CONVERSION BETWEEN EVAPOTRANSPIRATION REFERENCES AND METHODS

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ABSTRACT

Ratios of reference evapotranspiration for alfalfa (ET_r) and for grass (ET_0) are evaluated using measured ET_r and ET_0 from lysimeter systems at Kimberly, Idaho and Bushland, Texas. In addition, ratios are evaluated using estimates by the Kimberly Penman and ASCE Penman-Monteith evapotranspiration methods. An ET reference conversion equation from FAO-56 is also compared.The ASCE-PM and Kimberly Penman methods predict differently for both ET_r and ET_0 so that ratios of ET_r / ET_0 computed from both methods behave differently. Ratios of ET_r / ET_0 from lysimeter measurements averaged 1.15 at both locations.

Key Words: Reference Evapotranspiration, Alfalfa Reference, Grass Reference, ETr, ETo, Kimberly Penman, Penman-Monteith, FAO-56

INTRODUCTION AND BACKGROUND

Evapotranspiration (ET) is commonly predicted for routine engineering, irrigation, and water rights applications using the crop coefficient – reference evapotranspiration approach. Reference evapotranspiration (ET_{ref}) has traditionally been predicted for either of two types of reference crop: grass (ET_0) or alfalfa (ET_r). Each of these reference crops has had various "definitions" or descriptions applied. The grass reference has generally been a cool season variety such as fescue or perennial ryegrass clipped to maintain about 0.08 and 0.15 m height (Doorenbos and Pruitt, 1977). The alfalfa (lucerne) reference has been chiefly applied to varieties typically grown in the U.S. and is measured when the stand is 0.3 to 0.6 m in height (Wright, 1982; Jensen et al., 1990). Both references require sufficient plant density and leaf area to represent conditions of full ground cover and ground shading, with water management conditions that facilitate root extraction and transpiration, and with sufficient fetch of similar vegetation for near equilibrium with the boundary layer.

Two widely used equations for daily (24-h) calculations are the Kimberly Penman (Wright, 1982; 1996) as applied to both alfalfa and grass and ASCE Penman-Monteith (or derivative) (Allen et al, 1989; Jensen et al., 1990; Allen et al, 1998) as applied to both alfalfa and grass. These two equations are the focus of this paper.

Generally, the ET predicted for the alfalfa reference is greater than that for the grass reference because the alfalfa reference definition represents vegetation that is taller and has greater leaf area than does clipped grass. Therefore, the alfalfa reference ET definition reflects larger values for both aerodynamic and surface conductance. Albedo and emissivity of alfalfa and clipped grass are usually similar. The ratios of ET_r to ET_0 vary with weather and climate and may range from 1.05 for humid, calm conditions to 1.2 for semiarid, moderately windy conditions, and to 1.30 for arid, windy conditions.

In 1990, a panel organized by the Food and Agriculture Organization of the United Nations (FAO), in an effort to reduce ambiguity in the definition of the grass reference and to facilitate the calculation of ET_0 using the Penman-Monteith equation, defined a standardized grass reference as "A hypothetical reference crop with an assumed crop height of 0.12 m, a fixed surface resistance of 70 s m^{-1} and an albedo of 0.23." (Smith et al., 1991). The FAO Irrigation

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and Drainage Paper No. 56 implemented this definition within the structure of the Penman-Monteith equation (Allen et al., 1998).

The Technical Committee on Evapotranspiration in Irrigation and Hydrology of the American Society of Civil Engineers (Walter et al., 2000; Allen et al., 2000) has recommended the adoption of two *standardized* reference ET equations: ET_{rs} representing a tall crop (i.e., alfalfa) and ET_{os} representing a short crop (i.e., grass). The ASCE ET_{os} equation is equivalent to the FAO-56 ET_o equation for daily timestep applications.

There is a need to convert between references, especially when crop coefficients (K_c) developed for one are to be used with a different reference type. Two approaches for this conversion are evaluated in this paper. These are to:
1) Use a derived "equation" for predicting the relationship between ET_r and ET_o, for example equation 68 of FAO-56 that varies the ratio as a function of climate .
2) Develop ratios of ET_r/ET_o where either the numerator or denominator is calculated using the specific ET_{ref} equation that is to be used in making subsequent predictions of a specific crop ET (ET_o)and with the other denominator or numerator calculated using the ET_{ref} method that was used in developing the original K_c value.

The strength of approach no. 1 is that ratios of ET_r/ET_o are consistent within variations in climate and calculations of ET_r and ET_o are not required; its weakness is that the ET_r/ET_o ratio predicted may not relate to the underlying ET_{ref} used to develop the original K_c.

A substantial strength of approach no. 2 is that the conversion ratio ET_r/ET_o is based on the same ET_{ref} that was used in developing the original K_c value(s) and is based on the ET_{ref} equation that is to be used in applying the newly converted K_c. Therefore, there are no systematic biases introduced into the converted K_c that are purely an artifact of differences between two equations of the same reference type. A weakness of approach no. 2 is that the ET_{ref} used in developing K_c's in one region or climate may not perform the same in the new region or climate, so that a climatic bias may result. Another weakness is that ratios of ET_r/ET_o developed for the same location and climatic condition may vary according to the reference equation used in developing the K_c's to be converted and the reference equation to be applied at the location or region. Therefore, there is potential for inconsistency among ET_r/ET_o computed for a particular area.

FAO-56 equation 68 follows approach no. 1 for converting crop coefficients for reference type:

$$ET_r / ET_o = 1.2 + 0.58\left(0.04(u_2 - 2) - 0.004(RH_{min} - 45) \right) \quad (1)$$

where u_2 is mean wind speed at 2 m (m s^{-1}) and RH_{min} is daily minimum relative humidity (%). Generally u_2 and RH_{min} are averages for the particular growth stage. For example, at Kimberly, Idaho, $RH_{min} \approx 30\%$ and $u_2 \approx 2.2$ m s^{-1} during the summer months, so that Equation 1 predicts $ET_r/ET_o = 1.24$.

This paper evaluates the above methods for predicting ET_r/ET_o for purposes of conversion of crop coefficients for reference type. Lysimeter measurements of ET_r and ET_o are compared for Kimberly, Idaho and Bushland, Texas to complement ratios of ET_r/ET_o predicted from weather data alone.

PROCEDURE

Equation 1 along with the Kimberly Penman for alfalfa and for grass and the ASCE Penman-Monteith for alflalfa and for grass references were evaluated at two locations where paired measurements were available for both alfalfa and grass reference ET. Each ET_{ref} method was applied as directed in the original publications (Wright, 1982; 1996; Allen et al., 1989, Jensen et al., 1990). Exceptions were that the 1982 Kimberly Penman equation for ET_r was applied using exponentially based wind function coefficients by Wright (1987; Jensen et al., 1990) and the ASCE PM method was applied using net radiation (R_n) computed following FAO-56 and with daily soil heat flux (G) set equal to 0.

Daily, paired measurements of ET_0 and ET_r were available for Kimberly, Idaho and Bushland, Texas USDA-ARS locations. Kimberly lysimeter data were analyzed for 63 days from 1991, and Bushland lysimeter data were analyzed for 21 days in 1998 and 29 days in 1999. The Kimberly lysimeter system and grass and alfalfa crops have been described by Wright (1982; 1996). The Bushland grass lysimeter system was described by Schneider et al., (1998) and Howell et al., (1997; 2000 this proceedings). The larger Bushland weighing lysimeters used for the alfalfa have been described by Howell et al. (1995 and 1997). The grass grown at Kimberly on the lysimeters and field was a 'Fawn' tall fescue planted in 1986 and clipped so as to maintain the height at between 0.09 and 0.18 m, averaging 0.12 m for the days analyzed. The alfalfa grown at Kimberly in 1991 was 'WL-316' planted in 1990 and harvested about each 42 days. Height of lysimeter alfalfa for the days analyzed ranged from 0.34 m to 0.76 m, averaging 0.56 m. The lysimeter grass grown at Bushland was 'Emerald III' tall fescue (consisting of equal fractions of 'Jaguar II', 'Mustang', and 'Rebel II') planted in late 1994 and clipped so as to maintain the height at between 0.11 and 0.24 m, averaging 0.145 m for the days analyzed. The alfalfa grown at Bushland in 1998 and 1999 was 'Pioneer 5454' seeded at 28 kg/ha in late 1995 and harvested about each 40 days. Height of lysimeter alfalfa for the days analyzed ranged from 0.45 m to 0.69 m, averaging 0.57m..

RESULTS

Comparisons between ET equations and lysimeters

Because the ratio ET_r/ET_0 is impacted by the performance of the specific ET_{ref} method, the Kimberly Penman and Penman-Monteith methods are first compared against lysimeter measurements from the two locations. Results are shown in Table 1 for daily timesteps for Kimberly and for Bushland. Standard errors of estimate (SEE) for unadjusted predictions and ratios of predicted to measured ET are listed.

The 1982 form of the Kimberly Penman equation for ET_r performed better than the ASCE PM equation at both Kimberly and at Bushland. The ratio ET_{ref} / ET_{lys} was 1.0 for both methods at Kimberly, but the Kimberly Penman had a lower SEE. The standardized ASCE PM ET_r (height = 0.5 m) performed relatively well at Kimberly with ratio to lysimeter near 1.0. The standardized ET_r method predicted about 10% higher than the lysimeters at Bushland and the 1982 Kimberly ET_r predicted about 6% higher than lysimeters at Bushland,(Table1).

The ASCE PM method was applied in the standardized form for ET_r and ET_0 (Walter et al, 2000) where vegetation height (h) was fixed at h= 0.5 m for alfalfa and h = 0.12 m for grass. The standardized ASCE PM method predicted about 11% lower than measured ET for grass at Kimberly but only about 1% lower than the grassed lysimeter at Bushland (Table 1). The 1996 Kimberly Penman predicted ET_0 with substantially less error for Kimberly (SEE = 0.52 mm/day vs. 0.80mm/day for the standardized ASCE Penman-Monteith and with slightly less error at Bushland even though the Kimberly Penman overpredicted ET_0 at Bushland more than did the standardized ASCE P-M equation (Table 1).

The ASCE PM and the 1996 Kimberly Penman equation for ET_0 predicted about 10% and 20% higher than the grassed lysimeter at Bushland for 1998 data, respectively (not shown in Table 1), and they predicted
about 12% lower and 4% higher than the grassed lysimeter for 1999 data. The cause of the different behavior of the lysimeter between the two years is not clear, but 1998 was an extremely

dry and windy summer at Bushland (Howell et al., 2000) while 1999 was a more typical summer with the smaller grass fetch perhaps affecting the Bushland grass ET in 1998 to a greater extent. The lower ET_0 during 1998 relative to predicted ET_0 may have been partially caused by some stomatal closure induced by the extreme dryness of the advective environment. These conditions may not have been conducive for representing the hypothetical grass reference. The cooler and less advective conditions of 1999 and reduced impact on stomatal conductance may have

Table 1. Unadjusted standard errors of estimate and ratios at Kimberly and Bushland for ET_0 and ET_r methods vs. lysimeter measurements.

Method	Ref. Type	Kimberly (1991)		Bushland (1998, 1999)	
		SEE. mm/d	Ratio	SEE, mm/d	Ratio
1982 Kimberly Penman	ET_r	0.46	1.00	1.15*	1.06*
ASCE PM, h=0.5, rs=45 s/m	ET_r	0.65	1.00	1.65*	1.10*
1996 Kimberly Penman, by REF-ET, Rn from Wright 1982), G=0	ET_0	0.52	0.99	1.18	1.08
ASCE PM, h=0.12, rs=70 s/m	ET_0	0.80	0.89	1.29*	0.99*
ASCE PM, h=0.18, rs=50 s/m	ET_0	0.45	0.99	1.87*	1.14*
ASCE PM, h=0.12, rs=50 s/m	ET_0	0.52	0.95	1.55*	1.09*
ASCE PM, h=0.12, rs=30 s/m	ET_0	0.40	1.01	---	---

*measured R_n over alfalfa

facilitated the closer agreement between measured and predicted noted for 1999. Alfalfa was less impacted by the advective conditions of 1998. Alfalfa stomata tend to remain open unless the plant becomes substantially stressed. This behavior is partially facilitated by the more extensive root system of alfalfa relative to grass. The reference ET equations were considered to represent the advective conditions at Bushland quite well (Howell, 1998)Various combinations of values for h and surface resistance, r_s, in the ASCE PM method were evaluated for ET_0 at Kimberly in order to match lysimeter measurements(see Table 1). Different combinations of h and r_s were able to reproduce lysimeter measurements, for example h = 0.18 m and r_s = 50 s m^{-1} and h = 0.12 m and r_s = 30 s m^{-1}. Even though grass height averaged 0.12 m at Kimberly, the relatively short fetch of grass (about 100 m) surrounded by somewhat rougher agricultural crops may increase turbulence and therefore eddy transport above the grassed surface. Even with h = 0.18 m, a value r_s = 50 s m^{-1} was required to fit lysimeter measurements as opposed to the 70 s m^{-1} used with FAO-56 and ASCE standardardizations (Walter et al., 2000). When h=0.12 m was used to reflect observed h, r_s had to be reduced to 30 s m^{-1} in the daily application to match lysimeter measurements. The SEE was lowest for the combination of h=0.12 m and r_s = 30 s m^{-1}. However a value of r_s as low as 30 s m^{-1} may be difficult to justify compared to observations of r_s from some other studies. The clipped fescue grass grown at Kimberly was noted for its erect, leafy structure. Irrigation at Kimberly was by surface irrigation on about a 2 week schedule for grass and about a 4 week schedule for alfalfa.When h = 0.12 m and r_s = 50 s m^{-1} was used for grass at Kimberly, the ASCE PM method underpredicted the lysimeter by 5%. The value r_s = 50 s m^{-1} may represent a more "middle ground" estimate for r_s for the fescue grown at Kimberly The ASCE PM with r_s = 50 s m^{-1} predicted slightly lower grass ET than the lysimeter at Bushland, on average, for 1999 but predicted substantially higher than the lysimeter for 1998 for the reasons provided earlier. The average prediction for both years combined was 9% higher than the lysimeter with $r_s = 50\ s\ m^{-1}$ (Table 1). Because the explanations for the behavior difference in the Bushland grassed lysimeter between 1998 and 1999 are more or less speculative at this time, it is difficult to conclude that one year was a better representation of reference conditions than the other. Therefore it is difficult to make a recommendation for the best value to use for r_s for grass ET_0 (i.e., $r_s = 50\ s\ m^{-1}$ or $r_s = 70\ s\ m^{-1}$).

It appears that $r_s = 45\ s\ m^{-1}$ reproduces alfalfa ET_r adequately at both locations with perhaps some overprediction at Bushland. The SEE by the PM equation was greater than for the Kimberly Penman.

Ratios of ET_r to ET_0

Ratios of daily measured ET_r to measured ET_0 for Kimberly for the three growth periods during 1991 having full cover averaged 1.16, 1.12 and 1.17 and averaged 1.15 for the year. These ratios may appear to be somewhat lower than previously expected for the semiarid climate of Kimberly, based on some literature, and reflect the high ET rates measured from the grassed lysimeter. The standard deviation of measured ET_r/ET_0 over the 130 day period of measurement was 0.17. Ratios of measured ET_r to measured ET_0 for Bushland for conditions of full cover averaged 1.15 for 1999 data. Standard deviations for the 160 day period was 0.12.The daily values for ET_r/ET_0 from measurements at Kimberly compared with ratios of ET_r/ET_0 computed using the 1982 / 1996 Kimberly Penman and with ratios computed from ET_r and ET_0 from the ASCE PM equation are shown in Table 2. The day to day variation in ET_r/ET_0 was substantially greater for ET_r/ET_0 based on lysimeter measurements as compared to ratios based on ET equations (Table 2), with the standard deviation for the ratio based on the lysimeter equaling 0.17 for the data period. Averages for ratios for the complete growing season and year are summarized in Table 2 for Kimberly and for Bushland. Also shown in Table 2 are ET_r/ET_0 ratios as predicted by Eq. 1 (FAO-56 Eq. 68). These latter ratios do not vary substantially from day to day, even as compared to ratios based on lysimeter measurements. The standard deviation across the lysimeter period was only 0.02 at Kimberly and 0.04 at Bushland for Eq. 1.

The variation in ET_r/ET_0 from lysimeter measurements for Kimberly compared relatively closely with ratios of ET_r/ET_0 based on the Kimberly Penman for the same periods, in regard to magnitude (Table 2) and day to day variation, even though they are for different years. The ratios of ET_r/ET_0 based on the Kimberly Penman exhibit less variation during the middle and late portions of the growing season (June – Sept) than they do during the nongrowing season periods (Nov. – March) and the early part of the growing season.

Ratios of ET_r/ET_0 based on equations vary substantially from day to day and during the course of a year. but do not vary a great deal from year to year as shown for Kimberly in Figure 1a for the ASCE PM method. Ratios tend to increase during winter months. The standard deviations of monthly ET_r/ET_0 between years averaged 0.014 for the Kimberly Penman, 0.023 for the Penman-Monteith method and 0.009 for Eq. 1. Therefore, the average computed ratio of ET_r/ET_0 for a specific month should not be expected to vary by more than about 0.03 from year to year for the Kimberly Penman and by 0.05 for the ASCE Penman-Monteith method.

Figure 1b shows average ET_r/ET_0 by month for the lysimeter data set at Bushland based on the lysimeter and ET_{ref} equations and Eq. 1. Figures 1c and 1d show monthly ratios based on various combinations of ET_{ref} equations for Kimberly and Bushland using multiple years of data. The "82KPen ET_r / PM ET_0" ratios represent the type of conversion that would be done using approach 2 (see introduction) if alfalfa based coefficients developed using the Kimberly Penman equation were to be converted to grass based coefficients for use with the ASCE or FAO PM equation, or vice versa. The difference between sets of ET_r/ET_0 are substantial, indicating perhaps the need to apply approach 2 for converting K_c's as well as the need to compute ET_r/ET_0 ratios by month. The trends exhibited in ET_r/ET_0 ratios are similar between Kimberly and Bushland, although the ratios at Bushland average about 0.1 higher for the ASCE-PM equation. The magnitudes of ratios are similar between sites for the Kimberly Penman equation and are somewhat similar for the ratio of ET_r by the Kimberly Penman to ET_0 by the ASCE-PM. The large ratios of 1.42 and 1.44 for Bushland for ET_r/ET_0 by the standardized ASCE-PM equation reflect the advective, high wind environment of Bushland. Apparently, the PM equation with aerodynamic roughness and conductance varied to fit the vegetation type is more sensitive to this highly advective condition than is the Kimberly Penman equation.

Ratios of ET_r / ET_0 were additionally computed for the ASCE-PM method where r_s = 50 s/m was used for the ET_0 estimates. Average ratios and standard deviations are listed in Table 2 for the lysimeter data sets for Kimberly and Bushland. The average ET_r/ET_0 ratios came closer to those for the Kimberly Penman and for the lysimeter system, but were still somewhat higher. The large day to day scatter in the measured and computed ET_r/ET_0 ratios is of interest, but is probably not useful for carrying into conversion of K_c's . It is probably best to compute ET_r/ET_0 ratios and to make conversions in K_c either monthly or for each growth stage.

CONCLUSIONS

The Kimberly Penman equation had more consistent predictive accuracy (smaller SEE) for lysimeter measurements of alfalfa at Kimberly, Idaho and at Bushland, Texas. Prediction by the Kimberly Penman was better at Kimberly and similar to the standardized ASCE-PM equation at Bushland. The Bushland lysimeter installation provides a more unbiased opportunity for equation comparison since no Bushland data were used to develop any of the ET methods.

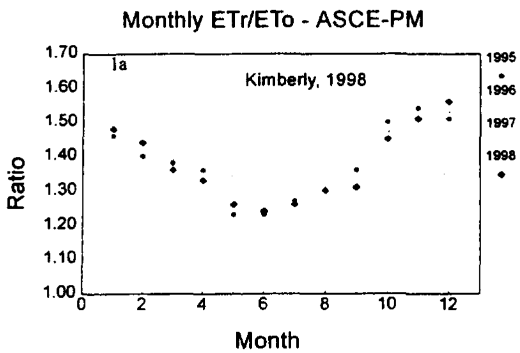
Future work towards development of a standardized form of the Penman-Monteith equation may need to consider reducing the value used for surface resistance from 70sm^{-1} to perhaps 50 s m^{-1} for daily time steps if the intention is to reproduce measurements of ET from clipped fescue at Kimberly and for some periods at Bushland. However, other considerations include maintaining a previously defined hypothetical ET_0 reference recommended by FAO to provide for consistency. This reference definition appears to represent a grassed surface having less stomatal conductance than the clipped fescue grown at Kimberly and in some cases at Bushland. Future measurements of crop ET will help to determine whether grass-based K_c's summarized in FAO-56 and in other publications are best based on the FAO definition for grass reference or if a "stronger" ET_0 reference should be considered.

There is sufficient deviation between ratios of ET_r/ET_0 between reference methods to suggest that approach 2 be used when possible to reduce bias caused by a method. Variation in ratios across the season indicates the need to calculate ratios monthly. Variation between the two locations indicates the need to calculate ratios for the particular region or location. There was some variation among years noted in average monthly ratios. The single equation approach of FAO 56 seems to predict values that are about 3 to 8% higher than the average observed lysimeter ratios and that are higher than ratios obtained using the Kimberly Penman equation and lower than ratios based on the ASCE PM method.

Table 2. Average ratios of ET_r/ET_o at Kimberly and Bushland.

Methods	Kimberly				Bushland			
	Lysimeter Period, 1991		Growing Season*, 1995-98	Annual, 1995-1998	Lysimeter Period, 1999		Growing Season*, 1997-98	Annual, 1997-98
	Ave. Ratio	Std. Dev. of Ratio			Ave. Ratio	Std. Dev. of Ratio		
Lysimeter / Lysimeter	1.15	0.17			1.15	0.12		
1982 Kimberly Penman ET_r / 1996 Kimberly Penman ET_o	1.18	0.05	1.19	1.21	1.16	0.05	1.22	1.26
ASCE PM ET_r / ASCE PM ET_o (standard)	1.29	0.07	1.32	1.34	1.34	0.07	1.42	1.44
ASCE PM ET_r / ASCE PM ET_o (r_s = 50 s/m for ET_o)	1.22	0.06			1.23	0.05		
1982 Kimberly Penman ET_r / ASCE PM ET_o	1.29	0.09	1.28	1.25	1.37	0.17	1.30	1.26
FAO-56 Eqn. 68	1.24	0.02	1.23	1.22	1.26	0.03	1.27	1.27

*Growing season is considered to be April – October for both sites.



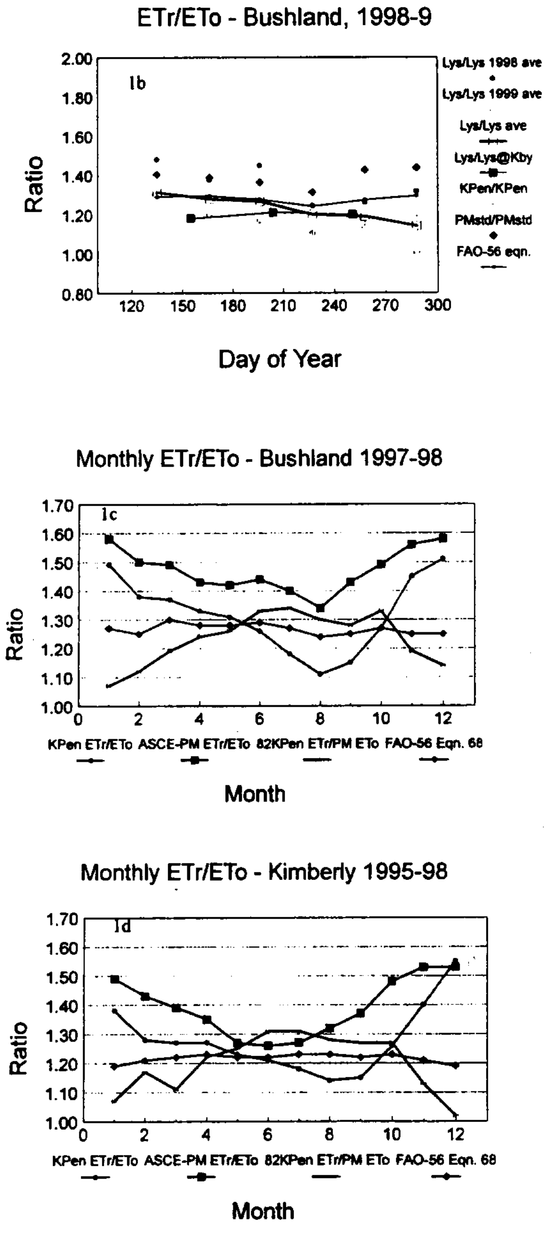


Figure 1. Ratios of ET_r to ET_0 for lysimeter measurements and from equations at Kimberly, 1991 and Bushland, 1998-99.

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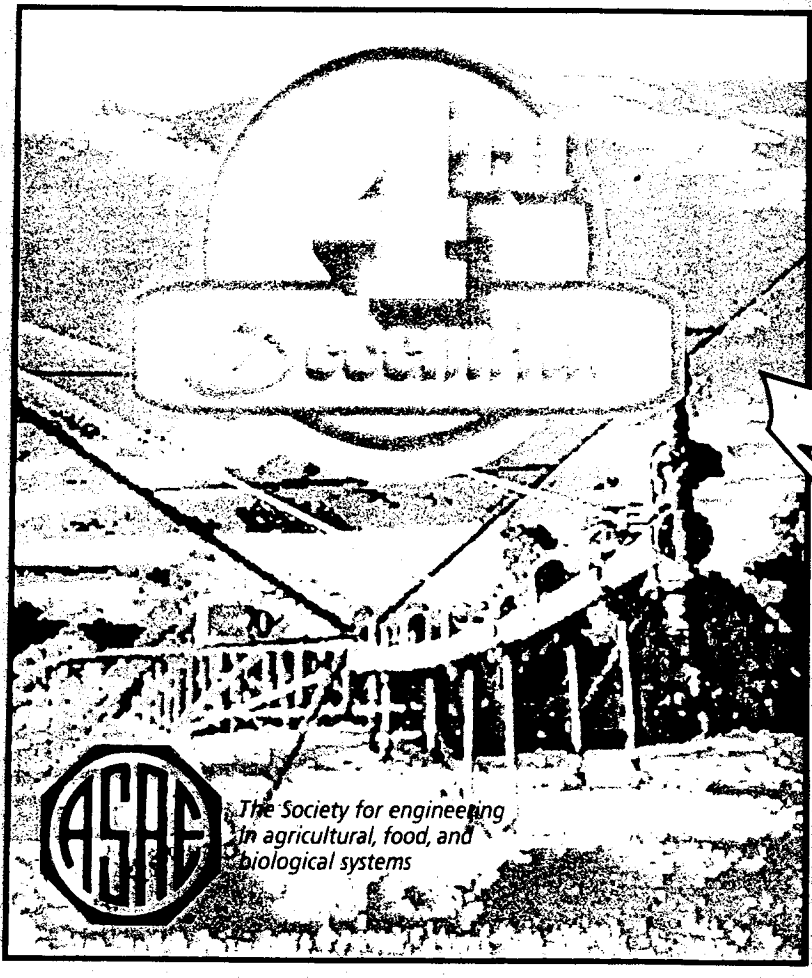

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