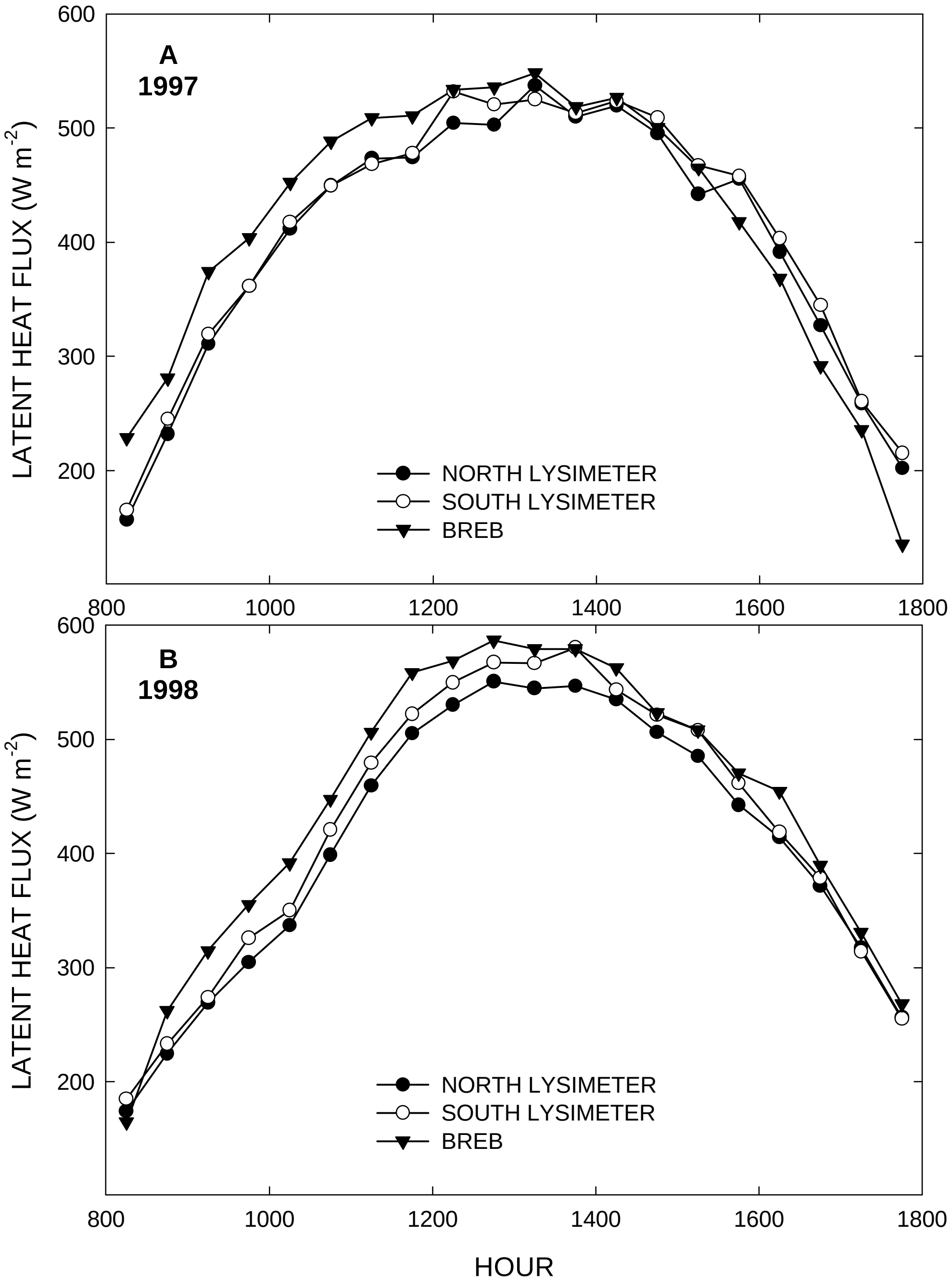

Figure 5. Mean diurnal alfalfa latent heat flux for 10 days in 1997 (A) and 12 days in 1998 (B), measured by the north and south lysimeters and estimated by the Bowen ratio-energy balance method (BREB).

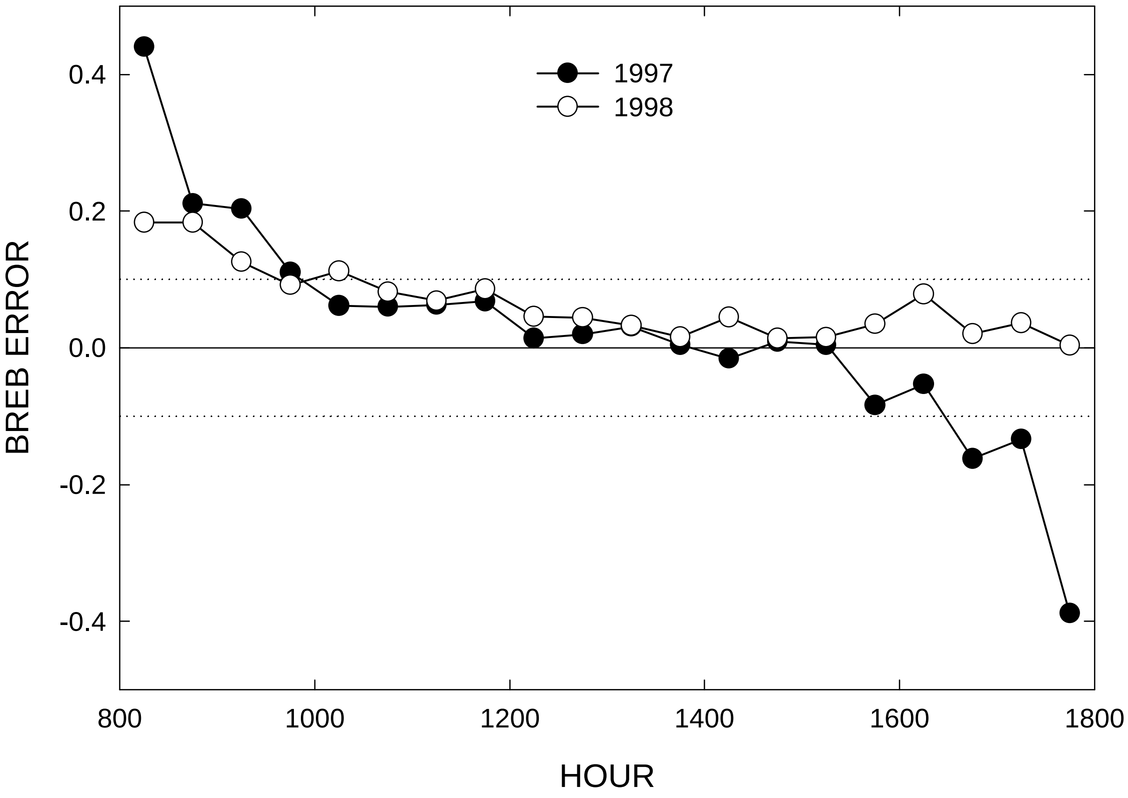

Figure 6. Mean diurnal error of BREB estimate of alfalfa latent heat flux compared with lysimeter latent heat flux, in 1997 and 1998.