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Derivation of Alfalfa and Grass Reference Evapotranspiration

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ABSTRACT

The evapotranspiration (ET) for a specified reference crop characterizes the rate at which water, when readily available within the root zone, is evaporated from the plant and soil surfaces in response to climatic conditions. Crop ET (ETc) for a given crop can be computed from reference ET and an appropriate ET crop coefficient (Kc). Reference ET's reported here were derived from meteorological and weighing lysimeter data obtained from 1968 through 1991 at the USDA-ARS, ET research site in southern Idaho (Kimberly). By 1982, the Penman method had been modified to provide an alfalfa-based reference ET (ETr); often referred to as the 1982 Kimberly-Penman method, for use with irrigated crops in arid regions. Now, because of world-wide interest in using a reference ET based on a clipped grass surface (ETo), wind functions, similar in nature to those used to compute ETr, have been derived to compute daily grass reference ET (ETrg), for 'Fawn' tall fescue grass, using the same meteorological data as used to compute ETr. On a seasonal basis, ETrg was 83% of ETr.

Keywords. Climatic data, Consumptive use, Crop water use.

INTRODUCTION

The practical estimation of crop evapotranspiration (ET) frequently involves calculating a reference or potential crop ET, and then applying suitable crop coefficients. The use of *reference crop ET* for a specified crop surface has largely replaced the use of the more general *potential crop ET*. Reference crop ET is the rate at which water will be evaporated from given plant and soil surfaces, with the surface specified, if water is readily available within the plant root zone. It may be expressed as the intensity of latent heat transfer per unit area or as an equivalent depth of water per unit time, which is convenient for irrigation purposes since it is then analogous to rainfall and irrigation amounts. The use of a reference crop ET permits a physically realistic characterization of the effect of the microclimate of a field on the evaporative transfer of water from the soil-plant system to the atmospheric air layers overlying the field. Alfalfa reference ET (ETr) and grass reference ET (ETo) are commonly used as reference ET's. Solar radiation intensity, air temperature, and humidity are the major meteorological factors affecting ETr or ETo in humid climates. In irrigated regions within arid climatic zones, windspeed is also important because of the macroscale or microscale horizontal advection of sensible heat to or from the evaporating surface. Detailed discussions of the reasons for defining a reference crop ET and the nature of the factors affecting these quantities are contained in detail in several general ET references (such as Jensen et al., 1990, Chap. 4).

Variations of the Penman combination equation are often used to define reference crop ET. The Penman method, as first introduced (Penman, 1948) and as later modified (Penman, 1963), utilized an equation combining energy balance and aerodynamic transfer terms to represent the amount of water evaporated. Penman's equation was developed for a short, green grass surface that completely shaded the ground, was of uniform height, and was never short of water. Much experience has shown that the original Penman equation, developed for a humid climate, is not universally applicable without modification, or a local calibration, to all climatic or crop

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situations. A wide variety of means of accomplishing this adaptation have resulted (Allen et al., 1989; Doorenbos and Pruitt, 1977; Jensen et al., 1990; Stewart and Nielsen, 1990).

Research in arid southern Idaho, as well as in similar regions, has shown that evaporation from irrigated tracts of land may exceed the equivalent rate of energy available from absorbed solar radiation (Wright and Jensen, 1972; 1978). To provide an ET representative of near maximum ET, Jensen et al. (1971) suggested alfalfa ET for use in irrigation scheduling procedures. Subsequently, alfalfa reference ET has been defined as daily ET for a well watered, full- cover alfalfa crop occupying an extensive surface, actively growing, standing erect, and at least 30-cm tall. The Penman equation was modified to specifically calculate alfalfa reference ET (ETr) (Wright and Jensen, 1972; Wright, 1982), and this method has come to be known generally as the 1982-Kimberly Penman Equation (Jensen et al., 1990). Alfalfa is advantageous for use in arid regions because it permits relatively high ET rates, responds to advective-sensible heat input, has a deep-root system so that irrigation intervals are less critical than with grass, and alfalfa is not dependent on nitrogen fertilization to maintain a dense stand.

While research on alfalfa ETr was progressing, major emphasis was also being given to grass reference ET (ETo) in an FAO publication (Doorenbos and Pruitt, 1977) because alfalfa is not grown in many areas of the world. Grass reference ET is defined as the ET from an extensive surface of 8 to 15-cm tall, green-grass cover of uniform height, well watered, actively growing, and completely shading the ground. Recently, the international committee revising the FAO publication has decided to keep ETo as the primary reference ET. In 1987 research was initiated at Kimberly with 'Fawn' tall fescue grass at the weighing lysimeter site to provide the information needed to modify the Penman equation to permit calculating grass reference ET for irrigated lands within arid regions (to be denoted ETrg herein to distinguish between the FAO procedures for computing ETo).

The purpose of this paper is to summarize the results of the Kimberly research in deriving ETr and ETrg using a modified Penman equation with locally available meteorological data and to compare the general nature of the two references. The derivation of the wind functions for the two surfaces is emphasized. The procedures for computing ETr were previously reported, but this is the first reporting of the grass reference wind function.

PROCEDURES

The functional relationships for the *Kimberly-Penman* combination equation were evaluated for irrigated crops in an arid climate using daily ET measured with two weighing lysimeters and energy balance and meteorological data obtained at the USDA-ARS Evapotranspiration Field Site near Kimberly, Idaho (see Wright, 1991, for a description of the research site). The general form of the Penman Combination Equation as used was:

$$(\lambda)(ET)=(\Delta/(\Delta+\gamma))(Rn-G)+(\gamma/(\Delta+\gamma))\,6.43\,(Wf)(es-ea) \quad (1)$$

where (λ) (ET) is the vapor flux density (units are omitted since they are adequately reviewed in ASCE Handbook 70, Jensen et al., 1990), Rn is net radiation flux density to the plant-soil system, G is soil heat flux density, Δ is the slope of the saturation vapor pressure-temperature curve, γ is the psychrometric constant, Wf is a wind function, es is the daily mean saturation vapor pressure determined for maximum and minimum air temperature, and ea is the existing vapor pressure of the air (equivalent to the saturation vapor pressure at existing dewpoint temperature of the air at approximately 8:00 a.m.). The difference term (es-ea) constitutes the vapor pressure deficit (VPD) of the air which was computed by the method described by Wright and Jensen (1972) and Wright (1982). Dividing the vapor flux density term, (λ)(ET), by λ, the latent heat of vaporization for existing air temperature, provides ET in depth equivalent units (similar to units of precipitation measurement).

Net radiation, Rn, which is not commonly measured at climatic stations, can be estimated from measured daily solar radiation using appropriate algorithms and data on air temperature and humidity, and local relationships of clear-day solar radiation. Those algorithms specifically derived at the Kimberly research site for full cover alfalfa include functions dependent on day of year for an albedo (reflectance) parameter and an adjustment coefficient for the earth's net emissivity (see Wright, 1982; Jensen et al., 1990). The time-dependent functions reflect effects of sun angle, day length, and changing properties of the earth's atmosphere during the year on Rn. The estimation of soil heat flux density from daily air temperature data is also covered in these references.

The wind function, Wf, can be expressed as a linear function of mean daily wind speed by:

$$Wf = aw + (bw)U \qquad (2)$$

where U is wind speed at some height (usually at 2 m) and aw and bw are empirically derived coefficients dependent upon the aerodynamic characteristics of the crop surface and general climatic characteristics of the region.

Three years (1969-71) of daily alfalfa and energy balance data for periods when the alfalfa crop satisfied reference crop criteria, from April through October, were used in the empirical derivation of the aw and bw coefficients of Eq. [2] to obtain an alfalfa-based wind function. To accomplish this, Eq. [1] was solved for Wf, and aw and bw of Eq. [2] were then determined by linear regression of Wf and U on a monthly basis. The coefficients aw and bw, which varied by month throughout the growing season, were each fitted to an exponential equation as a function of day of year (DOY).

In a similar manner, four years (1987, 1988, 1989, and 1991) of daily, lysimetrically measured ET for clipped fescue grass were used to derive a grass-based wind function (Wfg). Days were selected when grass conditions satisfied the criteria for a "*clipped reference grass surface*" for these derivations. In this initial derivation, the same functions were used to compute Rn for grass as were used for alfalfa since Rn measured over the two surfaces was mostly similar except for October (separate procedures may eventually be developed for grass net radiation). Regression coefficients for Wfg, denoted awg and bwg, for use with Eq. [2], were derived by linear regression of Wfg and U. These were likewise fitted to an exponential equation as a function of DOY.

RESULTS AND DISCUSSION

For the development of the alfalfa reference wind function, Wf, 349 days of lysimetrically measured daily ET met the reference standard criteria. Alfalfa ET data for the selected days are shown in Fig. 1. Intervals between selected periods represent times when the crop was beginning growth after dormancy or harvest, or conditions were otherwise unfavorable. From 14 to 21 days elapsed after harvest until the crop cover was sufficient to represent maximum ET and up to 30 days were required after growth began in the spring. Fall weather conditions sometimes prevented the alfalfa from reaching a full cover state. Frosty nights early and late in the season reduced crop ET for one or several days, and thus the ET did not represent reference crop conditions.

For the four years when reference grass was maintained at the lysimeter site, 569 days were selected for derivation of a grass reference wind function, Wfg, similar to the alfalfa wind function, Wf. Grass ET data for the selected days are shown in Fig. 2. After establishment of clipped grass reference conditions in the spring, the grass was essentially at reference condition

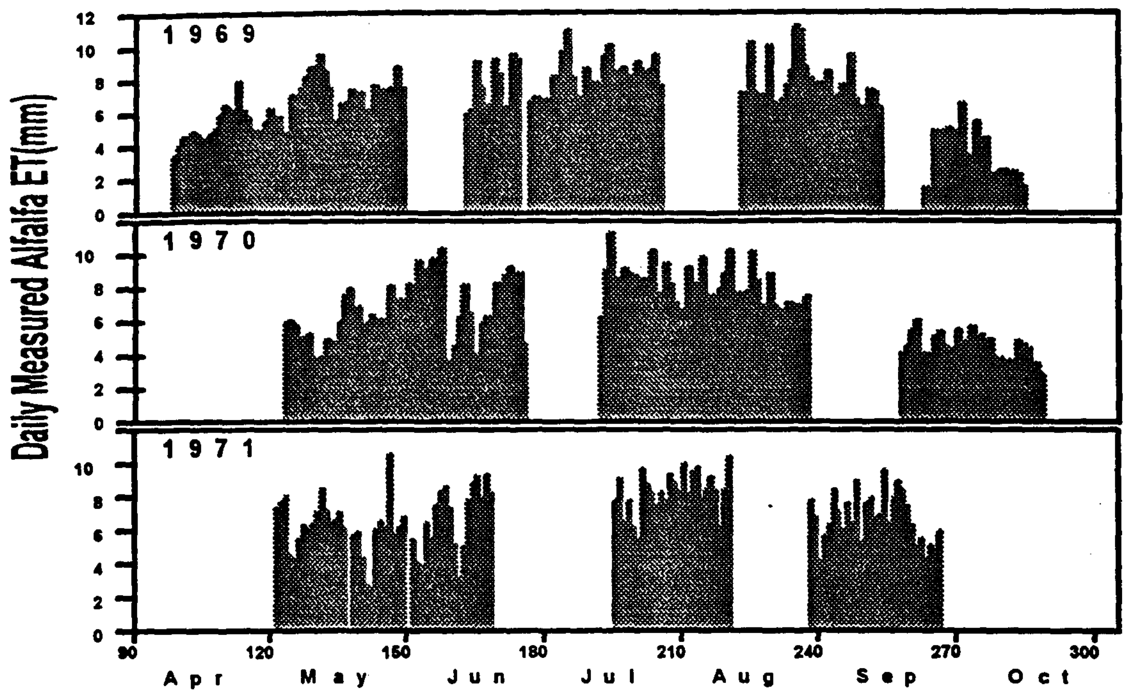

Figure 1. Daily, lysimetrically measured alfalfa reference ET for three growing seasons, Kimberly, ID.

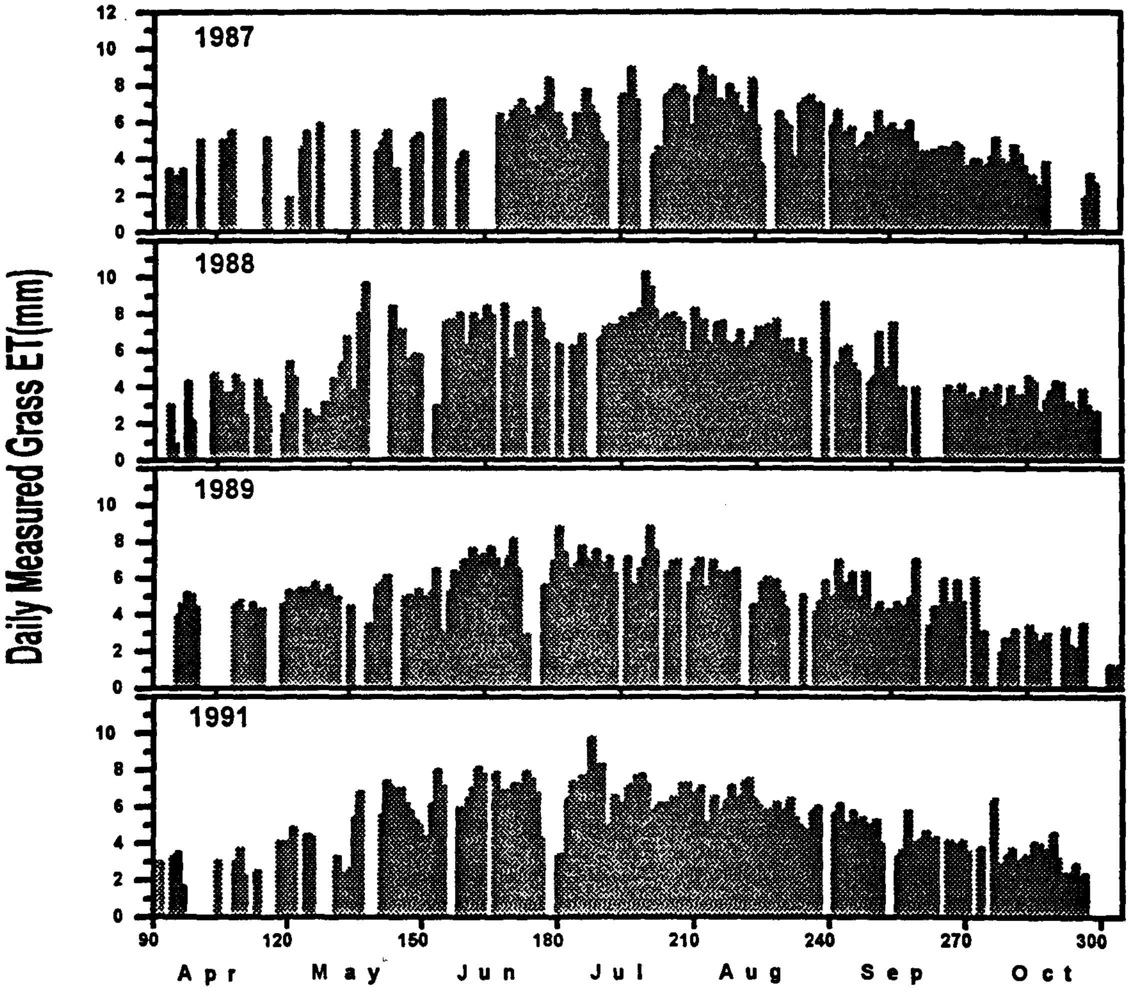

Figure 2. Daily, lysimetrically measured fescue grass reference ET for four growing seasons, Kimberly, ID.

for the remainder of the season. However, problems existed on some days , so not all days were elected. Days with rainfall, heavy frosts, and problems associated with irrigations or equipment were omitted from the analysis. Comparison of the grass ET values of Fig. 2 with the alfalfa ET values of Fig. 1 show similar daily variations and seasonal trends and the tendency for grass ET to be less than alfalfa ET, as would be expected. Alfalfa ET exceeded 10 mm/day on a few days, while grass ET exceeded 8 mm/day on a few days.

The general relationship of the derived grass wind function, Wfg, to mean daily wind speed, U, is shown in Fig. 3 for all selected days. While Fig. 3 shows considerable variability, plotting Wfg versus U on a monthly basis greatly reduced the variability. As with the alfalfa, the respective regression coefficients varied systematically with the time of year.

The exponential equations developed to fit the alfalfa wind function coefficients aw and bw, as previously reported (Jensen et al., 1990), were:

$$aw = 0.4 + 1.4 \exp(-((D-173)/58)^2) \quad (3)$$

$$bw = 0.605 + 0.345 \exp(-((D-243)/80)^2) \quad (4)$$

where D is the calendar day of year, DOY, and the values of Eq. [4] are for mean daily wind speed at 2-m height in m/s. The exponential equations derived from the data of Fig. 3 to similarly fit the monthly grass wind function coefficients, awg and bwg, were:

$$awg = 0.3 + 0.58 \exp(-((D-170)/45)^2) \quad (5)$$

$$bwg = 0.32 + 0.54 \exp(-((D-228)/67)^2) \quad (6)$$

where Eq. [6] is for U in m/s.

The variation of aw and bw for alfalfa and awg and bwg for grass during the April through October period is shown graphically in Fig. 4. The respective "a" coefficients, which

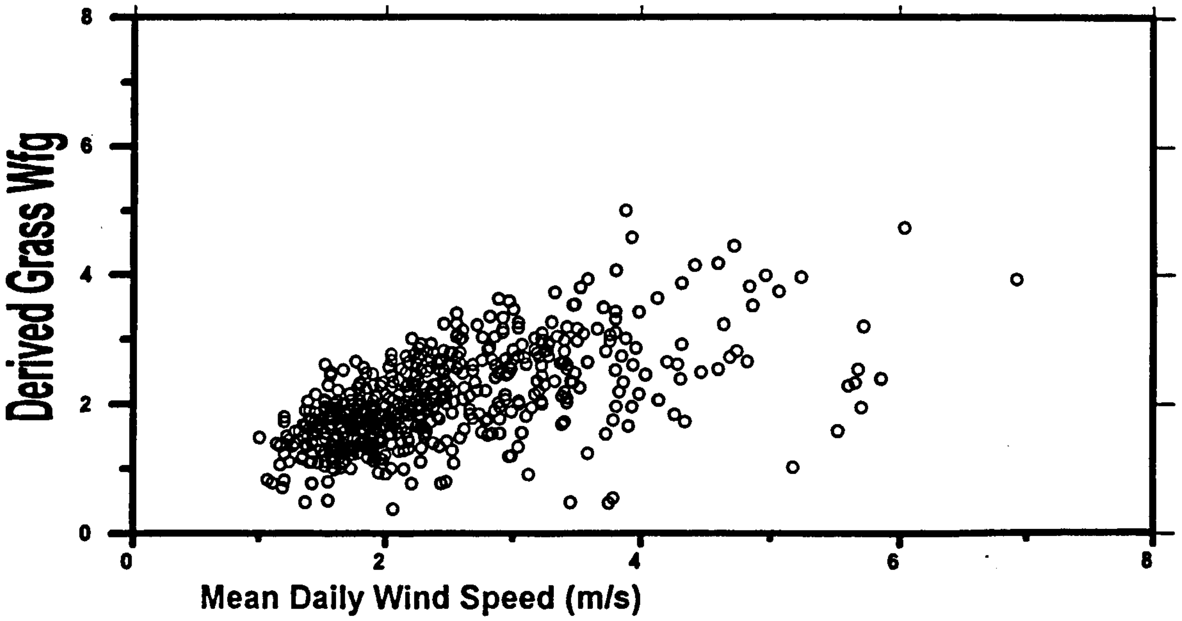

Figure 3. Daily values of the grass wind function, Wfg, derived from the lysimetrically measured grass ET and corresponding meteorological data, as a function of daily mean windspeed.

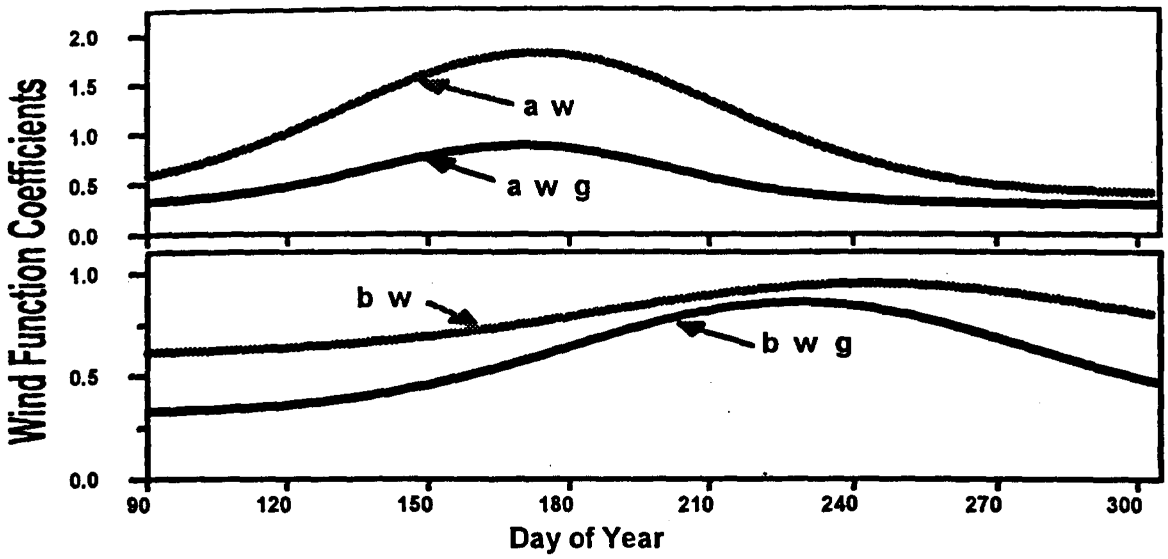

Figure 4. Seasonal trends of the variable wind function coefficients for alfalfa (aw and bw) and grass (awg and bwg).

peak at about the time of the summer solstice, appear to adjust for changes in day length. The respective "b" coefficients seem to account for changes in the dryness of the regions surrounding the irrigated landand for the effects of internal fields unirrigated late in the season after harvest of various crops. The Wfg coefficients are less than those for Wf, reflecting the lower ET rates of grass as compared to alfalfa.

Daily ETrg values, calculated with Eq. [1] and the grass wind function coefficients represented by Eqs. [5] and [6], are compared with corresponding lysimetrically measured daily grass ET in Fig. 5 for all the days used in the analysis. The relationship is essentially 1:1 with $R^2 = 0.93$. The cumulative total ETrg for all 569 days was 3,038 mm, compared to the total cumulative lysimeter ET of 3,015 mm, or 0.4% total difference. This comparison indeed consists of testing the calculated ETrg against the same data used to derive the wind function coefficients. The agreement between the calculated and measured values is a useful test, however, since for the most part the wind function derivation was a trial and error, piece-meal type of evaluation as opposed to a unique simultaneous solution for a given set of equations.

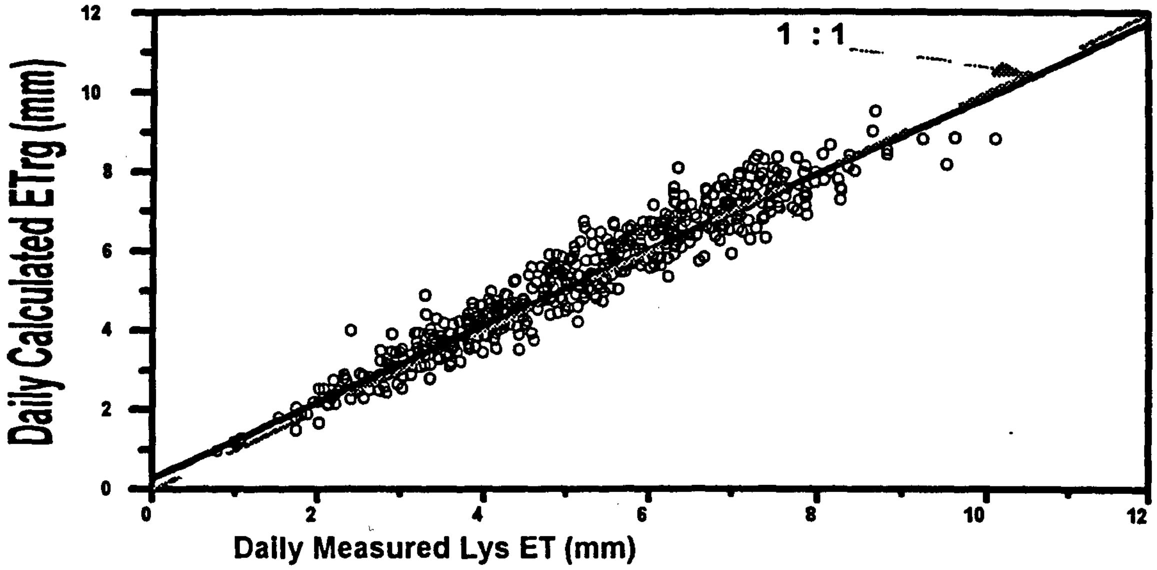

Figure 5. Comparison of grass reference ET, calculated with the modified Penman equation using a grass wind function, with lysimetrically measured fescue, reference grass ET.

A comparison of alfalfa ETr, computed using Eq. [1] and the respective wind function values represented by Eqs. [3] and [4], with grass ETrg, similarly computed using Eqs. [5] and [6], is given in Fig. 6, where the ratio ETrg/ETr is plotted as a function of day of year. The results show that the ratio averages about 0.75 early in the year, increases to about 0.875 around DOY 240, and then decreases rapidly again to 0.75 by DOY 290. This seasonal variation of the relationship of grass to alfalfa reference ET may reflect the relative response of the respective surfaces to evaporative demand and changes in general grass morphology during the season. The data of Fig. 6 indicate that grass reference ET is not a constant fraction of alfalfa reference ET throughout the season. Although as shown in Fig. 7, daily calculated ETrg is linearly related to ETr by: ETrg = 0.849 ETr - 0.121, $r^2 = 0.97$. For the entire data set, total ETrg = 3038 mm compared to ETr = 3661 so that on the average, grass reference ET was 82.9% of alfalfa reference ET.

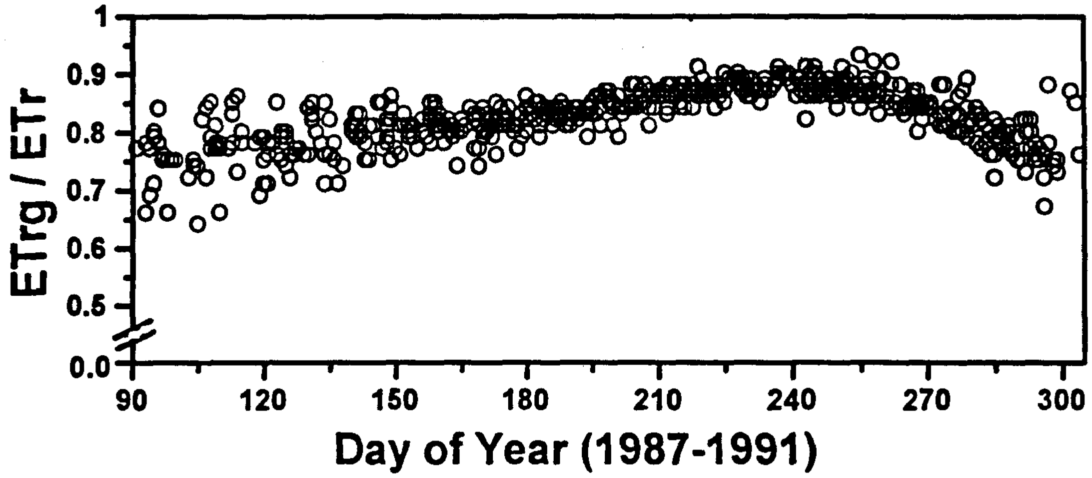

Figure 6. Ratio of calculated grass reference ET to alfalfa reference ET from April through October.

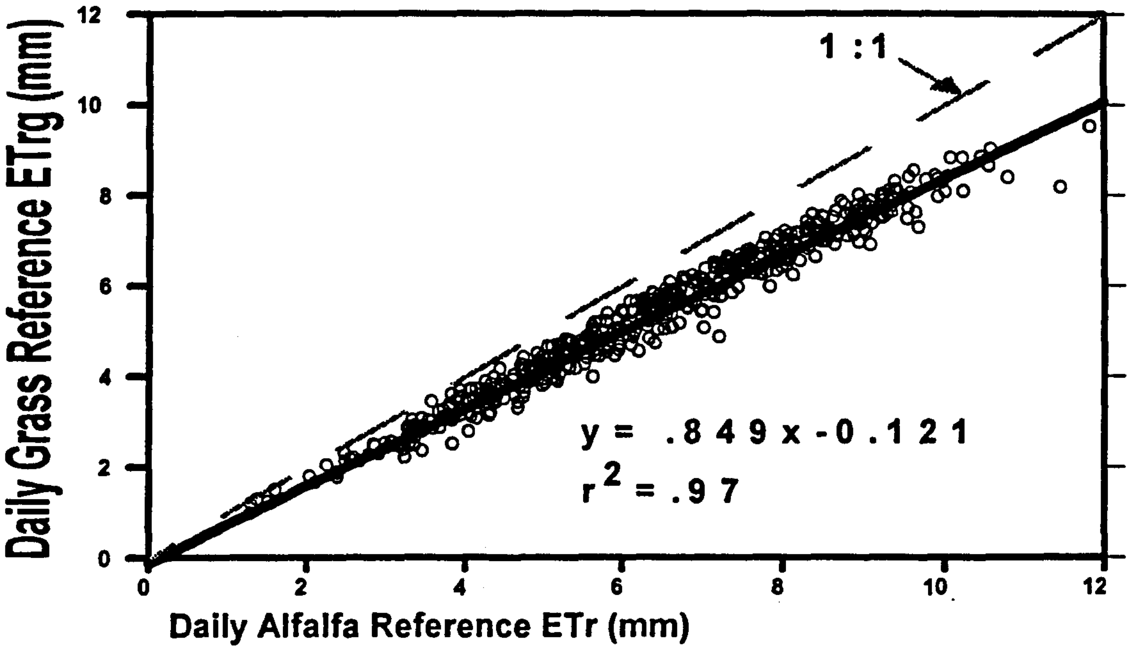

Figure 7. Daily calculated grass reference ET versus calculated alfalfa reference ET for the 569 days used in the wind function analysis.

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