Guidelines for Validating Bowen Ratio Data

J. O. Payero, C. M. U. Neale, J. L. Wright, R. G. Allen

Abstract. *For a variety of reasons, the measurement of latent heat flux using the Bowen ratio method can sometimes result in erroneous data. This study provides guidelines for detecting erroneous Bowen ratio data and illustrates the application of these guidelines by comparing Bowen ratio and lysimeter data collected over grass and alfalfa in southern Idaho. Errors in net radiation were detected by comparing measured with theoretical values. However, it was found that good theoretical procedures to validate soil heat flux data are lacking. Only empirical equations mainly used for remote sensing applications to obtain estimates close to noontime are available. Extremely inaccurate latent heat fluxes were easily filtered out by rejecting data when the calculated Bowen ratio (β) values were close to –1. A simplified procedure was proposed to reject fluxes with the wrong sign, and three different equations were used successfully to detect the occurrence of condensation inside the type of measurement system used in the study. Guidelines to assure adequate fetch are provided. Fetch did not affect the measured fluxes in this study, which may have been due to the similarity in surface properties between the crops under study and those in the surrounding fields.*

***Keywords**. Alfalfa, Bowen ratio, Energy balance, ET, Evapotranspiration, Grass, Latent heat flux, Lysimeter, Soil heat flux.*

Evapotranspiration (ET) from a surface can either be measured or estimated. Because measuring ET is difficult and requires specialized equipment, most applications use ET estimates instead of direct measurements. ET can be estimated from meteorological, crop, and soil information using a variety of methods, as reviewed by Doorenbos and Pruitt (1977), Jensen et al. (1990), and Allen et al. (1998). However, for some applications, especially in research, direct measurement of ET is necessary.

For decades, precision weighing lysimeters have been the standard for the direct measurement of ET. If lysimeters are not available, the Bowen ratio method is often used as an alternative to lysimetric measurements (Moran et al., 1989; Kustas et al., 1999; Devitt et al., 1998; Dugas et al., 1998; Prueger et al., 1997; Cellier and Olioso, 1993).

Although the theory for this method has been known for a long time (Bowen, 1926), its practical application has only been possible in recent decades, as adequate instrumentation has been developed. This method is based on the theory that one–dimensional fluxes of sensible and latent heat can be described in terms of flux–gradient relationships (Tanner, 1988):

$$H = \rho C_p K_h\ (\Delta T/\Delta z) \quad (1)$$

$$LE = (\lambda \rho \varepsilon K_w/P)(\Delta e/\Delta z) \quad (2)$$

where

H = sensible heat flux from the surface (W m^{-2})
LE = latent heat flux from the surface (W m^{-2})
ρ = air density (kg m^{-3})
C_p = specific heat of air at constant pressure (J kg^{-1} °C^{-1})
T = air temperature (°C)
z = height of measurement (m)
λ = latent heat of vaporization (J kg^{-1})
ε = ratio of the molecular weight of water to that of dry air (0.622)
P = atmospheric pressure (kPa)
e = vapor pressure (kPa)
K_h = eddy diffusivity for heat (m^2 s^{-1})
K_w = eddy diffusivity for water vapor (m^2 s^{-1}).

Bowen (1926) expressed the Bowen ratio (β) as:

$$\beta = H/LE \quad (3)$$

Substituting equations 1 and 2 into equation 3, and assuming $K_h = K_w$ (Verma et al., 1978; Cellier and Brunet, 1992), β can be obtained from (Bowen, 1926):

$$\beta = \gamma(\Delta T/\Delta e) \quad (4)$$

where $\gamma = (C_p P/\varepsilon\lambda)$ is the psychrometric constant (kPa °C^{-1}), and ΔT and Δe are obtained by measuring air temperature and vapor pressure or dew point at two heights above the top of the canopy, within the boundary layer.

The one–dimensional surface energy balance equation is as follows:

$$R_n - G = H + LE \quad (5)$$

where

R_n = net radiation (W m^{-2})
G = soil heat flux (W m^{-2}).

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All terms in this equation can be either positive or negative. The sign convention used in this study is that positive R_n values supply energy to the surface, while positive values of all the other terms remove energy from the surface (Allen et al., 1998).

Combining equations 3 and 5 results in the following equation to calculate LE from Bowen ratio data (Bowen, 1926):

$$LE = (R_n - G)/(1 + \beta) \qquad (6)$$

Because of the variety of measurements required for the application of this method, the danger of obtaining erroneous data is always present (Perez et al., 1999; Todd et al., 2000). Erroneous data can be obtained for different reasons, including limitation in the accuracy of the instruments, instrument malfunction, instrument installation problems, limitation of the method itself under certain conditions, data logger precision and programming problems, and human errors, among others.

Many researchers, for instance, have reported poor results with the Bowen ratio method under advective conditions (Fritschen, 1965; McIlroy, 1971; Blad and Rosenberg, 1974; Angus and Watts, 1984; Pruitt et al., 1987; Tanner et al., 1987; Todd et al., 2000). Ohmura (1982) warned against the possibility of obtaining erroneous results under certain conditions, and proposed some guidelines to validate data. Allen et al. (1994) encountered significant problems with spider web contamination on non–aspirated thermocouples affecting the temperature measurements. Allen (1996) discussed the identification of problems associated with bird droppings and dust affecting the quality of net radiation data.

Erroneous data can result if air temperature and dew point measurements are not made within the boundary layer for a particular surface (Angus and Watts, 1984; Tanner, 1988; Heilman et al., 1989). Errors can also arise if the assumption of equality between the eddy diffusivities for heat and water vapor is not met (Verma et al., 1978; Blad and Rosenberg, 1974; Cellier and Brunet, 1992; Laubach et al., 1994).

Obtaining valid Bowen ratio data requires careful instrument siting, installation, and on–site supervision. Bowen ratio measurements, however, are often made in remote places where daily supervision is not possible. In addition, since data are automatically collected and stored in short time steps (such as every 20 min), a large data set is collected in just a few days. Assuring data quality is then a challenging task, unless the collected data can be validated with reliable standard methods.

The purpose of this study was to develop guidelines for detecting erroneous Bowen ratio data and to illustrate the application of these guidelines by comparing Bowen ratio and lysimeter data collected for grass and alfalfa in southern Idaho.

METHODS

Bowen ratio and lysimeter data were collected on a clipped grass field (130 × 210 m) and an alfalfa field (147 × 170 m) at Kimberly, Idaho, from June to October of 1991. The alfalfa field was furrow irrigated, and the grass field was flood irrigated. The fields were within a large, nearly flat, irrigated area. A non–irrigated sagebrush–grass rangeland began about 50 km west of the fields and extended for hundreds of kilometers. Therefore, the prevailing western winds could transport dry air from the non–irrigated zone, supplying advective heat to the study area.

Bowen ratio measurements were made over the alfalfa field from day of year (DOY) 182 to 213 and from DOY 231 to 267. Measurements over the grass field were made from DOY 213 to 231 and from DOY 267 to 285. Measurements were made using a Model 023A Bowen ratio system (Campbell Scientific, Inc., Logan, Utah), previously described in detail by Tanner et al. (1987). The system used a single cooled–mirror hygrometer (Model Dew–10, General Eastern Corp., Watertown, Mass.) to measure the dew point from air drawn from two different heights. The resolution of the dew point measurement was ±0.003°C. The limitation of the system, however, was the stability of the hygrometer, which was approximately 0.05°C, yielding a vapor pressure resolution of ±0.01 kPa. The air temperature was measured at two heights with chromel–constantan thermocouples (76 μm) with two parallel junctions at each height. Although temperature was derived from a differential voltage measurement, which had no sensor offset error, its resolution was limited by the resolution of the data logger (0.006°C).

Net radiation was measured using a REBS Q*5 net radiometer (Radiation and Energy Balance Systems, Inc., Seattle, Wash.). The REBS Q*5 net radiometer was cross–calibrated with a Swissteco net radiometer (Oberriet, Switzerland) over a grass surface for a period of four days, which included cloudy and clear–sky conditions. The REBS Q*5 produced higher R_n values when $R_n < 0$ and $R_n > 300$ W m^{-2}. Good agreement between the two sensors was found for R_n values between 0 and 300 W m^{-2}. The R_n readings from the REBS Q*5 sensor were then adjusted by developing separate linear regressions for each range of R_n values ($R_n \leq 0$, $0 < R_n < 300$, and $R_n \geq 300$). The set of three equations resulted in a combined $r^2 = 0.999$.

Soil heat flux was calculated following Hanks and Ashcroft (1980) from measurements obtained using two HFT3 soil heat flux plates (Campbell Scientific, Inc., Logan, Utah) and four soil thermocouples. Each soil heat flux plate was placed at a depth of 0.08 m below the soil surface. Two soil thermocouples, constructed of copper–constantan wire, were installed in close proximity to each soil heat flux plate at depths of 0.02 m and 0.06 m below the soil surface. A 21X Micrologger (Campbell Scientific, Inc., Logan, Utah) was used to sample the sensors and store 20–min averages. From the 20–min averages, fluxes were then calculated with equations 4–6. Procedures given by Allen et al. (1989) were used to calculate γ and e.

The Bowen ratio system was placed close to the eastern edge of the field, providing a 150 m fetch with westerly winds. The Bowen ratio system was closely supervised, and general maintenance was provided at least once a week. Maintenance included cleaning and adjusting the cooled mirror, cleaning the thermocouples, if needed, and changing the air intake filters. Servicing the net radiometer included cleaning the domes, checking the desiccant, and making sure it was properly leveled. In addition, the heights of the lower and upper Bowen ratio arms were adjusted as needed, in response to increased crop height, as shown in table 1.

A weighing lysimeter was located close to the center of each field (previously described by Wright and Jensen, 1972, and Wright, 1982), which recorded mass changes every 10 min using a CR7 Measurement and Control System

Table 1. Adjustment in heights of the lower and upper Bowen ratio arms for different periods during the 1991 study.

DOY	Crop	Crop Height (m)	Measurement Height above Soil Surface (m)	
			Lower Arm	Upper Arm
182–189	Alfalfa	0.10–0.22	0.30	1.09
189–196	Alfalfa	0.22–0.38	0.74	1.32
196–205	Alfalfa	0.38–0.58	0.84	1.42
205–213	Alfalfa	0.58–0.75	1.00	1.50
213–231	Grass	0.11–0.19	0.56	1.46
231–247	Alfalfa	0.28–0.47	0.72	1.53
247–267	Alfalfa	0.47–0.58	0.87	1.53
267–270	Grass	0.11–0.15	0.54	1.41
270–285	Grass	0.15–0.23	0.41	1.09

(Campbell Scientific, Inc., Logan, Utah). To allow comparison between the lysimeter and Bowen ratio data, the data logger clocks between the two systems were synchronized. In addition, the mass changes recorded by the lysimeters during consecutive 20–min periods were transformed to units of W m^{-2} using the average latent heat of vaporization for that period. Latent heat of vaporization was calculated using the average of the air temperatures recorded at the lower and upper Bowen ratio arms.

In addition to the Bowen ratio and lysimeter measurements, solar radiation was measured using an Eppley pyranometer (The Eppley Laboratory, Inc., Newport, R.I.). Wind direction was measured at a height of 4 m using a Gill microvane (Gill Instruments, Ltd., Lymington, Hampshire, U.K.). In addition, plant height (*h*) and soil moisture were measured approximately every three days. Soil moisture was determined using the gravimetric method, from samples taken from a depth of 0 to 0.1 m.

Results and Discussion

Net Radiation

To detect errors in R_n data, Allen (1996) suggested comparing the measurements with R_n computed using measured solar radiation, air temperature, and vapor pressure. An equation to estimate daily R_n values has been developed by Brunt (1932), Brunt (1952), and Wright (1982), which can be modified to calculate daytime R_n for hourly or shorter periods as:

$$R_n = [(1 - \alpha)\, R_s - \sigma T_k^4\, (a_1 - 0.14 e_a^{1/2})\, \{a(R_s/R_{so}) - b\}] \quad (7)$$

where

R_n = net radiation (W m^{-2})
α = albedo (dimensionless)
R_s = solar radiation (W m^{-2})
σ = Stefan–Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4})
T_k = air temperature (K)
e_a = actual vapor pressure (kPa)
R_{so} = clear sky shortwave radiation (R_s with no clouds)
a, a_1, b = empirical coefficients.

Procedures to calculate a, a_1, and b for grass and alfalfa references were described by Wright (1982), Allen et al. (1989), and Jensen et al. (1990). Allen et al. (1998) and EWRI (2001) recommended using $a_1 = 0.34$, $a = 1.35$, and $b = 0.35$. Procedures to estimate R_{so} for hourly or shorter periods can be obtained from EWRI (2001).

Before calculating the R_n estimates using this equation, Allen (1996) recommended validating the integrity of the R_s data. Guidelines for validating R_s data have been proposed by Allen et al. (1998) and EWRI (2001). Under clear–sky conditions, plotting calculated R_n against measured R_n should result in a linear relationship with little scatter. This relationship, however, should not necessarily be expected to follow the 1:1 line for at least three reasons. One reason is that equation 7 contains empirical factors that have been calibrated to obtain daily averages rather than diurnal variations in R_n values. The second relates to the variation of albedo values due to diurnal and seasonal changes in solar angle (Wright, 1982; Dong et al., 1992) and cover conditions (Weiss, 1982; Brest and Goward, 1987; Irons et al., 1988; Ranson and Irons, 1991). The third reason has to do with differences in the measured R_n values due to the type and calibration of the net radiometer used, as shown by Kustas et al. (1998).

Although equation 7 could not be used to assure proper calibration of the R_n sensor, it could be used to ascertain the consistency of R_n measurements. Lack of consistency could result from sensor malfunction; accumulation of dust, mud, or salt; bird droppings or scratching on the domes; moisture condensation inside the domes; or lack of levelness of the R_n sensor or pyranometer (Allen, 1996). In addition to these problems, we have observed birds poking and breaking the upper dome of the REBS types of net radiometers, and insects laying eggs on the lower dome, which will result in faulty data.

Faulty data can be detected by establishing a confidence interval to compare the measured with the calculated R_n data (fig. 1). The width of this interval will mainly depend on how closely albedo estimates used in the calculations match real values. Roughly 95% of the points should fall within the regression estimates (R_n^) plus or minus twice the standard error of estimate (SEE). Data outside this confident interval, however, should not be routinely rejected, since this would mean that 5% of the data will be consistently rejected, but they should be reviewed carefully. This procedure allowed us to detect faulty R_n data due mainly to dust accumulation on the net radiometer domes and moisture condensation inside the domes.

Soil Heat Flux

Assessing the validity of G is a difficult task since there is no universally accepted equation to estimate diurnal variation of G values for different surfaces. Existing equations are empirical and, therefore, are specific for each crop and site. Most of these empirical equations have been developed by remote sensing researchers to estimate G values around solar noon, usually as a function of R_n and some measure of crop cover, such as leaf area index, plant height, or a vegetation index derived from remote sensing data.

Equations for different crops have been given by Choudhury et al. (1987), Clothier et al. (1986), Gutierrez and Meinzer (1994), Sene (1994), Moran et al. (1989), and Reicosky et al. (1994), among others. These equations are developed based on the observation that the G/R_n ratio calculated near noontime decreases linearly with increasing crop cover. For grass, which always has a complete cover, a fixed G/R_n ratio of around 0.1 is considered adequate by some researchers for daytime averages (Allen et al., 1998).

None of the previously developed equations, however, performed well for our site. Figure 2 shows the near–noon

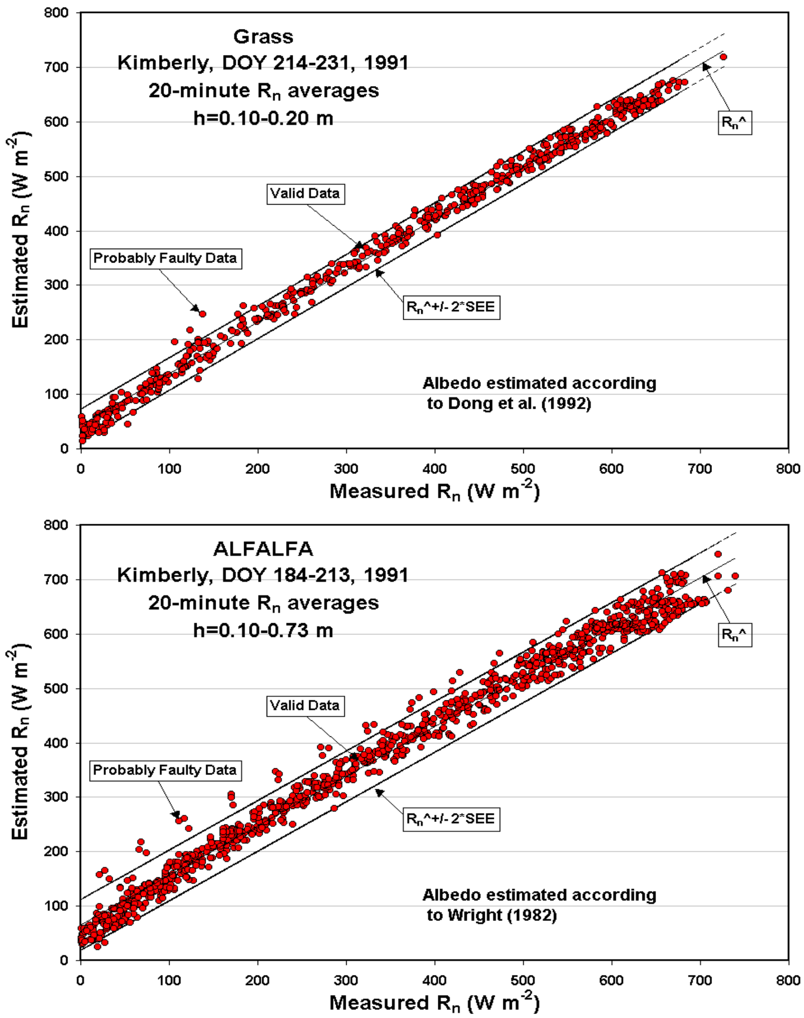


Figure 1. Confidence intervals for net radiation (R_n) data obtained over alfalfa and grass (*h* = plant height). Values of T_k and e_a in equation 7 are the average of measurements of the two Bowen ratio arms.

(Local Standard Time) G/R_n ratios as a function of plant height for alfalfa and grass measured at the Kimberly site. For alfalfa, it shows the expected linear pattern. For grass, since plant growth did not result in additional crop cover, the linearly decreasing pattern was not observed. Figure 2, however, does show a $G/R_n \approx 0.1$ for 0.12 m clipped grass.

If locally calibrated equations for the given crop are available, then they could be used to validate G data. However, one should bear in mind that these equations are not very precise and that measured G values change significantly with changes in solar angle (diurnal and seasonal), crop cover, soil moisture, soil type, and net radiation.

Extremely Inaccurate LE Fluxes

When $\beta \approx -1$, the LE fluxes calculated using equation 6 become unreasonable. This condition is frequently encountered during sunrise and sunset, when $(R_n - G) \approx 0$ (Fritschen, 1965), and with intense advection or precipitation (Ohmura, 1982). The condition has also been observed at midnight and midday under desert conditions, where LE fluxes are small (Malek et al., 1987), and at midday and early afternoon, under cloudy conditions (Pruitt et al., 1987).

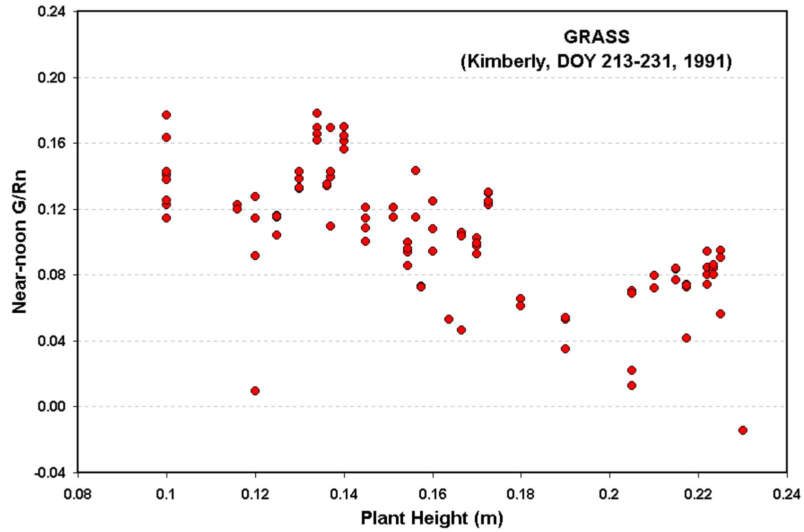
To address this problem, Ohmura (1982) proposed that β approaches –1 only when the temperature gradient falls within the range defined by the following inequality:

$$\{-(\Delta e/\gamma) - 2[(E_e/\gamma) + E_T]\} < \Delta T < \{-(\Delta e/\gamma) + 2[(E_e/\gamma) + E_T]\} \qquad (8)$$

where E_e and E_T are the resolution of the vapor pressure and temperature measurement, respectively, in the same units as *e* and T. Cellier and Brunet (1992), on the other hand, arguing that this condition mostly occurs during nighttime, when the accuracy of the Bowen ratio method is also low, proposed rejecting data when $R_n < 20$ W m^{-2}, which will reject all nighttime data. Tanner et al. (1987), however, proposed excluding only data when $-1.25 < \beta < -0.75$.

Spikes in the calculated LE fluxes in the alfalfa field when $\beta \approx -1$ are shown in figure 3. Rejecting data when $R_n < 20$ W m^{-2} (Cellier and Brunet, 1992) was not advisable in this case, since nighttime LE fluxes can be significant under the advective conditions (Malek, 1992).

The procedure proposed by Tanner et al. (1987) is a simple and effective method to address this problem, and it is therefore recommended. Figure 4 compares lysimeter and Bowen ratio LE fluxes, covering a 16–day period, after filtering Bowen ratio data when $-1.25 < \beta < -0.75$ (Tanner et al., 1987). Extremely inaccurate Bowen ratio LE fluxes were effectively rejected. Figure 4, however, shows a considerable number of outliers, indicating that other problems, which were not detected by this procedure, remained. Similar



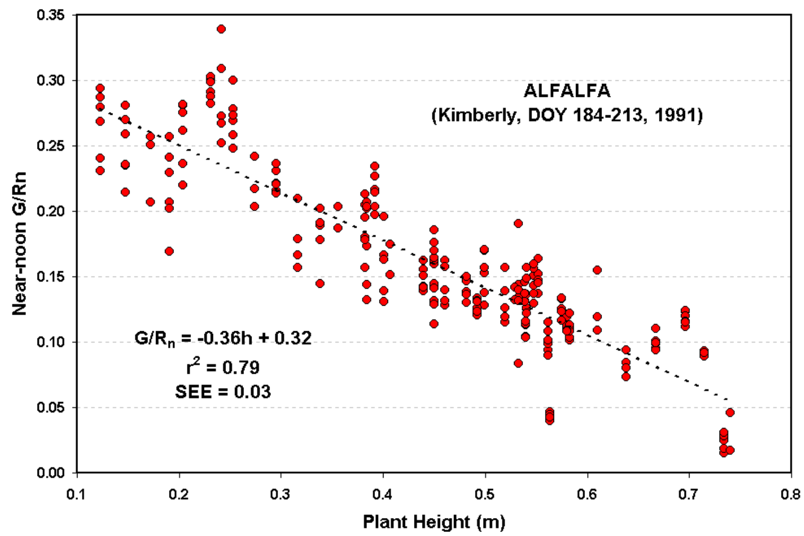


Figure 2. Near–noon G/R_n ratios as a function of plant height (*h*) for grass and alfalfa. Points represent 20–min averages collected between 11:00 and 14:00, Local Standard Time.

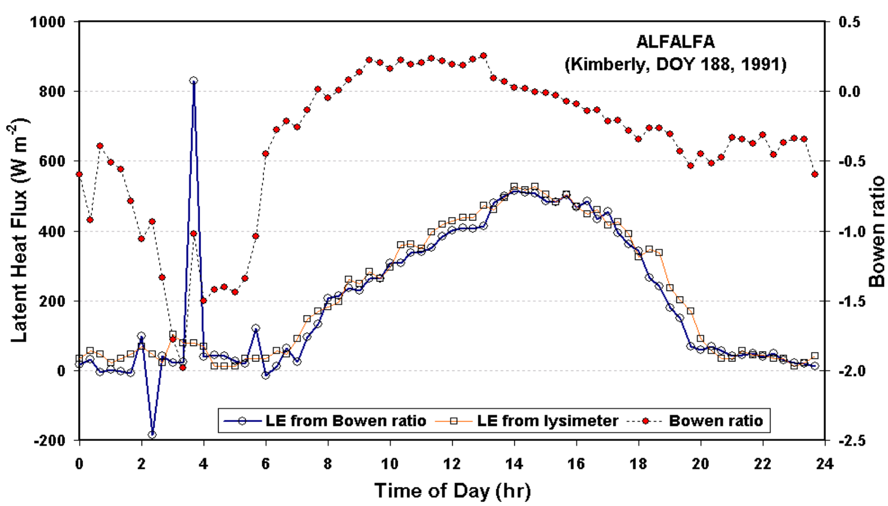


Figure 3. Similarity between Bowen ratio and lysimeter latent heat fluxes (LE), except when β ≈ –1.

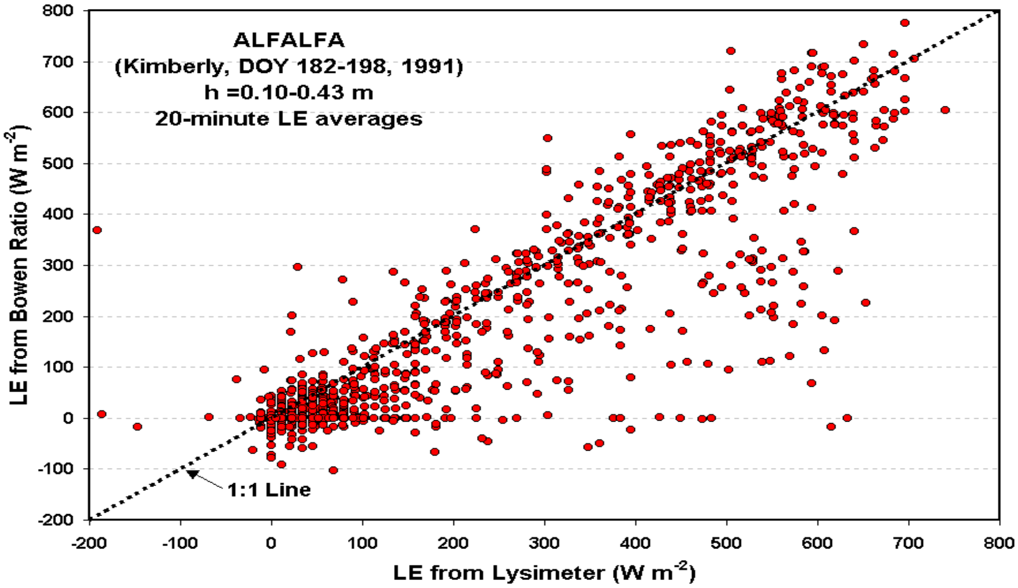


Figure 4. Comparison of Bowen ratio and lysimeter latent heat fluxes (LE) after excluding data when –1.25 < β < –0.75 (*h* = plant height).

results were obtained using equation 8, but it is a more complex procedure.

Fluxes with the Wrong Sign

Ohmura (1982) suggested that faulty Bowen ratio measurements could sometimes result in fluxes with the wrong sign and indicated that valid data should meet the following inequalities:

If $(R_n - G) > 0$, then $\lambda(\Delta e + \gamma\Delta T) > 0$ or $\Delta T > -\Delta e/\gamma$ (9)

If $(R_n - G) < 0$, then $\lambda(\Delta e + \gamma\Delta T) < 0$ or $\Delta T < -\Delta e/\gamma$ (10)

A simpler inequality than equations 9 and 10 that can be applied regardless of the sign of $(R_n - G)$ is:

$$\lambda(\Delta e + \gamma\Delta T)(R_n - G) > 0 \quad (11)$$

The application of equation 11 (multiplying the results by 10^{-6} to obtain a reasonable range of values) is shown in figure 5. Using this procedure, we were able to visually detect faulty data obtained during DOY 190–194. During this time, the switch that controls the thermoelectric cooler that contains the cooled mirror of the Bowen ratio system used in this study was inadvertently left in the "balance" position, instead of the "operate" position, after the mirror was cleaned and adjusted. This resulted in erroneous dew point data for that period. Figure 6 shows that rejecting data collected during that period eliminated most of the data outliers previously shown in figure 4. The process not only rejected the negative LE fluxes, but also some erroneous positive ones.

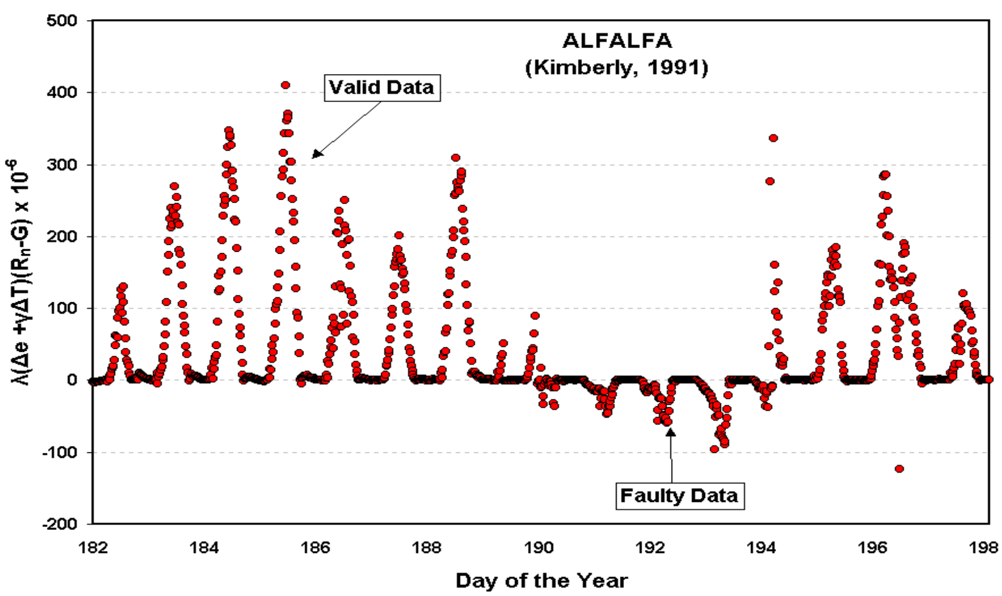


Figure 5. Using equation 11 to detect Bowen ratio data resulting in fluxes with the wrong sign.

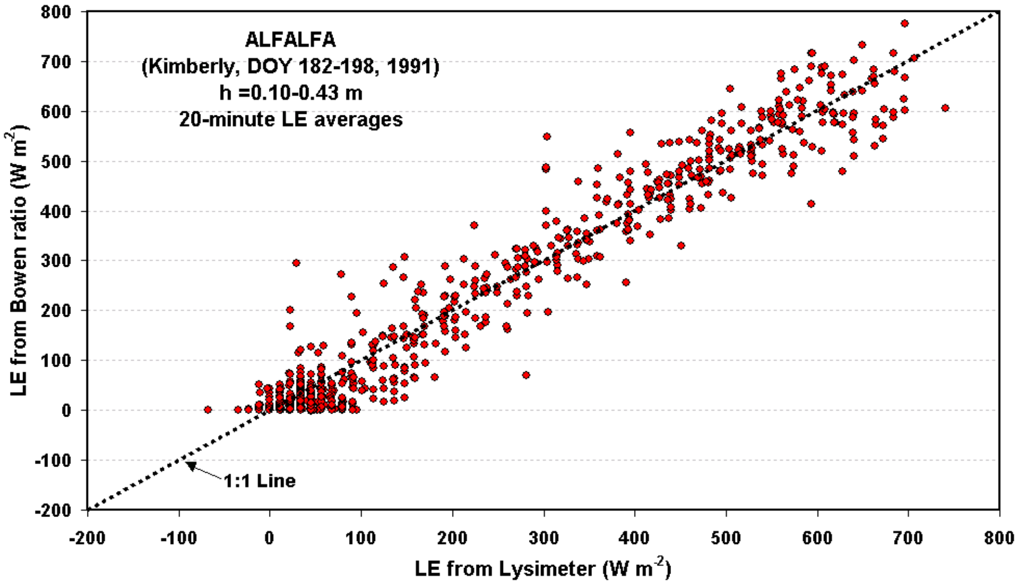


Figure 6. Comparison of Bowen ratio and lysimeter latent heat fluxes (LE) after excluding data when –1.25 < β < –0.75, and rejecting fluxes with the wrong sign using equation 11 (*h* = plant height). Regression analysis resulted in r^2 = 0.95 and SEE = 52 W m^{-2}.

Condensation inside Measuring System

Water sometimes condenses inside the air intake tubes of the type of Bowen ratio system used in this study, biasing the dew point measurements. This most likely occurs close to sunrise and during rainy or dew–fall periods. During such periods, the air temperature (T_a) and the recorded dew point (T_d) reach similar values, as shown in figure 7. For systems using a chilled mirror, valid data should always meet the following condition at both the lower and upper arms:

$$(T_a - T_d) > 0 \qquad (12)$$

Equation (12) works because air warms during daytime as it passes through the intake tubes. If previously condensed water is vaporized by the warmed air, the resulting measured T_d will often exceed the actual T_a measured at the arm. Figure 8 shows the application of this procedure to filter questionable data obtained during rainy periods. Another way to filter out data collected during periods of potential condensation and subsequent evaporation in chilled mirror–based systems is by checking if the temperature and humidity gradients, and therefore the calculated β values, have the correct sign. Since the humidity concentration above the crop canopy decreases with height, the humidity or vapor pressure gradient should be positive, except during rain or dew–fall periods, that is:

$$(e_L - e_U) > 0 \qquad (13)$$

where e_L and e_U are vapor pressures at the lower and upper Bowen ratio arms, respectively. Then, β normally carries the sign of the temperature gradient. The temperature gradient can be positive or negative, depending on whether lapse (unstable) or inversion (stable) conditions exist. The following inequality should hold under conditions of positive latent heat flux:

$$\beta(T_L - T_U) \geq 0 \qquad (14)$$

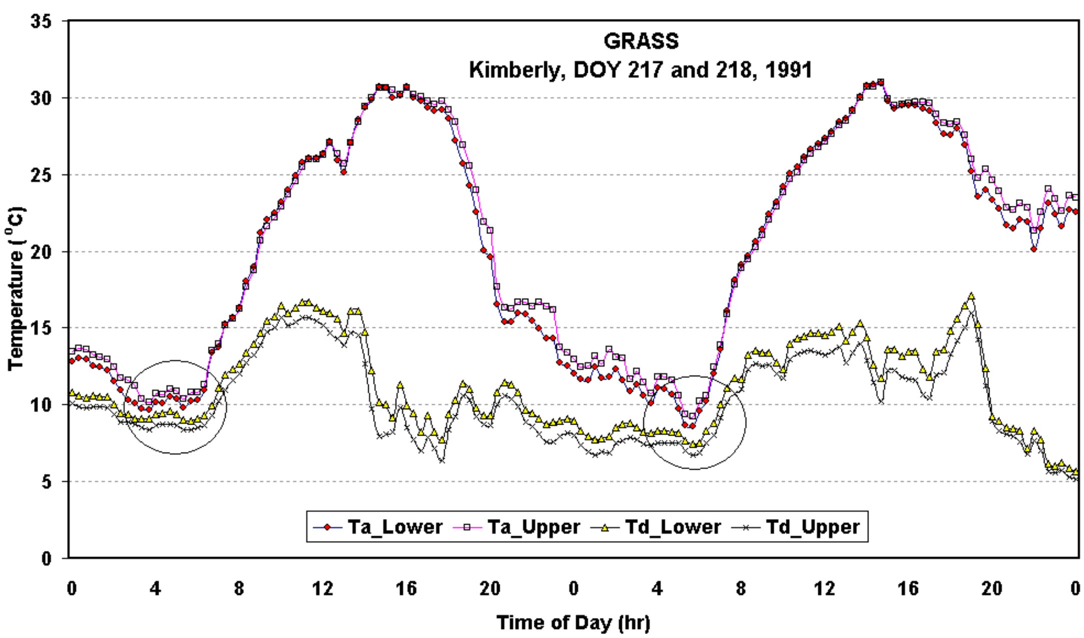


Figure 7. Comparison of air temperature (T_a) and dew point (T_d) at the lower and upper Bowen ratio arms.

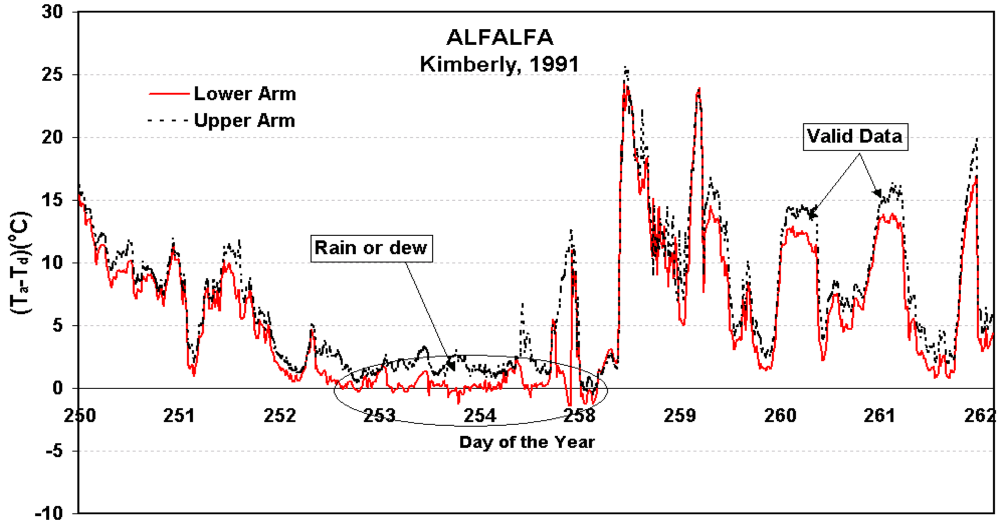


Figure 8. Difference between air temperature (T_a) and dew point (T_d) at both Bowen ratio arms.

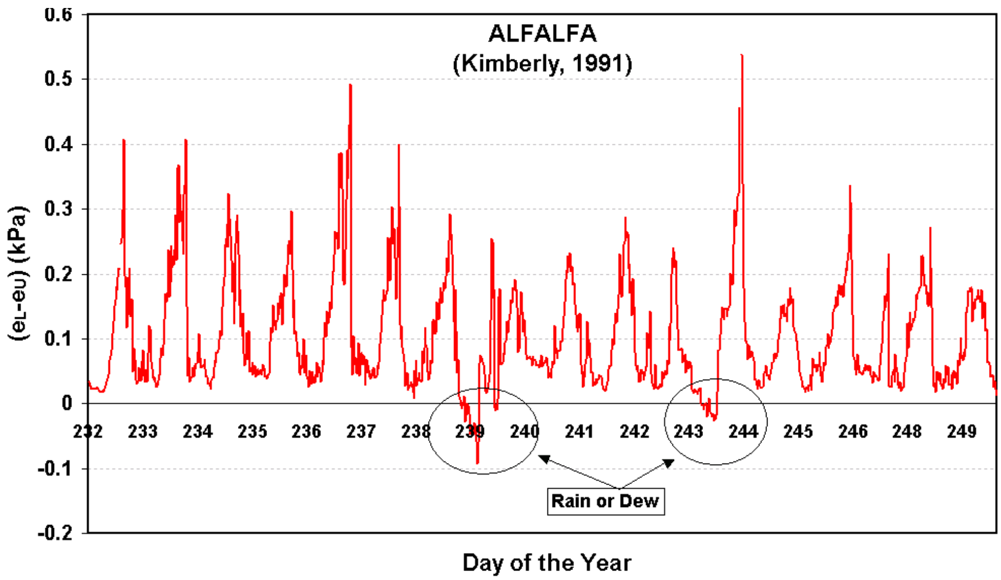


Figure 9. Difference between the vapor pressure measured at the lower (e_L) and upper (e_U) Bowen ratio arms.

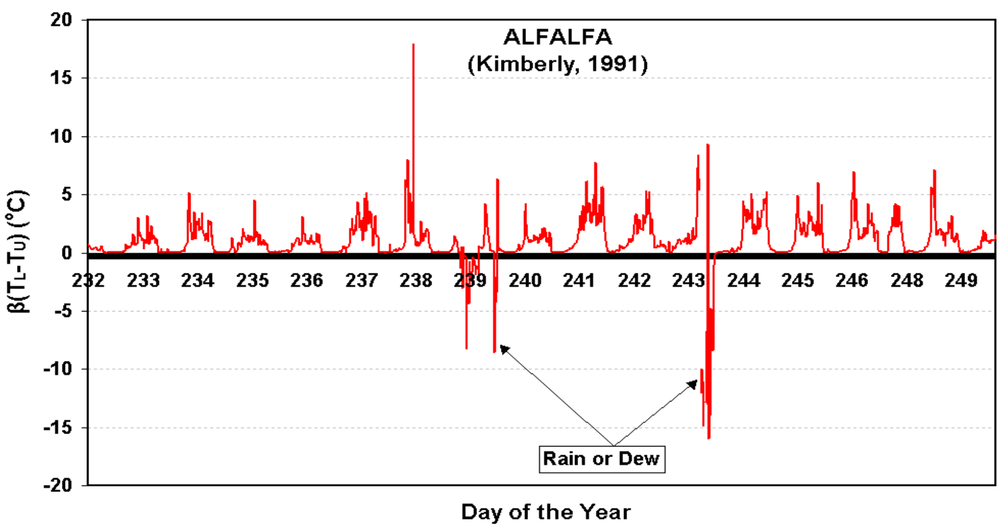


Figure 10. Product of the Bowen ratio (β) and the difference between the temperature at the lower (T_L) and upper (T_U) Bowen ratio arms.

where T_L and T_U are the air temperatures at the lower and upper Bowen ratio arms, respectively. Results of the application of equations 13 and 14 to filter data obtained during rainy or dew–fall periods are shown in figures 9 and 10.

Fetch Requirements

Another important consideration for validating Bowen ratio data is making sure that fetch requirements are properly met. A fetch to height ratio of 100:1 is usually considered adequate, although Heilman et al. (1989) found a ratio as low as 20:1 to be adequate for Bowen ratio measurements. Brutsaert (1982) proposed an equation to calculate minimum required fetch as:

$$X_f = [\{30(Z - d)\}/\{z_{om}^{0.125}\}]^{1.14} \quad (15)$$

where

X_f = minimum fetch distance required to complete boundary layer development (m)
Z = maximum sensor height above the ground (m)
d = zero plane displacement (m)
z_{om} = momentum roughness height of the surface (m).

According to Monteith (1973), d and z_{om} can be estimated as a function of plant height (h) as: $d = 0.63h$ and $z_{om} = 0.13h$. Equation 15 predicts X_f values that are about 14% lower than the usual 100:1 ratio for alfalfa (h = 0.5 m) for measurement heights between 1.5 to 2.0 m. For grass (h = 0.12 m), the X_f values are approximately 5% lower than the 100:1 ratio.

In this study, we calculated a percent of required fetch (PRF) value for every 20–min period as follows:

$$PRF = (X_a/X_f) \times 100 \quad (16)$$

where X_a = actual fetch (m), calculated using the wind direction data, the field dimensions, and the location of the instruments within the field.

Data meeting fetch requirement would then have a PRF ≥ 100%, and those with PRF < 100% should normally be rejected. When PRF ≥ 100%, the system will only measure the fluxes produced by the crop in the measuring field. When PRF < 100%, the measured fluxes represent a mixture of the fluxes in the measuring field and those of adjacent upwind areas.

In our study, however, we found no significant differences for the alfalfa and grass fields, when the 20–min Bowen ratio LE values with PRF > 100% and those with PRF < 100% were separated and each group was compared with the lysimeter data, using a two–sample comparison test. The average PRF when PRF < 100% was 41% and, 157% when PRF > 100%. Results of the analysis performed with the alfalfa data are shown in table 2. Similar results were also obtained with the grass data. Since these fields were within a large irrigated agricultural area, surrounded by other relatively short irrigated crops (sugar beets, wheat, and potatoes), these results may reflect the similarities in surface properties between the alfalfa and grass fields and those of surrounding fields. Despite our results, however, we recommend observing fetch requirements when using the Bowen ratio method.

Table 2. Statistics for the two–sample comparison between Bowen ratio and lysimeter 20–min LE values for alfalfa, separated in two groups of fetch conditions (α = 0.05).

	PRF < 100%		PRF > 100%	
Statistic	Bowen Ratio	Lysimeter	Bowen Ratio	Lysimeter
Means (W m^{-2})	353	355	400	401
No. of observations	465	465	749	749
Pearson corr. coeff.	0.94		0.93	
T	–0.21		–0.083	
t critical one–tail	1.646		1.646	
Conclusion	Not significant		Not significant	

Conclusion

Procedures were developed to assess the integrity of Bowen ratio data measured by cooled mirror–based systems. These procedures were applied to Bowen ratio data collected over alfalfa and grass at Kimberly, Idaho. Performance was evaluated comparing the Bowen ratio data with lysimetric measurements. Our results showed that net radiation data can be screened for validity by comparing measured values to those calculated using an R_n estimating equation, such as one proposed by Wright (1982), with the addition of a confidence interval. Good equations to validate soil heat flux data are lacking. Only empirical equations to estimate G values close to noontime, which have been developed for remote sensing applications, are available for specific situations.

Extremely inaccurate LE fluxes obtained by the Bowen ratio method occurring when $\beta \approx -1$ were easily eliminated by excluding data when $-1.25 < \beta < -0.75$, as proposed by Tanner et al. (1987). Fluxes with the wrong sign can be detected using equation 11. Condensation and subsequent evaporation inside the measuring system can also be a problem in the type of Bowen ratio systems used in this study, in which air was drawn thought a hose using a vacuum pump. Erroneous data resulting from condensation, which is likely to occur during rainy or dew–fall periods, can be detected using equations 12–14. If the rejected values need to be replaced, a method similar to that proposed by Pruitt et al. (1987) could be used.

Another important consideration for Bowen ratio measurements is making sure that fetch requirements are met. In our study, however, fetch conditions did not measurably affect the Bowen ratio LE measurements. This probably resulted because the study site was surrounded by other irrigated fields with surface properties similar to those of the crops under study.

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