Reprinted from *Agronomy Journal*
Vol. 89, No. 5

Bowen-Ratio Comparisons with Lysimeter Evapotranspiration

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ABSTRACT

Water use in agriculture by different cropping systems is of interest in determining crop water use efficiency of different tillage practices that will lead to reduced crop production risk. Lysimeters are considered the standard for evapotranspiration (ET) measurements; however, these units are often not replicated and are few in number at any given location. Our objective was to determine if a simple Bowen-ratio system with nonexchanging psychrometers could provide accurate measurements of ET from lentil (*Lens culinaris* Medikus) in a semiarid climate. The study was conducted in 1993 and 1994 on two adjacent 180- by 180-m fields with weighing lysimeters (1.68 by 1.68 by 1.83 m) located in the center of each field, on a Williams loam (fine-loamy, mixed Typic Argiboroll) soil near Sidney, MT. A Bowen-ratio system comprised of two nonexchanging psychrometers and anemometers at 0.25 and 1.25 m above the plant canopy surface was placed in the lentil field along with a net radiometer and soil heat flux plate. Precipitation during the growing season from planting to swathing was 367 mm in 1993 and 227 mm in 1994. In 1993, soil water content of the lysimeter was greater than the field after large precipitation events around Day of Year (DOY) 210, even though the lysimeter was drained. After this time, the lysimeter ET exceeded that measured by the Bowen-ratio system. Agreement was closer in 1994, when precipitation was near normal and there was no excess soil water in the lysimeter. Cumulative ET totals from the lysimeter were reflective of the seasonal precipitation patterns. Differences between the lysimeter and Bowen-ratio occurred when there was excess precipitation and inadequate drainage from the lysimeter. Half-hourly ET fluxes from lysimeter and Bowen-ratio values agreed to within 10% throughout the season. Bowen-ratio systems with nonexchanging psychrometers can provide satisfactory estimates of daily and seasonal ET and can be used to estimate ET in semiarid climates.

Crop water use as affected by different cropping systems is of major interest for purposes of planning, comparing systems, and allocating scarce water resources in semiarid regions. Methods of obtaining estimates of ET range from direct measurement techniques using lysimeters to energy balance measurements based on Bowen-ratio, flux profile, and eddy correlation techniques (Hatfield, 1990). Evapotranspiration measurements provide valuable information about temporal changes in water use by a cropping system; however, lysimeter methods can measure only one cropping system, unless there are multiple lysimeters installed at a given location. Micrometeorological techniques provide a way of comparing ET rates among different cropping systems and can be more easily located in multiple fields to estimate evaporation from a number of different cropping systems than lysimeters can.

The Bowen-ratio method is often used because of the simplicity of data collection, and because the robust nature of the system allows for long-term data acquisition. The technique has increased in popularity because of the recent improvements in field portable data acquisition systems and sensor accuracy and precision. The technique was first proposed by Bowen (1926) and recast in the following relationship:

$$\beta = H/\lambda E = \alpha(C_p\Delta T/\lambda\Delta e) \qquad [1]$$

where β is the Bowen-ratio, H is sensible heat flux (W m^{-2}), λE is latent heat flux (W m^{-2}), α is the ratio of the turbulent transfer coefficients for sensible heat and water vapor (K_h/K_w, both in units of m^2 s^{-1}), C_p is specific heat of air at constant pressure (J kg^{-1}°C^{-1}), ΔT is the air temperature gradient (°C) between two heights above the surface, λ is latent heat of vaporization (J kg^{-1}), and Δe is the gradient of vapor pressure (kPa) at the same two heights as T under nonadvective conditions. The surface energy balance can be expressed as:

$$R_n = G + H + \lambda E \qquad [2]$$

where R_n is net irradiance (W m^{-2}), G is soil heat flux (W m^{-2}), and H and λE are as defined for Eq. [1]. Positive values of R_n and G are toward the surface, while H and λE are away from the soil or crop surface. Using Eq. [1] and [2] and solving for λE yields the following estimate of evaporation:

$$\lambda E = (R_n - G)/(1 + \beta) \qquad [3]$$

where λE, R_n, and G are as defined before and β is the Bowen-ratio (Eq. [1]).

It has been shown that exchanging vertical positions of psychrometers can reduce potential errors due to sensor bias. Gay (1988) showed that exchanging psychrometers decreases the potential sensor bias problems and could lead to increased reliability of performance of Bowen-ratio systems. However, there have been few comparisons of nonexchanged static systems with lysimeters.

Comparisons between the Bowen-ratio technique and a lysimeter have been conducted, and differences of less than 10% between the two methods have been reported (Denmead and McIlroy, 1970; Fritschen, 1965; Pruitt and Lourence, 1968; Tanner, 1960). Limitations of the Bowen-ratio method generally occur near sunrise and sunset, because of small gradients in T and e that result in β values approaching -1 or ∞. Limitations can also occur with crops of nonuniform cover and under condi-

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Published in Agron. J. 89:730–736 (1997).

Abbreviations: DOY, Day of Year; ET, evapotranspiration; LAI, leaf area index; LE, lysimeter evaporation; SEE, standard error of the estimate.

tions of advection, commonly found in semiarid agriculture. Bausch and Bernard (1992) compared a spatially averaging Bowen-ratio system with a lysimeter near Bushland, TX, during two clear days and found that the Bowen-ratio underestimated the lysimeter λE by 1.4%. The largest difference between the two methods occurred on the day following an irrigation, when the Bowen-ratio underestimated the lysimeter λE by 8%. Other calibrations have been conducted by Revheim and Jordan (1976), who found the Bowen-ratio to provide agreement within 10% of lysimeters. Direct comparisons between Bowen-ratio and lysimeter methods have been done for short periods (<1 wk) and under a limited range of atmospheric conditions.

Estimates of regional-scale ET and comparisons of water use among cropping systems require techniques that are robust and capable of being used in a variety of locations. Evaluation of water use to provide a better understanding of the impact of different cropping practices on water conservation is becoming increasingly important in both semiarid and humid climates. Aase and Tanaka (1987) showed that, during the summer months, there was little difference between tillage practices and crop residue on ET. During the spring months, however, both crop residue and shallow tillage decreased soil water evaporation compared with bare soil. Evaluating differences in water use requires techniques that can be used to monitor daily and seasonal estimates of ET and that are capable of providing accurate estimates over a range of tillage, crop, and surface conditions. Our objective was to compare season-long estimates of daily ET using Bowen-ratio and lysimeter methods for a cropped surface in the semiarid climate of the northern Great Plains. In our study, the Bowen-ratio system consisted of nonexchanging psychrometers for air temperature and water vapor estimates. Our goal was to provide confidence in a robust micrometeorological method for ET estimation that can potentially extend information to a broader regional context from research plots.

MATERIALS AND METHODS

The study was conducted as part of a larger experiment to compare water use of lentil (*Lens culinaris* Medikus cv. Indianhead) and fallow systems in eastern Montana on a Williams loam (fine-loamy, mixed Typic Argiboroll) (Aase et al., 1996). Two precision weighing lysimeters, 1.68 by 1.68 by 1.83 m, similar to those described by Ritchie and Burnett (1968) were used to measure lentil ET and fallow soil water evaporation. The lysimeters were constructed and installed in 1977 and were located in the center of adjacent 180- by 180-m fields typical of strip tillage practices common to the northern Great Plains. Both lysimeters were calibrated at the beginning of each season in 1993 and 1994. Aase et al. (1996) found no apparent differences in growth or yield between the field and lysimeter area.

Black lentil was no-till seeded into wheat (*Triticum aestivum* L.) residue on the north lysimeter field on 14 May 1993 (DOY 134) with a disk-opener no-till drill with a 0.19-m row spacing at a seeding rate of 59 kg ha^{-1}. A 0.6-m-wide area surrounding the lysimeter and the lysimeter itself were hand seeded at the same time. Throughout the season there were few observable differences between growth in the lysimeter and in the field (Aase et al., 1996). The south field and lysimeter were maintained in chemical fallow in 1993 following the wheat crop. On 5 May 1994 (DOY 125), the chemical fallow field was planted to lentil using the same method and rate as in 1993. The north lysimeter was maintained as a chemical fallow treatment in 1994. There were no observable differences in surface residue amounts between the field and lysimeter.

After plant emergence, Bowen-ratio equipment was installed in the lentil field approximately 10 m northwest of the lysimeter. Instrumentation consisted of two aspirated psychrometers mounted on a moveable arm with a 1.0-m separation between psychrometers. The arm could be adjusted to maintain the heights of the psychrometers at 0.25 and 1.25 m above the soil canopy surface. These were periodically repositioned to accommodate the changing canopy height throughout the season. Psychrometers were mounted on the crossarm and maintained in the same position throughout the season. There was no vertical exchange between the psychrometers. Psychrometers consisted of 20 gauge copper–constantan thermocouples sealed with waterproof material (liquid plastic coat) and mounted inside a dual-shielded, insulated cylindrical unit aspirated with an electric fan. Wet-bulb thermocouples were placed in a ceramic wick that was connected to a constant-head, insulated reservoir of distilled water. The ceramic wicks were replaced weekly with new units. To evaluate potential bias of the wet and dry thermocouples, the psychrometers were compared with one another prior to placement in the field and immediately after removal. Comparisons between the psychrometers were made by placing the units at the same level and comparing differences between both dry- and wet-bulb temperature readings. Differences between the two psychrometers were less than the manufacturer's stated error of the thermocouples of ±0.2°C.

Two photochopper anemometers (R.M. Young Co.,[1] Model 12012, Traverse City, MI) were positioned on a crossarm at the same height as the psychrometers to collect windspeed information as part of a larger objective on the estimation of surface resistances in semiarid crops. The unit was positioned in the field on a 2 m tall by 25 mm diameter galvanized steel pole (2 m tall by 25 mm diam.) that provided stability and ease of maintenance and operation. Net irradiance was measured with a Radiation and Energy Balance Systems (REBS) model Q*6 net radiometer (Radiation and Energy Balance Systems, Seattle, WA), positioned 2 m above the soil surface. Soil heat flux was measured with a REBS model HFT-3 flux plate positioned 0.1 m below the soil surface and midway between the rows. Net radiometers and soil heat flux plates were calibrated at the beginning and end of each season.

Soil temperatures were measured at 0.01, 0.05, and 0.1 m to estimate the heat storage term in the soil layer above the heat flux plate. The soil heat storage term calculation requires information on bulk density, soil temperature at two depths, and an estimate of soil moisture content. Soil moisture estimates were obtained from periodic neutron probe measurements within the field area. The method used for calculating the heat storage term is described in Hanks and Ashcroft (1980, p. 125–143).

Bowen-ratio measurements commenced after crop emergence and continued until just prior to harvest. Signals from lysimeters and micrometeorological equipment were recorded on Campbell Scientific 21X data acquisition systems (Campbell Scientific, Logan, UT) every 60 s, averaged or totaled every 30 min, and summed every 24 h.

Data were screened for inconsistencies due to instrumentation problems, calibrations were applied to lysimeter data,

[1] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may also be suitable.

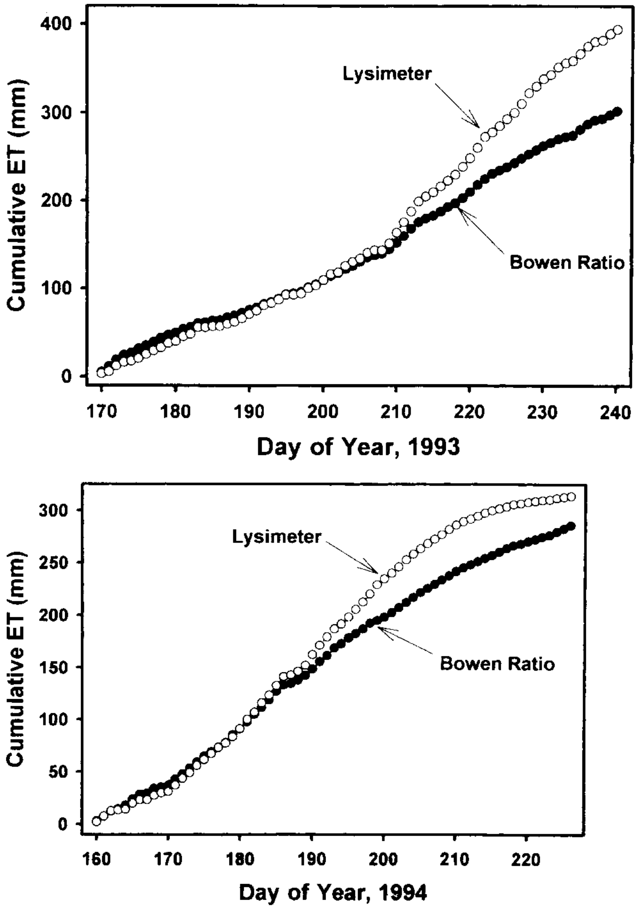

Fig. 1. Cumulative evapotranspiration (ET) from lysimeter and Bowen-ratio methods in (a) 1993 and (b) 1994 for lentil grown at Sidney, MT.

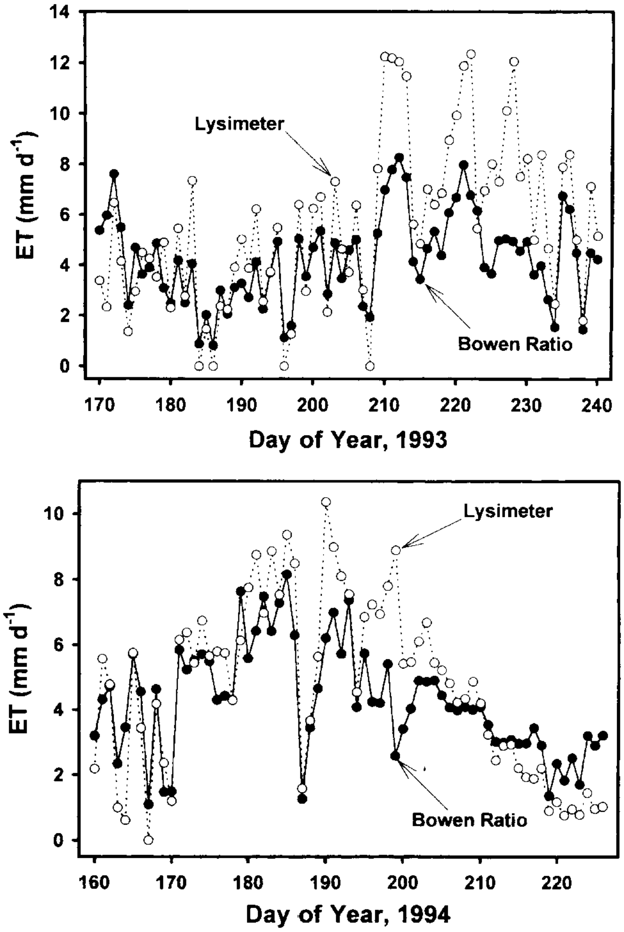

Fig. 2. Daily totals of evapotranspiration (ET) from lysimeter and Bowen-ratio methods in (a) 1993 and (b) 1994 for lentil grown at Sidney, MT.

and 30-min values of all meteorological parameters and water use values were calculated. Actual water vapor pressures at two heights above the surface were calculated using dry- and wet-bulb temperature data from the psychrometers. Saturation vapor pressure was calculated from dry-bulb temperature data using Tetens' (1930) method. Using the saturation vapor pressure results and wet-bulb temperature data, actual vapor pressure was calculated using Ferrel's technique as described by Harrison (1965).

Lysimeter totals were corrected for precipitation using a nearby tipping bucket raingage. Evapotranspiration from the Bowen-ratio method was computed during periods when net irradiance was >0.0 (W m^{-2}) for half-hourly intervals and totaled to derive daily ET totals. Lysimeter measurements showed that there was negligible water evaporation or condensation during the night throughout the season. This was verified through examination of half-hour changes in lysimeter weights that showed <0.01 mm of evaporation during the night. It is not possible to obtain satisfactorily accurate Bowen-ratio measurements during nighttime periods.

RESULTS AND DISCUSSION

Daily and Seasonal Evapotranspiration

Cumulative lentil lysimeter ET in 1993 was nearly 400 mm from DOY 175 through DOY 240 (Fig. 1a) for an average of 6.1 mm d^{-1}; Bowen-ratio totals were 280 mm (4.3 mm d^{-1}). In 1994, the lysimeter cumulative ET was 320 mm, for a daily average of 4.9 mm d^{-1}, while the Bowen-ratio totals were 290 mm, with a daily average of 4.5 mm d^{-1} (Fig. 1b). The Bowen-ratio and lysimeter values showed similar seasonal trends and responses to changes in daily meteorological conditions throughout the season, although significant differences between methods were observed. The lysimeter and Bowen-ratio methods showed good agreement in cumulative totals until DOY 210 in 1993 (Fig. 1a) and until DOY 190 in 1994 (Fig. 1b). The lysimeter continued to have a higher water evaporation rate after the methods diverged. Closer examination of the 1993 cumulative totals show that differences were attributed to a short time from DOY 210 to 215 following a rain of >60 mm. There were other periods during the latter part of the season following rain events in which the lysimeter exhibited increased evaporation amounts. This was less evident in 1994, when rainfall events were smaller.

Daily totals of evaporation for the lysimeter and Bowen-ratio were seasonally consistent in trend, with some disagreement between methods (Fig. 2a,b). Differences among daily ET values were initially small in both years. Daily totals from lysimeter and Bowen-ratio systems detail these changes throughout the season (Fig. 2a,b). In 1994, the methods diverged after DOY 190

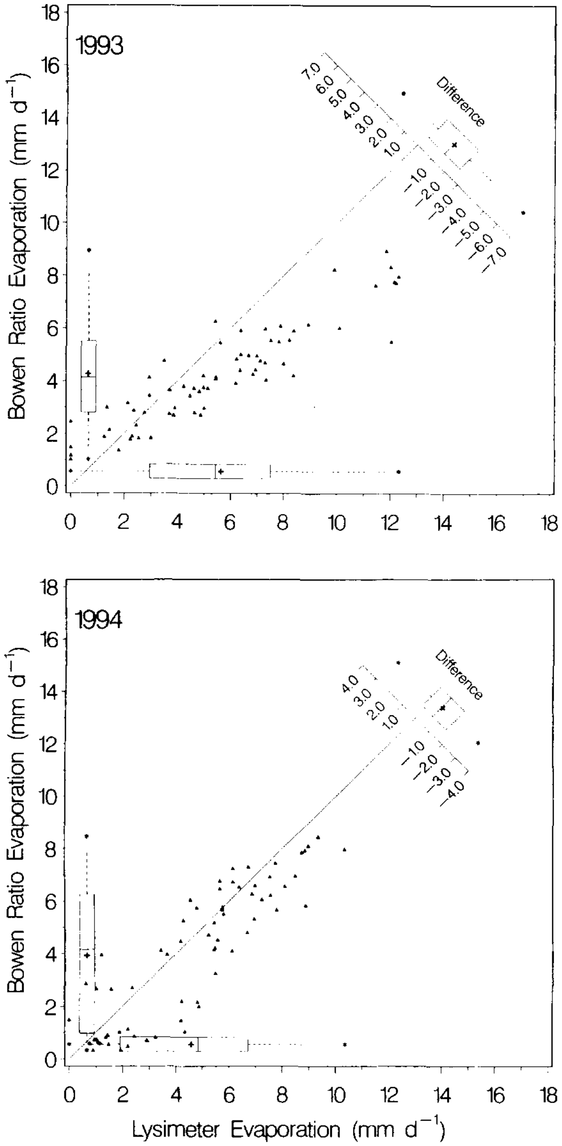

Fig. 3. Comparison of Bowen-ratio and lysimeter daily evapotranspiration (ET) totals for a lentil crop grown near Sidney, MT, in (a) 1993 and (b) 1994. Box graphs along the lysimeter and Bowen-ratio axes represent the mean, median, quartiles, and range of observed data. The box graph for difference shows the mean, median, and quartiles between the two methods.

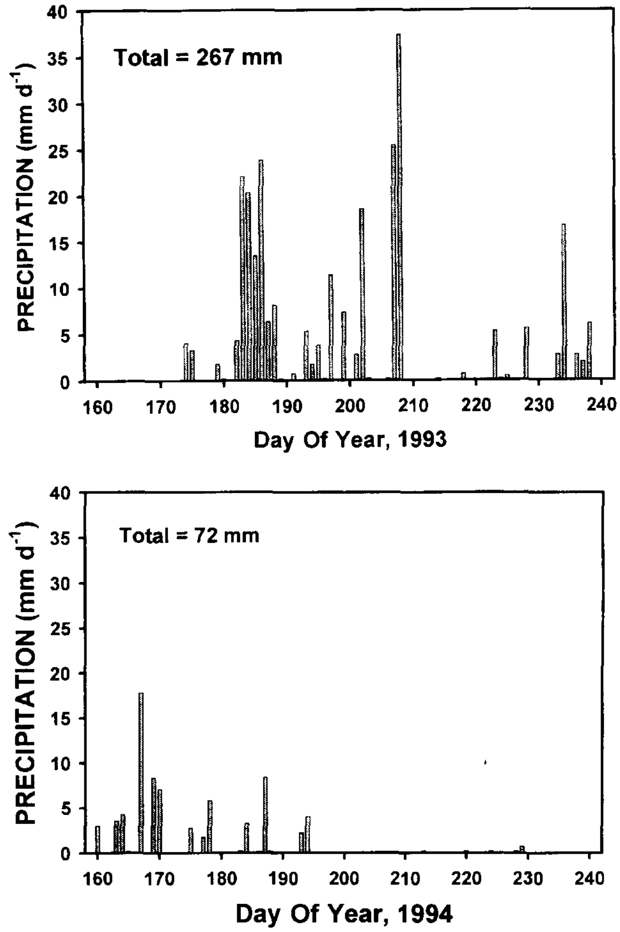

Fig. 4. Growing season rainfall at the lysimeter site near Sidney, MT, in (a) 1993 and (b) 1994.

and the Bowen-ratio decreased rapidly (Fig. 2b). After DOY 216 in 1994, Bowen-ratio estimates were consistently larger than lysimeter values and remained so until the end of the season.

Comparisons between Bowen-ratio and lysimeter daily estimates of ET were made by computing the difference between the two methods. We computed the mean, median, quartiles, and range of both lysimeter and Bowen-ratio daily estimates of ET in an attempt to show more descriptive statistics for the measured data (Fig. 3a,b). The largest cumulative actual ET differences between the two years were from the lentil lysimeter. Comparing Bowen-ratio and lysimeter estimates for 1993 showed that the lentil lysimeter had larger daily ET values than the Bowen-ratio method (Fig. 3a) and, although the fit between the two data sets was good, the Bowen-ratio underestimated the lysimeter, as evidenced by the slope of the line equal to 0.55, an intercept of 1.17, an r^2 of 0.87, and a standard error of the estimate (SEE) of 0.69. The Bowen-ratio underestimated the lysimeter by 1.5 mm d^{-1} and had a range of differences from 1.5 to -6.7 mm d^{-1} (Fig. 3a). The reason for this underestimation was due to near-saturated conditions of the lysimeter. Increased ET from the lysimeter may be due to either increased soil water evaporation or plant transpiration; however, it is not possible to separate these processes with a single measurement. Nonetheless, differences between the Bowen-ratio and lysimeter show that there was increased soil water availability within the lysimeter relative to the field. There were periodic soil water measurements with a neutron probe to confirm these observations, but these were insufficient to compute a soil water balance.

In 1994, agreement between Bowen-ratio and lysimeter measurements improved, although more scatter about the 1:1 line was observed. The mean difference was 0.0 and the distribution was more evenly distributed about 0.0 (Fig. 3b). The slope for the 1994 data was 0.89, with an intercept of -0.14, an r^2 of 0.82, and a SEE of 1.12 (Fig. 3b). Evidence that the lysimeter had access to more water than the field was revealed in

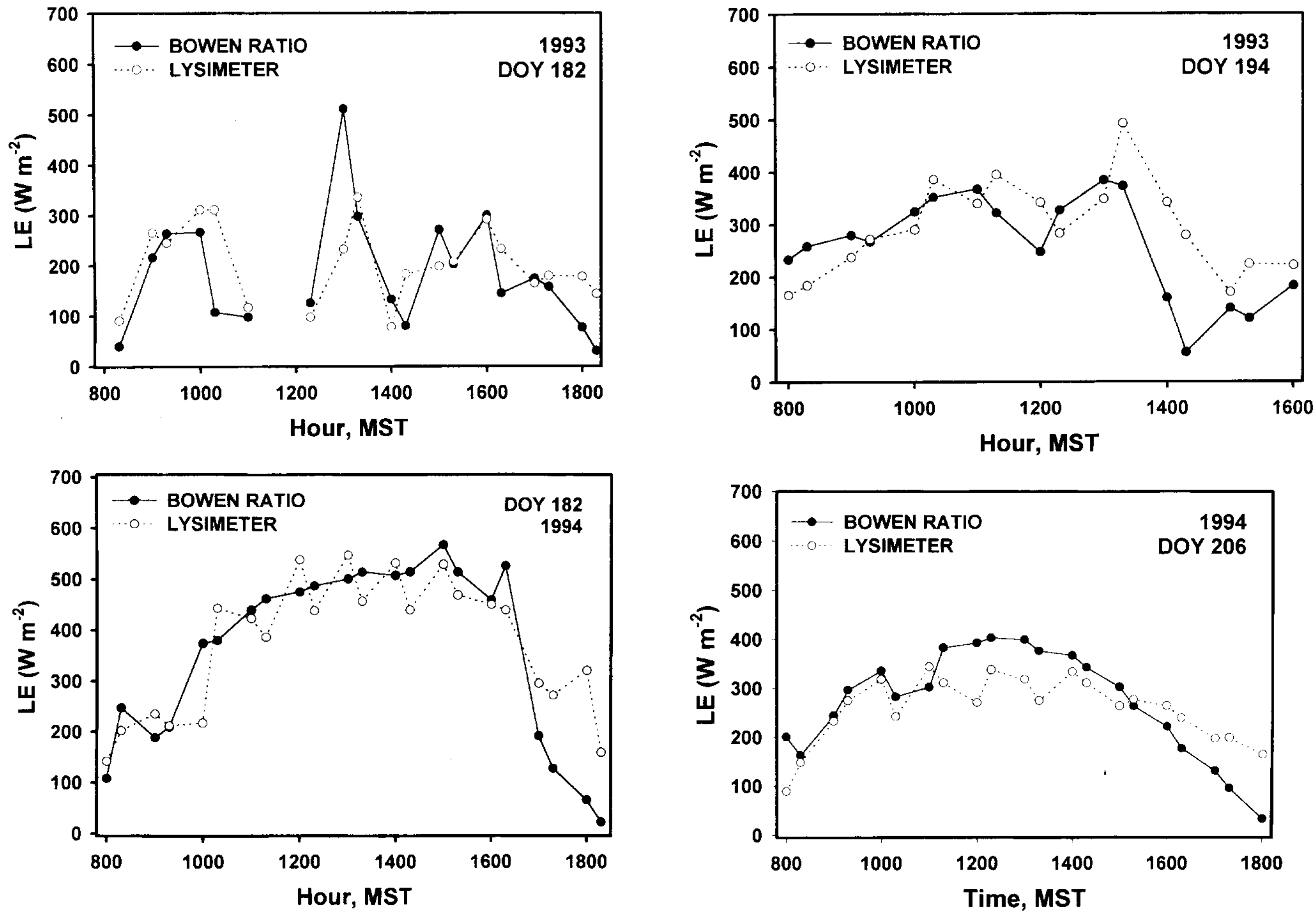

Fig. 5. Hourly measurements of evapotranspiration (ET) from Bowen-ratio and lysimeter methods for a lentil crop near Sidney, MT, in (a) DOY 182 and (b) DOY 194 of 1993 and on (c) DOY 182 and (d) DOY 206 of 1994. DOY, Day of Year.

the wide range of evaporation rates from the lysimeter, particularly at the lower Bowen-ratio rates (Fig. 3a). This is shown in the daily ET rates in both years (Fig. 2a,b).

Seasonal Rain

Rain varied significantly between 1993 and 1994. In 1993, there was 367 mm during the growing season and in 1994 there was 227 mm. Rain during the period of measurement was 267 mm in 1993 and 72 mm in 1994. There was abundant rain during the first half of the 1993 season (Fig. 4a), while in 1994 all significant rain fell during the first half of the season (Fig. 4b). Differences in cumulative ET patterns and daily totals between the Bowen-ratio and lysimeter were a result of a drainage problem with the lysimeters enhanced by the above-normal precipitation amounts in 1993. The lysimeter was constructed with drainage systems to remove excess water from the bottom of the lysimeter. However, in 1993, due to above-normal precipitation, this system did not adequately remove excess water, and the soil in the lysimeter was near saturation throughout most of the season. The soil environment was not saturated to the point of causing any effect on plant growth, because the lysimeter had some drainage. In 1993, due to the near saturation condition of the soil, the lentil lysimeter was able to maintain higher ET rates compared with the rest of the field. Evapotranspiration rates of nearly 12 mm d^{-1} from the lysimeter were recorded, while the Bowen-ratio values for daily totals were 8 mm d^{-1} for the same days (Fig. 2a). In 1994, there were a few days with higher ET totals from the lysimeter than with the Bowen-ratio, and many of these days occurred when daily ET totals were <4 mm d^{-1} (Fig. 2b). Differences between Bowen-ratio estimates and lysimeter values can be explained by the lysimeter design, which resulted in apparent slower drainage of excess soil water, leading to increased soil water content in the lysimeter volume. It is also possible that the lysimeter captured more rainfall during the rain events because of the trapping effect of the rim not allowing water to move from the lysimeter area. These observations emphasize the need for caution in evaluating data collected from any system over a growing season to ensure that there is no bias incorporated into the interpretation of performance. Data collected in 1994 were from fields that had been maintained as chemical fallow plots in 1993, with the stored soil water from the previous year available to the crop during the next growing season. This accounted for the ET increase above the rain during the season.

Bowen-ratio estimates of ET occurred from an area approximately 30 times the lysimeter area, and any difference in water movement or storage in the lysimeter will result in difficulties when comparing techniques. In this study, drainage differences appear to have resulted in deviations between the Bowen-ratio estimates and lysimeter measurements. Differences between methods would not be noticeable in typical years in a semiarid climate; however, with isolated data this could cause a bias in the interpretation of the results.

Hourly Evapotranspiration

Hourly values of ET agreed reasonably well between Bowen-ratio and lentil lysimeter except for periods immediately following large rain events. To examine the relationship between hourly Bowen-ratio and lysimeter measurements of ET within a day, values of ET from selected days were compared using half-hourly ET measurements. These days were selected to represent both clear and cloudy days when the lysimeter was not subjected to large rain events. There was a large range in half-hourly lysimeter evaporation (LE) values for the four days shown in Fig. 5. On DOY 182 in 1993 during which the crop LAI was estimated to be approximately 2.3, there was a period of sunshine in a mostly cloudy day during which both methods tracked each other well (Fig. 5a). Later in the season on DOY 194, when it was mostly clear, Bowen-ratio and lysimeter values were within 30 W m^{-2} of each other throughout most of the day (Fig. 5b). Beginning on DOY 211 (Fig. 2a), lysimeter ET significantly exceeded Bowen-ratio estimates throughout the rest of the season (12 mm vs. 8 mm as an example for DOY 211). This was after over 60 mm of rain occurred over DOY 207 and 208. Half-hourly comparisons between lysimeter and Bowen-ratio values showed consistently larger lysimeter ET fluxes over the diurnal range of the period. This suggests two possibilities as to why this occurred. First, after a large precipitation event, the lysimeter contained more soil water relative to the field, since drainage was not possible because of the lysimeter barrier. Thus, considerably more soil water was available for evaporation. Second, heavy precipitation caused some of the lentil foliage to be extended beyond the edge of the lysimeter rim, thus increasing the area of net radiation capture relative to the actual lysimeter area. It is possible that a combination of these two events resulted in the lysimeter estimates greatly exceeding the Bowen-ratio estimates from DOY 211 through DOY 230 during 1993. In 1994, Bowen-ratio and lysimeter values were in closer agreement on DOY 182 (Fig. 5c). However, on DOY 206, with a calculated crop LAI of 3.3, the Bowen-ratio exceeded the lysimeter by as much as 100 W m^{-2} during the midday period, although there were periods of both over- and underestimation by the Bowen-ratio compared with the lysimeter (Fig. 5d). These days are illustrative of typical differences observed throughout both seasons on half-hourly observations.

A direct comparison of Bowen-ratio estimates with lysimeter measurements for the combined data from Fig. 5 showed good agreement (Fig. 6). The intercept was −36.1 W m^{-2}, which was not statistically different from 0.0. The slope was 1.13, with an r^2 of 0.95 and a SEE of 38.44. We compared the results between methods and found the mean difference to be 0.0, with the mean of the Bowen-ratio and lysimeter about 230 W m^{-2} (Fig. 6). Examination of individual means and quartiles shows that these two methods have similar responses (Fig. 6). The Bowen-ratio method can estimate half-hourly ET with accuracy over a range of meteorological conditions. The range of days we examined showed the Bowen-ratio system to be randomly distributed about the lysimeter observations, suggesting that there was no significant bias in the results produced by the nonexchange system. Daily totals in our study were influenced by changes in soil water availability in the lysimeter as compared with the field. For daily and seasonal estimates of ET, it is possible to use a simple Bowen-ratio system with nonexchanging psychrometers and achieve results on water use that can be used to evaluate different tillage and cropping practices in semiarid climates.

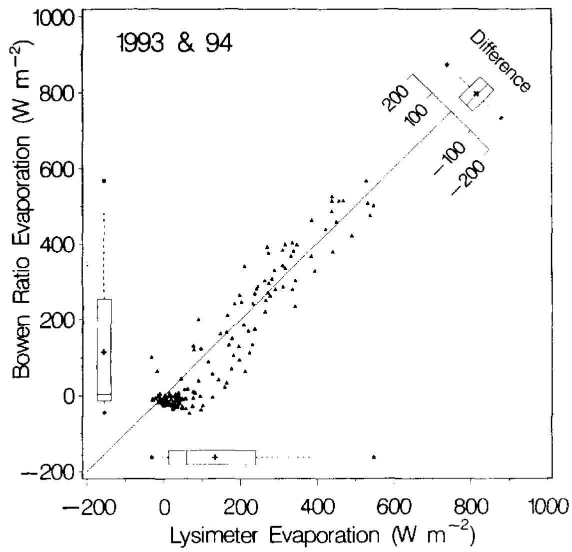

Fig. 6. Comparison of hourly evapotranspiration (ET) from the Bowen-ratio and lysimeter methods for four selected days from 1993 and 1994 in a lentil field near Sidney, MT. Symbols on the lysimeter and Bowen-ratio axes represent the mean, median, quartiles, and range of observed data. The box graph for difference shows the mean, median, and quartiles between the two methods.

CONCLUSIONS

Bowen-ratio estimates with nonexchanging psychrometers performed well in semiarid conditions compared with lysimeter measurements. Differences in ET estimates in this study were caused by increased soil water in the lysimeter following large rain events. Inadequate drainage in the lysimeter relative to the overall field may be responsible for these observations. Lysimeter seasonal ET totals were larger in 1993, a year with above-normal rainfall, and only slightly larger in 1994. Observations of half-hourly values from the Bowen-ratio system were randomly distributed about the lysimeter observations, except when the lysimeter was near saturation. The Bowen-ratio technique can provide good estimates of ET over larger areas than is possible with lysimeters. These data provide confidence in using a simple, nonexchanging Bowen-ratio method to obtain accurate estimates of ET. Throughout a growing season in a semiarid climate, the Bowen-ratio system can be used to assess differences in water use among different practices in areas without lysimeter installations.

ACKNOWLEDGMENTS

The authors wish to acknowledge the contributions of David Meek in the form of statistical analyses and interpretation of the data that significantly enhanced our understanding of the results.

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