DISSERTATION

EVALUATING THE ASCE STANDARDIZED PENMAN-MONTEITH EQUATION AND DEVELOPING CROP COEFFICIENTS OF ALFALFA USING A WEIGHING LYSIMETER IN SOUTHEAST COLORADO

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ABSTRACT

EVALUATING THE ASCE STANDARDIZED PENMAN-MONTEITH EQUATION AND DEVELOPING CROP COEFFICIENTS OF ALFALFA USING A WEIGHING LYSIMETER IN SOUTHEAST COLORADO

Quantification and efficient irrigation application of crop water requirements are potential ways for water resources conservation and sustainability. Reference evapotranspiration (ET_{ref}) is a very important variable in the quantification of crop water requirement. The ASCE standardized ET_{ref} equation has been recommended recently for calculating ET_{ref}. However it has not been tested under Colorado conditions. In addition, crop coefficients (K_c) for use with the ASCE standardized reference ET equation have not been developed in Colorado. Crop coefficients that have been used by the Colorado Division of Water Resources were estimated from Kimberly, Idaho and Bushland, Texas even though the growing conditions such as soil, elevation, climate and environmental factors in Colorado are different than in Kimberly and Bushland. They were developed using reference ET equations other than the ASCE standardized PM ET_{ref} equation and later they were adapted for use with the ASCE standardized PM ET_{ref} equation (Allen et al., 2007).

The objectives of this study were to test the performance of the ASCE standardized ET_{ref} equation for calculating alfalfa reference ET under southeast Colorado conditions and to develop compatible crop coefficients of alfalfa that apply to the region. A corollary objective was to determine if the full version of the Penman-Monteith

equation could better match measured alfalfa ET from the lysimeter when reference conditions were satisfied.

A precise weighing lysimeter was used to measure alfalfa ET and to develop crop coefficients of alfalfa at Rocky Ford in Southeast Colorado. The lysimeter was filled with a 3 m × 3 m x 2.4 m undisturbed soil monolith and alfalfa (Genoa variety) was planted in the lysimeter and in 4 ha of surrounding field in August 2007. Alfalfa was harvested four times in each of the 2008, 2009 and 2010 growing seasons. ET_{ref} was calculated using the hourly ASCE standardized PM ET_{rs} (standardized reference evapotranspiration for tall reference crop) and full version Penman-Monteith equations using climate data from an automatic weather station installed at the lysimeter site. Crop coefficients of alfalfa were calculated by dividing daily measured ET from the lysimeter by the corresponding daily ASCE standardized reference ET.

Season total alfalfa ET from the lysimeter ranged from 1179 mm to 1455 mm. Maximum daily water use of alfalfa was around 14.4 mm/day in 2010 season due to relatively high maximum temperature, high solar radiation and high wind speed. Average daily ET for 2008, 2009 and 2010 was 5.7 mm/day, 6.0 mm/day and 6.9 mm/day, respectively.

Hourly calculated ET_{rs} values agreed well with measured ET from the lysimeter whenever alfalfa was under reference conditions (height of at least 50 cm and no soil water stress). Residuals between calculated ET_{rs} and measured lysimeter ET increased as air temperature increased and as relative humidity decreased. Greater residuals were obtained when 80 % of the footprint length was not in the field. During some periods, there was lack of adequate fetch and this contributed to greater differences between the ASCE standardized ET_{rs} and lysimeter ET. Good agreement between ASCE standardized ET_{rs} and lysimeter ET was obtained when at least 80% of the ET flux footprint was inside the alfalfa field

The alfalfa growth stage, climate, precipitation and soil water content were major factors that shaped the crop coefficient curves. The first cutting cycle, which had slower growth due to cooler weather, had smaller crop coefficients, whereas later cutting cycles with rapid growth had larger crop coefficients. The maximum crop coefficients were below 1.2 in 2008 (water stressed) and at or slightly above 1.2 in 2009 and 2010. The K_{cr} values greater than 1.0 were due to ET_c from the lysimeter being greater than ET_{rs} from ASCE standardized PM. Periods when alfalfa in the lysimeter was taller than alfalfa in the immediate surroundings and when the canopy extended outside the lysimeter boundary (3 m × 3 m) contributed to K_{cr} values greater than 1.0. Precipitation interception by the alfalfa canopy increased evaporation and caused outliers in the crop coefficient values. Crop coefficients were greatly affected by soil water content. A reduction in the alfalfa crop coefficients was observed at the end of some cutting cycles that coincided with reductions in soil water content.

The average leaf area index (LAI) at a height of 50 cm was 4.34 m^2/m^2 and there was a high correlation between LAI and alfalfa height with R^2 of 0.94, but the relationships were not the same as suggested by Allen et al. (1994). ET_{ref} values calculated by the full version of the Penman-Monteith equation deviated more from the lysimeter ET compared to the ASCE standardized ET_{ref} equation.

Full version of Penman Monteith showed very good agreement with ASCE standardized ET. Using the full version of the Penman-Monteith equation did not improve agreement with lysimeter ET at reference conditions.

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CHAPTER ONE: INTRODUCTION

Accurate quantification of crop water requirements (evapotranspiration, ET) is needed for optimizing water productivity, efficient use of water resources and improving management practices to reduce surface and groundwater deterioration (Irmak et al., 2006). Accurate estimates of crop water requirements depend on precise measurements of reference evapotranspiration (ET_{ref}) and accurate estimates of a crop coefficient for the crop being grown. Several equations have been developed to quantify ET_{ref}. These equations range from very simple models that require only one or two climatic factors to more sophisticated and accurate equations (Intenfisu et al., 2003). The Penman-Monteith (PM) equation is the most accurate and widely used combination equation to calculate ET_{ref}. It has gained acceptance because it is more physically based (thermodynamic and aerodynamic) on the relevant processes. Several studies have proved that ET_{ref} values calculated by PM equation fit well with measured ET in many places and under various climatic regions (ASCE-EWRI. 2005). The Penman-Monteith method was adopted by Food and Agriculture Organization (FAO) and American Society of Civil Engineers (ASCE) for calculating ET_{ref}. In 1999, ASCE standardized the application of the PM equation for better transfer of crop coefficient (Kc) values and for wider acceptance by users worldwide (ASCE-EWRI, 2005). ASCE simplified and clarified ASCE-PM ET_{ref} application by using a single equation. It can be used for both clipped short (grass) and tall (alfalfa) references, and for daily and hourly time steps (Gavilan et al., 2008). ASCE standardized reference ET equation has recently become the recommended equation to quantify ET_{ref}.

In Colorado, crop water use estimates for water rights purposes has been estimated using the Blanney-Criddle formula, which is gradually being replaced by the ASCE standardized ET_{ref} equation for some applications (Straw, 2004). For example, the ASCE standardized ET_{ref} equation has been approved by the U.S. Supreme Court for calculating crop ET in the Arkansas River Basin of Colorado to maintain compliance with the Arkansas River compact between Colorado and Kansas (Andales et al., 2010). ASCE standardized ET_{ref} equation has not been tested under Colorado conditions. Evaluating ET_{ref} equations under local conditions is desired to ensure its accuracy for calculating crop water requirement.

Crop coefficients (K_c), which give the ratio between a given crop evapotranspiration and that of a reference crop, are widely used to determine crop water use and to determine when and how much water to apply with irrigation (Howell et al., 2006). Even though K_c values for most crops are available in the literature, developing them under local conditions is recommended for more accurate calculation of ET that accounts for local climate, environmental, and crop management factors (Evett et al., 1998). Local crop coefficients to use with the ASCE standardized reference ET equation have not been developed in Colorado. Crop coefficients that have been used by the Colorado Division of Water Resources are estimated from Kimberly, Idaho and Bushland, Texas even though the growing conditions such as soil, elevation and climate in Colorado are different than in Kimberly and Bushland (Berrada et al., 2008). They have been developed using reference ET equations other than ASCE-PM ET_{ref} equation and later they were adapted for use with the ASCE standardized PM ET_{ref} equation (Allen et al., 2007).

For these reasons, and to ensure compliance with the Arkansas River compact between Colorado and Kansas, a couple of large weighing lysimeter (one large and one smaller) funded by the Colorado Water Conservation Board were built in the Arkansas River Valley (Berrada et al., 2008). Precision weighing lysimeters have been used for precise quantification of crop ET. The long term goal of this lysimeter project is to get accurate estimation of water requirements for different irrigated crops in the Arkansas River Valley, primarily for estimating depletions in the Arkansas River and complying with the compact with Kansas. Historically, alfalfa has been used as the reference crop in Colorado (Andales et al., 2010). It was the first crop planted in the lysimeter in order to compare measured ET_{ref} from the lysimeter with calculated ET_{ref} using the ASCE standardized PM equation and to develop crop coefficients for alfalfa for local climatic conditions and management practices (Straw, 2004).

The objectives of this study were to test the performance of the ASCE standardized ET_{ref} equation for calculating alfalfa reference evapotranspiration under southeast Colorado conditions and to develop local crop coefficients of alfalfa based on the ASCE standardized reference ET equation.

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CHAPTER TWO: EVALUATING THE ASCE STANDARDIZED PENMAN-MONTEITH EQUATION USING A WEIGHING LYSIMETER IN SOUTHEAST COLORADO

ABSTRACT

Accurate determination of crop evapotranspiration (ET) can help in efficient irrigation water management. The American Society of Civil Engineers (ASCE) Standardized Penman Monteith ET equation (ASCE Standardized PM-ET_r) is the recommended equation for computing reference ET. Evaluations of ASCE standardized PM-ET_{rs} (standardized reference ET for tall reference crop) equation using a weighing lysimeter are limited. The objective of this study was to evaluate and test the performance of ASCE standardized PM-ET_{rs} using a weighing lysimeter in Southeast Colorado. A precision weighing lysimeter was installed at the Arkansas Valley Research Center in southeast Colorado to measure ET for the tall reference crop (alfalfa). ET_{rs} was calculated using ASCE standardized PM ET_{rs} using climate variables from a complete automatic weather station installed at the lysimeter site. The results indicated that hourly ET_{rs} values agreed well with measured alfalfa ET whenever alfalfa didn't experience soil water stress. During soil water stress periods, measured ET was lower than calculated ET_{rs}. Residual analysis showed that errors (the difference between calculated ET_{rs} and measured lysimeter ET) increased with temperature and as relative humidity decreased. Errors reached to 0.37 mm/hr under high temperature.

INTRODUCTION

Application of more water than crop requirements has adverse impacts on water resources and the environment. It is important to use water efficiently, especially in arid and semi-arid regions where water supplies are limited. Accurate determination of crop water consumptive use (i.e., crop evapotranspiration, ET_c) is critical for efficient irrigation water management. Accurate evapotranspiration quantification is necessary for many applications in different areas as it is often the largest component of water and energy balances (Suleiman and Hoogenboom, 2009). It is required for water productivity optimization, irrigation scheduling and water resources planning (Irmak et al., 2006). ET_c is defined as the amount of water lost by evaporation from plant and soil surfaces, plus the amount of water transpired from plant canopies. It can be measured directly using weighing lysimeters or estimated by the combination of reference evapotranspiration (ET_{ref}) and crop coefficients (K_c). ET_{ref} reflects local climatic conditions whereas K_c reflects the crop characteristics such as growth stage since sowing date, leaf area, plant height, crop development, canopy cover and canopy resistance and also reflects the soil and climate conditions (Irmak et al., 2005). ET_{ref} is defined as the rate of evapotranspiration from an actively growing reference crop with a uniform height grown on an extensive area and not short of water (Jensen et al., 1990; Allen et al., 1998). Two ET_{ref} surfaces have been used as a reference for ET: clipped short crop (grass) and tall crop (alfalfa).

Even though lysimeters are the standard tool to measure ET (Tolk et al., 2005), this technique is difficult, costly and time consuming (Irmak et al., 2005). In addition, it is not easy to grow a reference crop because the crop should have exactly the same growth, height and leaf area index both inside and surrounding the lysimeter (Allen et al., 1998). For this reason, the reference ET method is the common method around the world. Several equations have been developed to calculate ET_{ref}. Most of these equations have been empirically developed and are not readily transferable to locations different from where they were developed (Allen et al., 1998). In 1948, Penman introduced the first combination-based (thermodynamic and aerodynamic) equation to determine evaporation from an open water surface (Irmak et al., 2006). The Penman equation was then improved by other scientists who extended it to cropped surfaces by introducing aerodynamic and surface resistance parameters. This is commonly referred to as the Penman-Monteith equation (Jensen et al., 1990). Food and Agriculture Organization (FAO) has adopted Penman-Monteith as a standard for ET_{ref} determination (Itenfisu et al., 2003). FAO Penman-Monteith (FAO-PM) is the simple, more physically based equation requiring several climatic and crop dependent parameters (Allen et al., 1998). Several studies have proven that ET_{ref} calculated using Penman-Monteith equation gives close values to measured ET_{ref} (Grazhdani et al., 2010) and gives reasonable results under diverse climatic conditions (Suleiman and Hoogenboom, 2009).

In 1999, the Irrigation Association (IA) requested the Evapotranspiration in Irrigation and Hydrology Committee-Environmental and Water Resources Institute, American Society of Civil Engineers ASCE-ET to develop an equation to standardize the calculation of ET_{ref} for better transfer of Kc values and to be widely accepted by users worldwide (ASCE-EWRI, 2005). The Committee used ASCE-PM as the base equation and simplified some terms related to aerodynamic and surface resistances based on the height of the reference crop. They adopted two ET_{ref} surfaces, clipped short (grass) and tall crop (alfalfa). ET_{os} refers to standardized reference evapotranspiration from a short crop whereas ET_{rs} refers to standardized reference evapotranspiration from a tall crop. ET_{os} is defined as evapotranspiration from short crop having a height of 12 cm and a daily surface resistance of 70 s/m whereas ET_{rs} is defined as the evapotranspiration from tall crop having a height of 50 cm and a daily surface resistance of 45 s/m (ASCE-EWRI, 2005).

Since that time, several studies have been conducted to evaluate and compare ASCE standardized PM equations with other ET_{ref} equations. Evaluating ET_{ref} equations under local conditions is desired to ensure its accuracy for calculating crop water requirements. Most of these studies have been concentrated on the ASCE-PM ET_{os} equation more than ASCE-PM ET_{rs}. Other evaluations are only a comparison between ASCE-PM ET_{rs} with other ET_{ref} equations. Evaluations of ASCE standardized PM ET_{rs} equation for tall crop using weighing lysimeters are limited. Itenfisu et al. (2003) conducted comparisons among the common ET_{ref} equations including the recommended ASCE standardized PM ET_{rs} using weather data from 49 sites in 16 states in the United States. They found that ASCE standardized PM ET_{ro} and FAO-56-PM agreed best with the full form of ASCE-PM. They also found that the ASCE standardized PM ET_{rs} showed much less deviation than 1982 Kimberly Penman equation. ASCE standardized PM (ET_{os} and ET_{rs}) also gave the best agreement between hourly and daily computations. They supported the adoption of the standardized PM recommended by ASCE. Irmak et al. (2008) found large differences between ASCE-PM ET_r versus other equations. They recommended using ASCE standardized PM ET_r when needed climatic data are available and of a good quality.

In Colorado, the Agricultural Meteorological Network (COAGMET) has been using the Kimberly-Penman equation to calculate crop water requirement due to availability of crop coefficients that were developed for the Kimberly-Penman model (Andales et al., 2009). The ASCE standardized ET_{rs} has not yet been evaluated under Colorado conditions. The objective of this study was to evaluate and test the performance of the ASCE standardized PM ET_{rs} using a precise weighing lysimeter in Southeast Colorado.

MATERIALS AND METHODS

Location of lysimeter

A weighing lysimeter was installed at the Arkansas Valley Research Center, Rocky Ford in southeast Colorado (latitude 38^o 2' 17.30", longitude 103^o 41' 17.60", altitude 1,274 m above sea level). The lysimeter is located in the center of a 159 m x 256 m field surrounded by 7 m wide dirt roads from three sides and about 22 ha of surrounding irrigated fields planted with different crops such as corn, canola, oats and vegetables. It was constructed for evaluating the American Society of Civil Engineers (ASCE) standardized Penman Monteith (PM) equation and to compute actual evapotranspiration (ET_c) and crop coefficients (K_c) for various crops under soil and environmental conditions of Arkansas Valley. The long term average precipitation is 299.7 mm. The average maximum and minimum temperatures are 21.1^o C and 2.39^o C (Berrada et al., 2008).

Alfalfa planting and irrigation

Alfalfa (Genoa variety) was planted mechanically in the surrounding field and by hand in the lysimeter on 9 August 2007 at a rate of 21.3 kg/ha. Alfalfa in the lysimeter was treated the same as the surrounding field (irrigation, fertilization and harvesting) to insure that both grow under similar conditions. The soil monolith was irrigated manually to mimic the furrow irrigation of the surrounding field. Water was delivered from the water supply ditch to the lysimeter furrows through a flow meter and hose. Alfalfa was harvested four times in 2008, 2009 and 2010. The height of alfalfa was measured weekly to determine the time when alfalfa reached 50 cm in height, which is the tall reference crop height assumed in the ASCE standardized PM equation.

ET_c measured by Lysimeter

Actual evapotranspiration (ET_c) of alfalfa was measured using the weighing lysimeter. Berrada et al. (2008) gave a detailed description of the weighing lysimeter. The large lysimeter consists of an inner tank of 3 m x 3 m x 2.4 m filled with undisturbed soil (soil monolith) and an outer containment tank. The soil tank moves freely within the outer tank and the two are separated at the top by a fraction of an inch. Water that percolates through the soil monolith is collected in two drainage tanks suspended from the scale frame that supports the soil tank, so that there is no overall weight change as water drains into the tanks. One tank collects water from the internal portion of the monolith and the other tank collects water from the perimeter of the monolith.

The weighing mechanism consists of a mechanical lever scale-load cell combination. The load cells are connected to a Campbell Scientific CR-7 data logger which records the weight of the inner tank plus soil every 10 seconds. The readings are given in millivolts per volt (mV/V). A thorough calibration was performed to convert the load cell output in mV/V to the weight of water in kilograms. The procedure was similar to the one developed by USDA-ARS at Bushland, TX (Howell et al., 1995). The coefficient (slope of the regression line) determined for application to the change in load cell readings as the lysimeter gains or losses mass is 685 kg/mV/V, which is equivalent to a change of 76 mm of water on the lysimeter for a change of 1 mV/V in the load cell output. The calibration equation of the load cell is y = 685.4x -142.9 (y is weight in Kg and x is the load cell output in mV/V). The standard deviation of the weight measurements (accuracy) was less than 0.02%.

For evaluation of the ASCE standardized PM equation, ET_c values were used when alfalfa was at and above 50 cm in height because it is difficult to keep alfalfa height constant at 50 cm and taking ETc values when alfalfa height at 50 cm end up with few values. Hourly ET_c values were measured by taking the difference between hourly changes in the weight of the lysimeter. Daily ET_c from the monolith was computed using the water balance equation:

$$\mathrm{ET} = \mathrm{P} + \mathrm{Irr} - \mathrm{D} \pm \Delta S \qquad \text{Eq. (1)}$$

where ET is evapotranspiration, ΔS is change in soil water content as measured by lysimeter weight changes, P is precipitation, Irr is irrigation, and D is drainage, which was zero during the period of study. Capillary rise and runoff are zero in the lysimeter system.

The surface area of the lysimeter is 3 m x 3 m (9 m^2). As alfalfa inside the lysimeter grew, it extended outside the lysimeter edges, increasing the area that was subjected to evapotranspiration. The horizontal extension of alfalfa outside the edges was measured weekly in the last cutting cycle of 2010 (by taking the average horizontal measurement of alfalfa extending from the four sides of the lysimeter) to adjust and correct the evaporative area. The alfalfa extended outside the lysimeter edge versus number of days after harvest was plotted and the equation was used to correct the evaporative area. The corrected area was used to adjust ET_c values measured from the lysimeter.

Soil water content measurement

Soil water content was monitored by neutron attenuation (CPN 503 DR) at 20 cm increments down to 190 cm. Two access tubes were installed inside the monolith and four were installed immediately outside the lysimeter. The neutron probe was calibrated based on the Evett et al. method which was described in detail by Berrada et al. (2008).

Climatic data collection

A complete automatic weather station was installed at the lysimeter site to measure climate variables above the monolith. Variables included rainfall, wind speed, temperature, radiation, barometric pressure, soil temperature, and soil heat flux. Climatic data was recorded every 15 minutes. Data were routinely plotted and compared to duplicate sensors or to an automatic weather station located approximately 415 m to the west. The details of the sensors and their placement were described in Berrada et al. (2008). The sensors used were:

- Rainfall was measured by the TE525 tipping bucket rain-gauge located 2 m above the ground.

- Wind speed and direction were measured by the RM Young 03101 Wind Sentry cup anemometer and RM Young Wind Monitor (prop-anemometer) respectively located 2 m above the ground.
- Air temperature and relative humidity were measured by the Vaisala HMP45 located 1.5 m above the ground.
- Barometric pressure was measured by Vaisala PTB101B
- Net radiation was measured with REBS Q7 net radiometer located 1.5 m above the ground.
- Incoming and reflected radiation were measured using K&Z pyranometer CM14 located 1 m above the monolith.
- Crop canopy temperature was measured with infrared temperature sensors located 1 m above the monolith.
- Soil temperature was measured by temperature sensors installed at depths of 10 mm, 40 mm 0.5 m, 1.0 m and 2.0 m.
- Soil heat flux was measured by flux plates placed at 10 cm below the monolith surface.

Computation of ET_{rs}

The American Society of Civil Engineers (ASCE-PM) standardized ET_{rs} equation was used to compute reference evapotranspiration on an hourly time step using climatic data obtained from the weather station located above the lysimeter. The tall crop (alfalfa) standardized reference ET equation was used:

$$ET_{rs} = \frac{0.408\,\Delta\,(R_n\ - G) + \gamma\,\frac{C_n}{T + 273}\,u_2(e_s - e_a)}{\Delta + \ \gamma(1 + C_d u_2)} \qquad \text{Eq. (2)}$$

where ET_{rs} is standardized reference crop evapotranspiration for tall surfaces (mm/h); R_n is calculated net radiation at the crop surface (MJ/m^2/h); G is soil heat flux density at the soil surface (MJ/m^2/h); T is mean hourly air temperature at 1.5 to 2.5-m height (°C); u_2 is mean hourly wind speed at 2-m height (m/s); e_s = saturation vapor pressure at 1.5 to 2.5-m height (kPa); e_a is mean actual vapor pressure at 1.5 to 2.5-m height (kPa); Δ is slope of the saturation vapor pressure-temperature curve (kPa/°C); γ is psychrometric constant (kPa/°C); C_n (a numerator constant depends on the reference crop) equal to 66 for tall reference and hourly time step (K·mm· s^3 /Mg/h); C_d (a denominator constant depends on the reference crop) equal to 0.25 (daytime) and 1.7 (nighttime) for tall reference and hourly time step (s/m); and the units for the 0.408 coefficient are m^2 mm / MJ. The calculation procedures for the terms in the standardized ASCE-PM equation followed the equations in the ASCE-EWRI (2005) publication.

Wind speed adjustment

The ET_{rs} calculated by ASCE standardized PM equation uses wind speed measured at 2 m height over smooth surface like clipped grass. The wind speed at the lysimeter was measured at 2 m above the ground but alfalfa had variable height during the growing season. At most times alfalfa height was greater than clipped grass. The wind speed adjustment algorithm described by Ley et al. (2009) was used to adjust wind speeds over variable height of alfalfa to equivalent wind speeds at 2 m over grass.

$$u_{z,v} = u_{z,w} \frac{\ln\left(\frac{Z_{IBL,w} - d_w}{Z_{om,w}}\right) \ln\left(\frac{Z_{IBL,v} - d_R}{Z_{om,R}}\right) \ln\left(\frac{Z_v - d_v}{Z_{om,v}}\right)}{\ln\left(\frac{Z_w - d_w}{Z_{om,w}}\right) \ln\left(\frac{Z_{IBL,w} - d_R}{Z_{om,R}}\right) \ln\left(\frac{Z_{IBL,v} - d_v}{Z_{om,w}}\right)} \qquad \text{Eq. (3)}$$

where $u_{z,v}$ is the adjusted wind speed (m/s) at z_v elevation (m) on ground covered with vegetation of type V; $u_{z,w}$ is the measured wind speed (m/s) at z_w elevation (m) above the ground surface; $z_{IBL,w}$ and $z_{IBL,v}$ are the heights (m) of the internal boundary layer (IBL) over the weather measurement surface (W) and over surface (V) to which wind is being translated; d_w , d_R ,and d_v are the zero plane displacement heights (m) taken as 0.67h for the weather measurement vegetation, regional vegetation (R), and the vegetation surface; $z_{om,w}$, $z_{om,R}$, $z_{om,v}$ are aerodynamic roughness lengths (m) taken as 0.123h for each surface condition (W, R, and V); and h is the vegetation height (m) for each surface condition (W, R, and V). $Z_{IBL,w}$, $Z_{IBL,R}$, and $Z_{IBL,v}$ are calculated using the following equation:

$$Z_{IBL} = d + 0.33\, z_{om}{}^{0.125} \times X_f{}^{0.875} \qquad \text{Eq. (4)}$$

where d is the zero plane displacement heights (m) and X_f is the horizontal distance downwind. Alfalfa height was measured weekly. The height of the alfalfa was used to adjust wind speed using the above equations.

Fetch requirement

Fetch requirement was estimated by measuring footprint length. The footprint was used to examine the effectiveness of existing fetch and determine the influences of the upwind surface on source point of measurement. It is defined as the contribution of upwind surface area to a source point of measurement (Amiro, 1998). Fetch requirement was calculated based on an analytical model developed by Hsieh et al. (2000):

$$x = \frac{-|L|}{k^2\ \ln(^{\mathrm{F}}/_{\mathrm{S}_0})}\ D(^{z_u}/_{|L|})^P \qquad \text{Eq. (5)}$$

where x is the fetch requirement (downwind distance), F/S_0 is desired normalized flux, k is von Karman constant (0.4), D and P are constants depending on the atmosphereic stability conditions, for unstable (D = 0.28; P = 0.59), near-neutral (D = 0.97; P = 1), and stable (D = 2.44; P = 1.33) stratification, L is the Monin-Obukhov stabilitylength, $z_u = z_m(\ln(z_m + z_o) - 1 + z_o + z_m)$, z_m the measurement height, z_o is roughness length for momentum transfer (0.123 h), h is the height of the crop.

F/S0 was taken equal to 0.9. The existing fetch was calculated based on the wind direction and the geometry of the lysimeter in the field (Figure 1). The dimension of the field is 158.5 m by 256.1 m. The ratio of existing fetch to the requirement indicated the adequacy of the fetch for the conditions.

Evaluation and statistical analysis

Many statistics are used to evaluate models. Root-Mean-Square Error (RMSE) is one of the most widely used statistical indicators in environmental estimation models (Jacovides and Kontoyiannis, 1995, and Wallach et al., 2006). Small RMSE values indicate good performance. RMSE does not provide indication about over and under estimation of a model (Jacovides and Kontoyiannis, 1995). Index of agreement (d) is another widely used indicator to measure performance of a model (Harmel and Smith, 2007). It ranges between one and zero. A value of 1 means a perfect agreement, while a value of 0 means a poor agreement. Mean Bias Error (MBE) is also used as an indicator of performance; it measures the mean difference between calculated and measured values

(Wallach et al., 2006). Positive values mean over-estimation and negative values mean under-estimation.

For evaluation of the standardized ASCE-PM ET_{rs} equation, ET values from the lysimeter were taken when the height of alfalfa was at or above 50 cm. Least square regression lines were calculated for each period up to an alfalfa cutting for 2008, 2009, and 2010 seasons and coefficients of determination (R^2) were determined. The performance of standardized ASCE-PM ET was examined using Root-Mean-Square Error (RMSE), Relative Error (RE), index of agreement (d) and Mean Bias Error (MBE) using the following formulas:

$$\mathrm{RMSE} = \left(1/\mathrm{N}\sum_{i=1}^{\mathrm{N}}(\mathrm{y_i} - \mathrm{x_i})^2\right)^{1/2} \qquad \text{Eq. (6)}$$

where RMSE is root-mean-square error where the lower the RMSE, the better the agreement; in this formula, y_i is the calculated ET_{rs}; x_i is the measured ET from the lysimeter; and N is the total number of observations.

Relative Error (RE) was calculated as follows:

$$\mathrm{RE} = \left(\frac{\mathrm{y_i} - \mathrm{x_i}}{\mathrm{x_i}}\right) \times 100 \qquad \text{Eq. (7)}$$

where RE is relative error used to indicate the percent of the errors. It can be positive or negative. Positive values mean the percentage of over-estimation and negative values mean the percentage of under-estimation, y_i is the calculated ET_{rs} and x_i is the measured ET.

$$\mathrm{d} = 1 - \left(\frac{\sum_{i=1}^{\mathrm{N}}(\mathrm{y_i} - \mathrm{x_i})^2}{\sum_{i=1}^{\mathrm{N}}(|\mathrm{y_i}'| - |\mathrm{x_i}'|)^2}\right) \qquad \text{Eq. (8)}$$

where d is index of agreement, it is between one and zero. A value of 1 means a perfect agreement, while a value of 0 means a poor agreement, $\mathbf{y_i}' = \mathbf{y_i} - \bar{\mathbf{x}}$ and $\mathbf{x_i}' = \mathbf{x_i} - \bar{\mathbf{x}}$, y_i is the calculated ET_{rs}; x_i is the measured ET, and $\bar{\mathbf{x}}$ is the mean measured value.

$$\mathrm{MBE} = 1/\mathrm{N}\sum_{i=1}^{\mathrm{N}}(\mathrm{y_i} - \mathrm{x_i}) \qquad \text{Eq. (9)}$$

where MBE is mean bias error; y_i is the calculated ET_{rs}; x_i is the measured ET; and N is the total number of observations.

RESULTS AND DISCUSSION

Neutron Moisture readings

Soil water content (SWC) was monitored to ensure that the crop wasn't experiencing soil water stress throughout the growing season. It was measured using neutron attenuation method. Neutron moisture meter readings at a depth of 30 cm, 50 cm, 90 cm, and 150 cm for 2008, 2009 and 2010 are shown in figures (2), (3), and (4) respectively. Field capacity (FC) and permanent wilting point (PWP) were measured for each soil layer using pressure plate apparatus, which then were adjusted using neutron moisture values. Highest soil water content after irrigation and three days precipitation was taken as FC and lowest soil water content was taken as PWP since soil water content didn’t go below this level even under soil water stress events. Management allowed deficit (MAD) was taken as 50% of total available water. FC, PWP, and MAD were determined for each depth of measurement. Figure (2) indicated that alfalfa experienced water stress at depths below 30 cm almost the whole 2008 season. At a depth of 30 cm the soil water fluctuated throughout the growing season, but most of the time the SWC was above SWC at MAD. Soil water content at depths of 50 cm, 90 cm, and 150 cm was always below MAD. In 2009, neutron moisture meter readings indicated that the crop experienced water stress only at the beginning of the season during cutting cycle one at all measured depths. Soil water content then stayed above MAD the rest of the growing season (figure 3). The situation in 2010 was totally different. Alfalfa did not experience any soil water stress at all depths as shown in figure (4). Soil water content was above MAD, except at a depth of 50 cm where it fluctuated around the MAD.

Crop height and area adjustment

For ASCE standardized PM ET_r, reference crop (alfalfa) height is assumed to be 50 cm. The canopy height of alfalfa on the lysimeter was measured weekly. The periods when alfalfa height was 50 cm and greater were determined and were used in evaluating the standardized ASCE-PM ET_{rs}. Figure (5) shows the height of alfalfa for the 2008, 2009 and 2010 seasons. Alfalfa was tallest in the first three cutting cycles. In the last cutting cycles, alfalfa was shorter, due to cooler weather beginning in October of each year. The height of alfalfa in the fourth cutting cycle of 2008 did not reach 50 cm, so data when alfalfa height was 30 cm and above were also used during this period. Height measurements were used to adjust wind speed above alfalfa since the ET_{rs} calculated by ASCE-PM ET_{rs} uses wind speed measured at 2 m height over smooth surface like clipped grass (12 cm height). At most times, alfalfa height was greater than clipped grass. Regression lines between height and DOY were drawn and daily calculated heights were used to adjust the wind speed above alfalfa.

Evapotranspiration area was also adjusted based on the length of alfalfa extending beyond the lysimeter edge. It was found that the surface dimensions of the alfalfa canopy on the lysimeter increased from 3 m × 3 m up to 3.26 m × 3.26 m, indicating that the evaporative area of the alfalfa increased from 9 m^2 at the beginning of each cutting cycle up to an average of 10.6 m^2 just before cutting. Alfalfa extended beyond the edge of the lysimeter due to lodging (especially after precipitation events that wetted the canopy) and also due to the difference in height between alfalfa on the lysimeter and the surrounding field. It was found that the alfalfa in the lysimeter was sometimes taller than in the surrounding area by about 10 cm (Figure 5) because of soil settling around the lysimeter after construction and possibly increased foot traffic during data collection, lysimeter maintenance, and harvesting events.

Hourly measured ET_{ref} versus calculated ET_{rs}

Hourly alfalfa ET_c was measured by taking the difference in the weight of the lysimeter between two consecutive hours. Measured ET_c values when alfalfa height was at 50 cm and above were used to compare with the ASCE standardized PM ET_{rs}. The days with irrigations, precipitation and working maintenance on the lysimeter were totally excluded from the evaluation. For the comparison, these selected alfalfa ET_c values measured by the lysimeter are referred to as measured ET_{ref} and the ASCE standardized PM ET_{rs} is referred to as calculated ET_{rs}. The regression lines of calculated ET_{rs} versus measured ET_{ref} were drawn for each cutting cycle. As mentioned earlier, the alfalfa on the lysimeter experienced soil water stress in 2008 and in early 2009 so it was not surprising that soil water stress was reflected in regression lines for the first cutting cycle in 2008 and 2009 when measured ET_{ref} values were lower than calculated ET_{rs}. Under soil water stress, water is harder for crops to extract because it is strongly held by capillary and absorptive forces (Allen et al., 1998). Soil water stress also induces stomatal closure, which results in an increase in stomatal resistance to transpiration. Although alfalfa experienced soil water stress throughout 2008 growing season, regression lines for cutting cycles 2, 3 and 4 fitted well and calculated ET_{rs} values had a good agreement with measured ET_{ref}. Measured ET_{ref} for cutting cycle 4 was taken when alfalfa height was at least 30 cm. Figure (6) shows that the coefficients of determination (R^2), based on least square regression fits, values ranged from 0.92 to 0.98. The performance indicators and statistical analysis of hourly ET values for each cutting cycle of 2008, 2009 and 2010 seasons are shown in table (1). Larger RMSE (0.18 mm/h) and larger RE (32.8 %) were observed between calculated ET_{rs} and measured ET_{ref} at the first cutting cycle compared to other cutting cycles in 2008. Other cutting cycles showed good fits and good agreements between calculated and measured ET_{ref} (index of agreement range from 0.979 to 0.994). The good agreement in cutting cycles 2, 3 and 4 of 2008, even with soil water stress in the lower soil layers, could be explained by the root depth of alfalfa being shallow since alfalfa was planted in August 2007. The alfalfa may have been able to meet its ET requirements by extracting water from shallow soil layers where SWC exceeded the MAD. Mean bias error (MBE) values (range from 0.006 mm/hr to 0.101 mm/hr) for 2008 show that calculated ET_{rs} values exceeded measured ET_{ref} in the first, second and fourth cutting cycles and were less than ET_{ref} in the third cutting cycle (MBE = -0.002 mm/h). Although in the fourth cutting cycle alfalfa height did not reach 50 cm, calculated ET_{rs} values agreed well with measured values. This could be because the alfalfa canopy surface was still able to capture the available energy for ET, even with a canopy height of just 30 cm (calculated LAI = 3.69).

For the 2009 season, alfalfa at the first cutting cycle was under soil water stress, so the first cutting cycle has the largest RMSE (0.31 mm/hr) and the largest RE (125.48

%) even greater than during the 2008 season due to high soil water stress early in 2009 and deeper roots. It also had a lower index of agreement (0.691) than other cutting cycles. The other cutting cycles had lower RMSE (0.06 mm/hr - 0.11 mm/hr) and a good agreement (0.979 – 0.993) between calculated ET_{rs} and measured ET_{ref}. Mean bias error (MBE) values indicated that calculated ET_{rs} values exceeded measured ET_{ref} in the first and forth cutting cycles and were less than ET_{ref} in the second and third cutting cycles. R^2 values were 0.81, 0.97, 0.97, and 0.96 for first, second, third, and the fourth cutting cycles (Figure 7).

The 2010 season showed the best agreement between calculated ET_{rs} and measured ET_{ref} (Figure 7). Regression lines for the 2010 season indicated better correlation than 2008 and 2009 seasons since there wasn't soil water stress (Figure 8). The R^2 and index of agreement values were large at all cutting cycles. R^2 values ranged between 0.97 and 0.99. These results indicated that calculated ET_{rs} values agreed well with measured ET_{ref} (index of agreements range from 0.986 to 0.995). RMSE values range from 0.05 mm/hr to 0.11 mm/hr. Bias values showed that calculated ET_{rs} values slightly exceeded measured ET_{ref} for the first cutting cycle and were slightly less than ET_{ref} for the last three cutting cycles.

Daily measured ET_{ref} versus calculated ET_{rs}

Daily ET_{ref} was measured by the lysimeter using the water balance equation applied between 24:00 each day. ET_{rs} was also calculated for the same time period using ASCE standardized PM equation on an hourly basis and the sum of 24 hourly ET_{rs} values were used for comparison to daily measured ET_{ref}. Figures 9, 10, and 11 show daily comparisons for 2008, 2009, and 2010 seasons, respectively. The correlation between daily measured ET_{ref} values and calculated ET_{rs} generally showed the same trends as in the hourly evaluation even though with fewer data points due to limited number of days when alfalfa height was at and above 50 cm. The first cutting cycles of 2008 and 2009 had highest RMSE (2.75 mm/day for 2008 and 4.79 mm/day for 2009) and highest RE values (33.75% for 2008 and 116.96 % for 2009) and showed poor agreement (index of agreements are 0.752 for 2008 and 0.281 for 2009) between daily calculated ET_{rs} values and measured ET_{ref} because of soil water stress (Table 2). Other cutting cycles of 2008 and 2009 and all cuttings in 2010 season showed better agreement between daily calculated ET_{rs} values and measured ET_{ref}. Index of agreement ranged from 0.821 to 0.965.

Residual analysis

It is evident from Figures 5 through 10 that deviations between measured ET_{ref} and calculated ET_{rs} increase with increasing ET. Residuals (the difference between calculated ET_{rs} and measured ET_{ref}) were plotted versus climatic variables (air temperature, relative humidity, wind speed and solar radiation) excluding all the days when alfalfa was under soil water stress, as shown in Figures 12 to 14. The absolute difference between calculated ET_{rs} and measured ET_{ref} (residual) tended to increase as temperature increased and as relative humidity decreased. That could be due to either ASCE standardized ET_{rs} not predicting consistently well at high temperature and low relative humidity or the alfalfa was not consistently under reference condition. Although the residuals tended to be larger, there were no obvious bias errors associated with temperature or relative humidity.

It is well known that in the Penman Monteith derivation, Penman (1948) assumed a linear function between saturation vapor pressure and air temperature to eliminate surface temperatures which complicated the calculations of evapotranspiration (Lascano and van Bavel, 2007). This assumption is true when the air and surface temperatures are close to each other. However, this linear relationship could result in errors when Penman-Monteith is used under arid climate and when there is a big difference between surface and air temperatures.

Non-reference conditions at the lysimeter contributed in large errors between the calculated ET_{rs} and measured ET_{ref}. Alfalfa in the lysimeter was under soil water stress the whole season of 2008 and the first cutting cycle of 2009. Alfalfa was also taller than in the surrounding area during some periods of 2008, 2009, and 2010 seasons. Soil water stress and taller alfalfa have affected measured evapotranspiration, lower ET was found under soil water stress, and higher ET values were found when alfalfa in the lysimeter was taller than the surrounded field.

Effect of footprint length on evapotranspiration

Required fetch for the lysimeter and weather instruments was calculated for the second and the third cutting cycles of 2009 to study the effect of existing fetch on evapotranspiration estimation. Required fetch was compared with existing fetch of the field. Desired normalized flux (F/S_0) was taken equal to 90%, which meant that if the existing fetch equaled the required fetch, then 80% of the footprint length was in the field. If the existing fetch was less than the required fetch (calculated using footprint length), then it meant that 80 % of the footprint length was not in the field, represented by "No" in Figure 15. If the existing fetch was greater than the required fetch, then it meant that 80 % of the footprint length was in the field (represented by “Yes” in Figure 15). The ratio of existing to the required fetch was also calculated. Values less than 1 meant that the existing fetch was inadequate, and could contribute to larger residuals between the ASCE standardized PM ET_{rs} and lysimeter ET_{ref}. Values of 1 and higher meant that the existing fetch was adequate.

Residuals were classified into “Yes” and “No” categories (Fig. 15). Residuals were also plotted versus the ratio of existing to required fetch (Fig. 16). Figure 15 shows that residuals were larger when 80 % of the footprint length was not in the field (“No”) for both cutting cycles. These results indicated that lack of fetch contributed to the residuals between ASCE standardized PM ET_{rs} and lysimeter ET_{ref}. Residuals also increased as the ratio of existing to the required fetch decreased (Fig. 16). At higher ratios, good agreements between ASCE standardized ET_{rs} and lysimeter ET_{ref} were obtained and errors increased at lower ratios (Fig. 17). ASCE standardized ET_{rs} fitted better with lysimeter ET_{ref} when 80 % of the footprint length was in the field (RE = - 2.33) than when 80% of the foot print length was not in the field (RE = - 8.15) as shown in figure (18) and table (3).

CONCLUSION

The ASCE standardized PM equation is the recommended equation to compute reference evapotranspiration. ET_{rs} (tall reference) values computed by ASCE standardized PM equation were compared with alfalfa ET from a precision weighing lysimeter during periods when the alfalfa crop was in reference conditions (at least 50 cm tall; adequate soil water). Even though some challenges were encountered, such as occasional soil water stress and alfalfa extending beyond the edge of the lysimeter, encouraging results were obtained from this study. It was found that hourly calculated ET_{rs} values agreed well (index of agreement values reached 0.995) with measured ET_{ref} whenever reference conditions were satisfied. The residuals (differences between calculated ET_{rs} and measured ET_{ref}), which increased with higher temperatures and lower relative humidities, provided evidence that the ASCE standardized PM equation was inadequate under conditions of high temperature and low relative humidity. Although the field dimension was 158.5 m × 256.1 m, results of the fetch analysis clearly indicated that the fetch around the lysimeter and weather instruments was not adequate for significant periods of time. ASCE standardized ET_{rs} fitted better with lysimeter ET_{ref} under adequate fetch (RE = - 2.33) than under inadequate fetch (RE = - 8.15).

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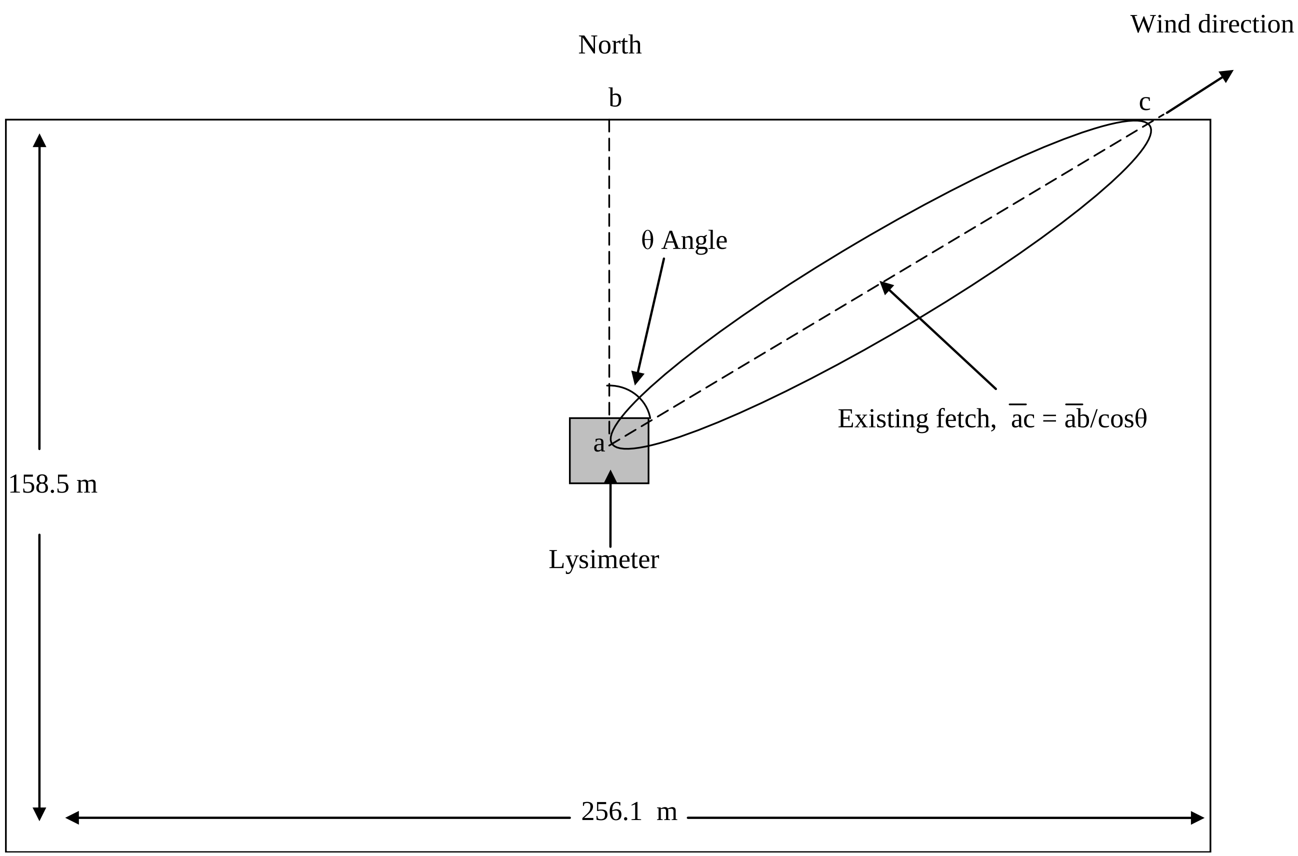


Fig. 1. A sketch showing the calculations of existing fetch using trigonometry and wind direction angle.

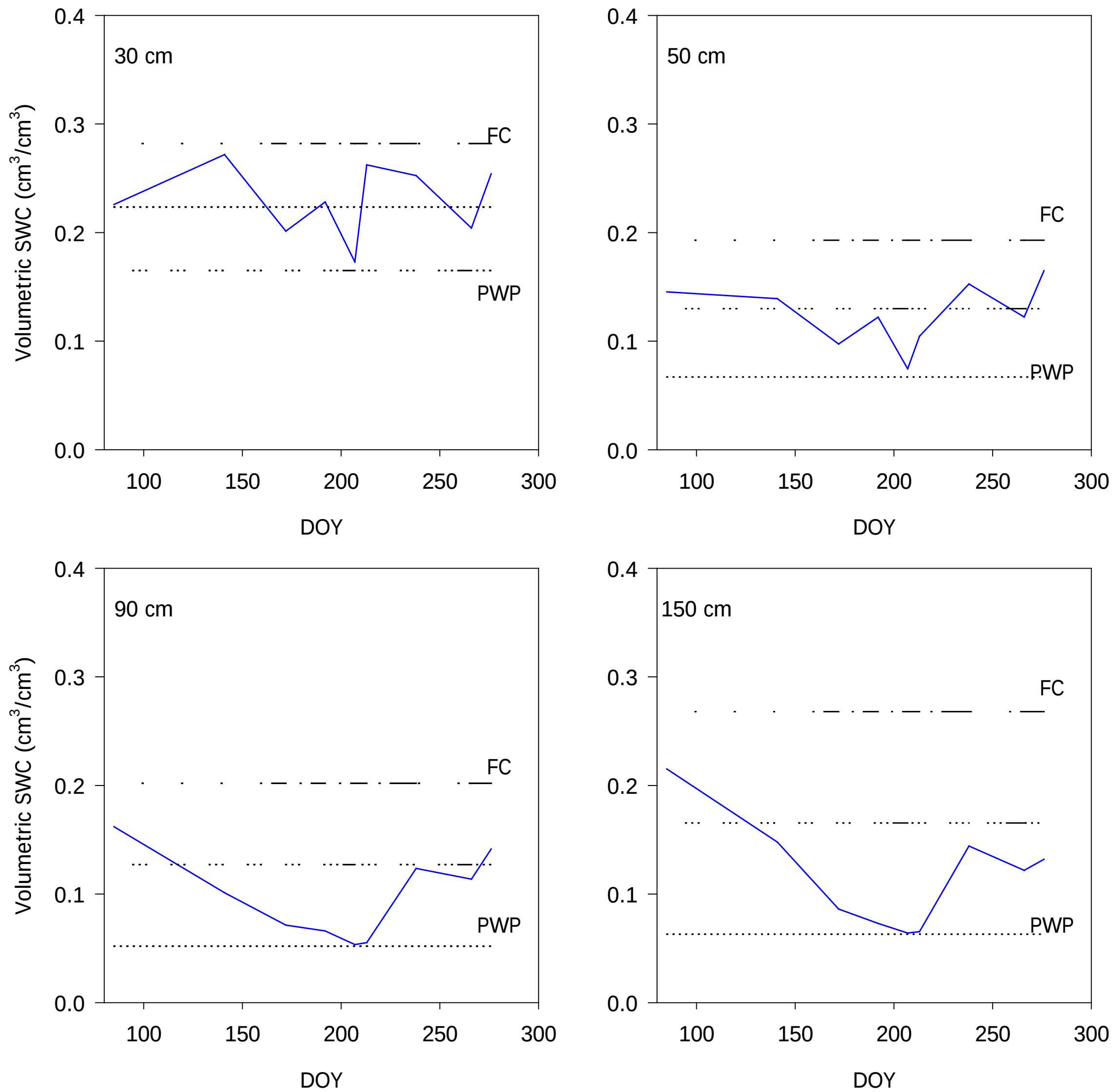


Fig. 2. Volumetric soil water content (cm^3/cm^3) throughout the 2008 growing season as measured by neutron moisture meter at 30 cm, 50 cm, 90 cm and 150 cm

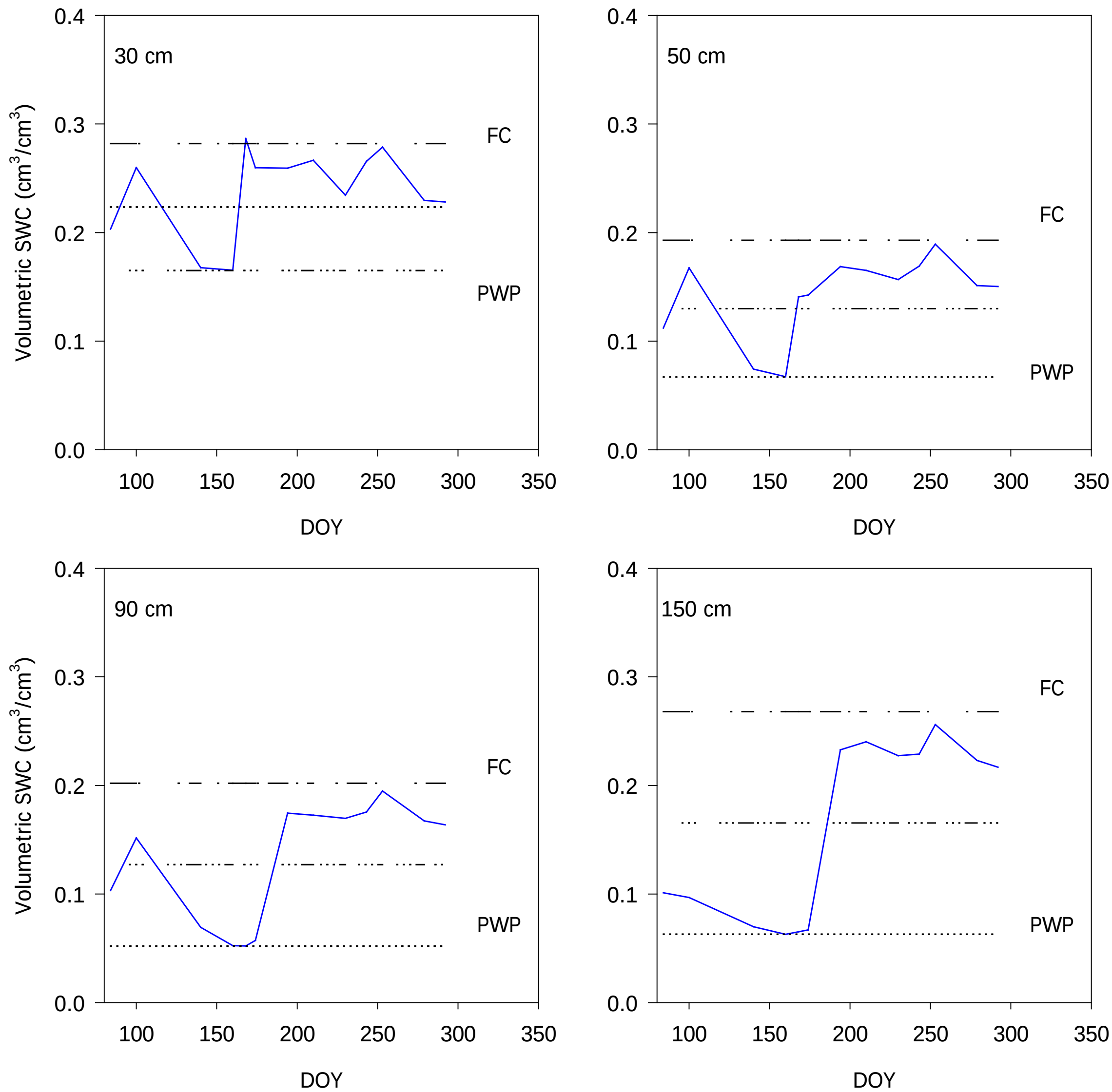


Fig. 3. Volumetric soil water content (cm^3/cm^3) throughout the 2009 growing season as measured by neutron moisture meter at 30 cm, 50 cm, 90 cm and 150 cm

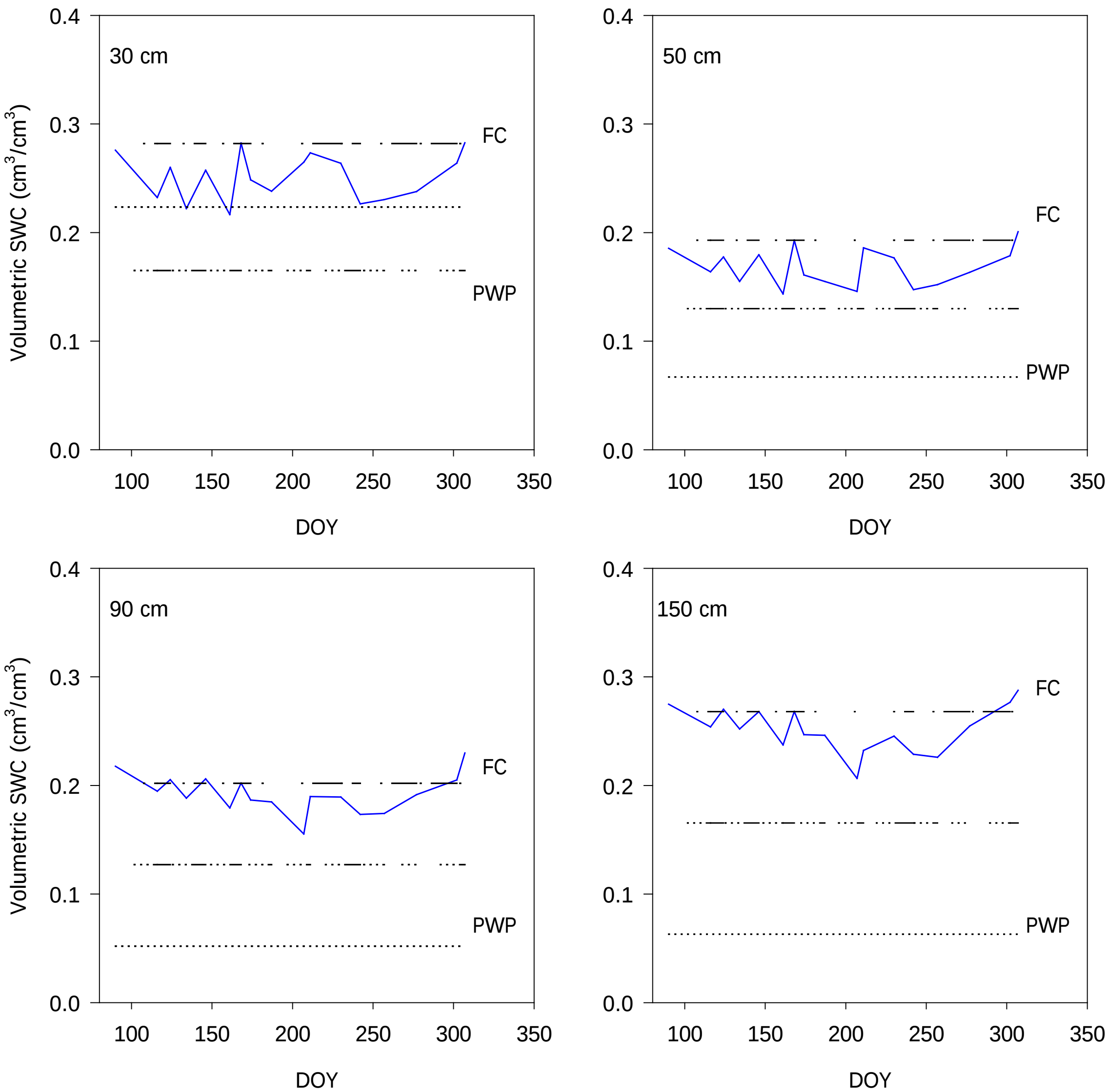


Fig. 4. Volumetric soil water content (cm^3/cm^3) throughout the 2010 growing season as measured by neutron moisture meter at 30 cm, 50 cm, 90 cm and 150 cm

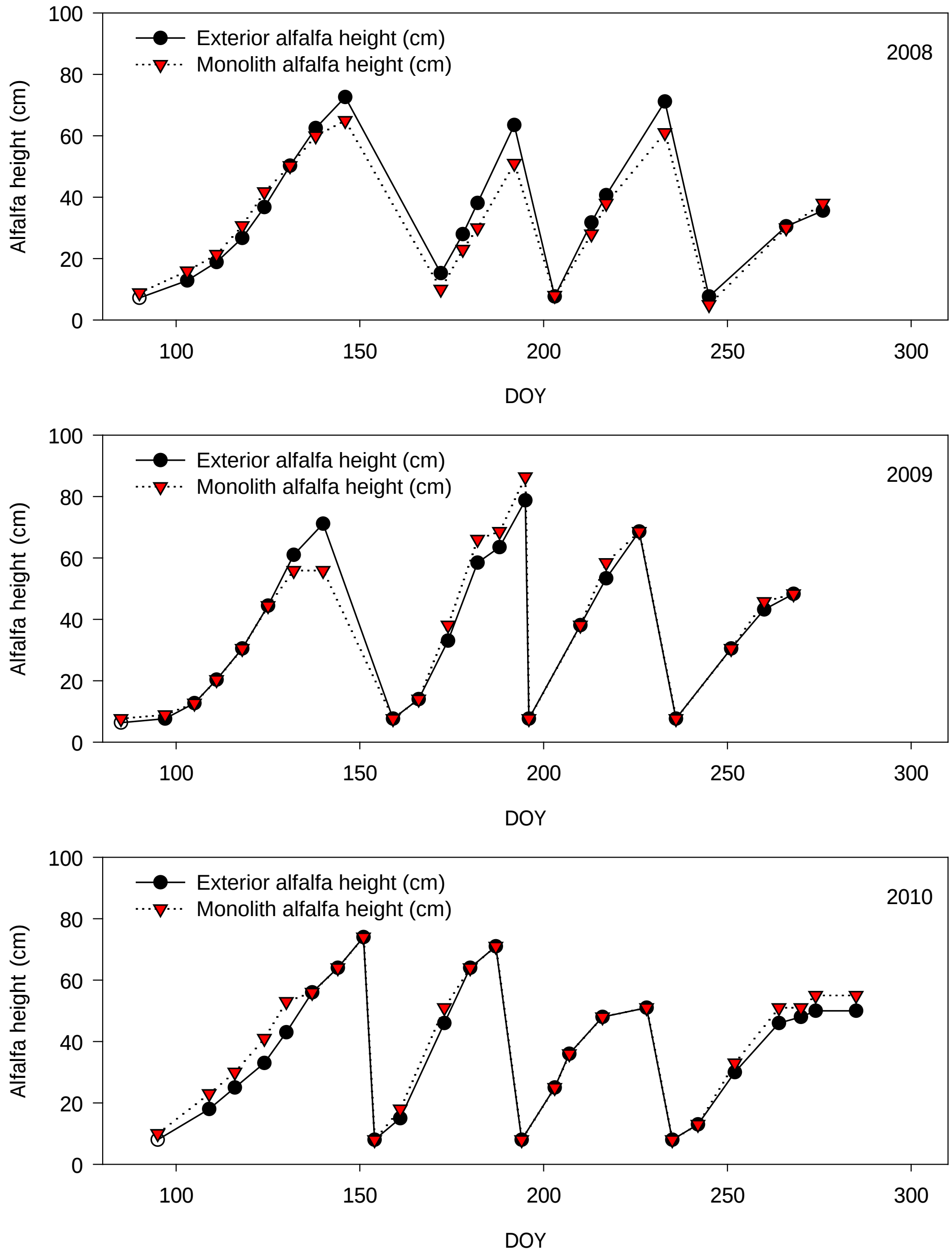


Fig. 5. Monolith and exterior alfalfa height for each cutting cycle of 2008, 2009 and 2010 seasons.

Table 1. Statistical evaluation of hourly ASCE-PM ET_{rs} and lysimeter ET_{ref} for each cut of the 2008, 2009 and 2010 seasons

Season	Cuts	ASCE-PM ETrs (mm/hr)			ET lysimeter (mm/hr)			RMSE	RE	Index of	MBE
		Mean	Max	Min	Mean	Max	Min	mm/hr	%	agreement	mm/hr
2008	Cut 1	0.39	1.51	-0.03	0.29	1.06	-0.07	0.18	32.80	0.936	0.101
	Cut 2	0.36	1.20	-0.04	0.35	1.06	-0.02	0.05	1.78	0.994	0.006
	Cut 3	0.28	1.20	-0.04	0.28	1.27	-0.05	0.09	-0.90	0.982	-0.002
	Cut 4	0.17	0.92	-0.06	0.16	0.86	-0.02	0.06	10.81	0.979	0.017
2009	Cut 1	0.35	1.58	-0.04	0.16	0.53	-0.02	0.31	125.48	0.691	0.196
	Cut 2	0.36	1.16	-0.02	0.42	1.46	-0.03	0.11	-14.69	0.979	-0.062
	Cut 3	0.33	1.15	-0.04	0.34	1.28	-0.02	0.06	-4.05	0.993	-0.014
	Cut 4	0.23	1.17	-0.06	0.21	0.94	-0.01	0.07	8.18	0.984	0.017
2010	Cut 1	0.36	1.48	-0.04	0.32	1.27	-0.03	0.08	13.66	0.986	0.043
	Cut 2	0.42	1.28	-0.05	0.47	1.48	-0.02	0.11	-11.00	0.984	-0.052
	Cut 3	0.31	1.17	-0.05	0.33	1.21	-0.02	0.05	-6.39	0.995	-0.021
	Cut 4	0.20	1.22	-0.05	0.24	1.36	-0.01	0.06	-16.63	0.990	-0.040

Table 2. Statistical evaluation of daily ASCE-PM ET_{rs} and lysimeter ET_{ref} for each cut of the 2008, 2009 and 2010 seasons

Season	Cuts	ASCE-PM ETrs (mm/day)			ET lysimeter (mm/day)			RMSE	RE	Index of	MBE
		Mean	Max	Min	Mean	Max	Min	mm/day	%	agreement	mm/day
2008	Cut 1	9.07	15.21	2.54	6.78	10.34	2.12	2.75	33.75	0.752	2.289
	Cut 2	8.82	12.14	6.57	8.42	9.51	5.99	0.92	4.76	0.862	0.400
	Cut 3	6.46	10.67	1.44	6.48	9.73	1.53	0.93	-0.20	0.949	-0.013
	Cut 4	3.89	6.12	0.25	3.59	5.64	0.26	0.52	8.54	0.968	0.306
2009	Cut 1	7.59	13.45	1.72	3.50	5.16	1.57	4.79	116.96	0.281	4.092
	Cut 2	8.17	10.30	5.32	9.56	12.80	6.15	1.49	-14.52	0.821	-1.388
	Cut 3	7.60	10.25	3.33	7.97	11.35	3.44	0.62	-4.72	0.965	-0.376
	Cut 4	4.97	10.30	1.67	4.70	8.46	1.83	0.80	5.64	0.952	0.265
2010	Cut 1	7.69	13.70	2.86	6.88	11.88	2.55	1.04	11.75	0.961	0.809
	Cut 2	9.05	13.01	5.37	10.25	14.42	6.15	1.31	-11.69	0.917	-1.198
	Cut 3	6.83	9.60	4.06	7.38	9.71	5.04	0.63	-7.50	0.944	-0.553
	Cut 4	4.79	7.87	2.82	5.74	8.87	3.54	0.97	-16.58	0.914	-0.952

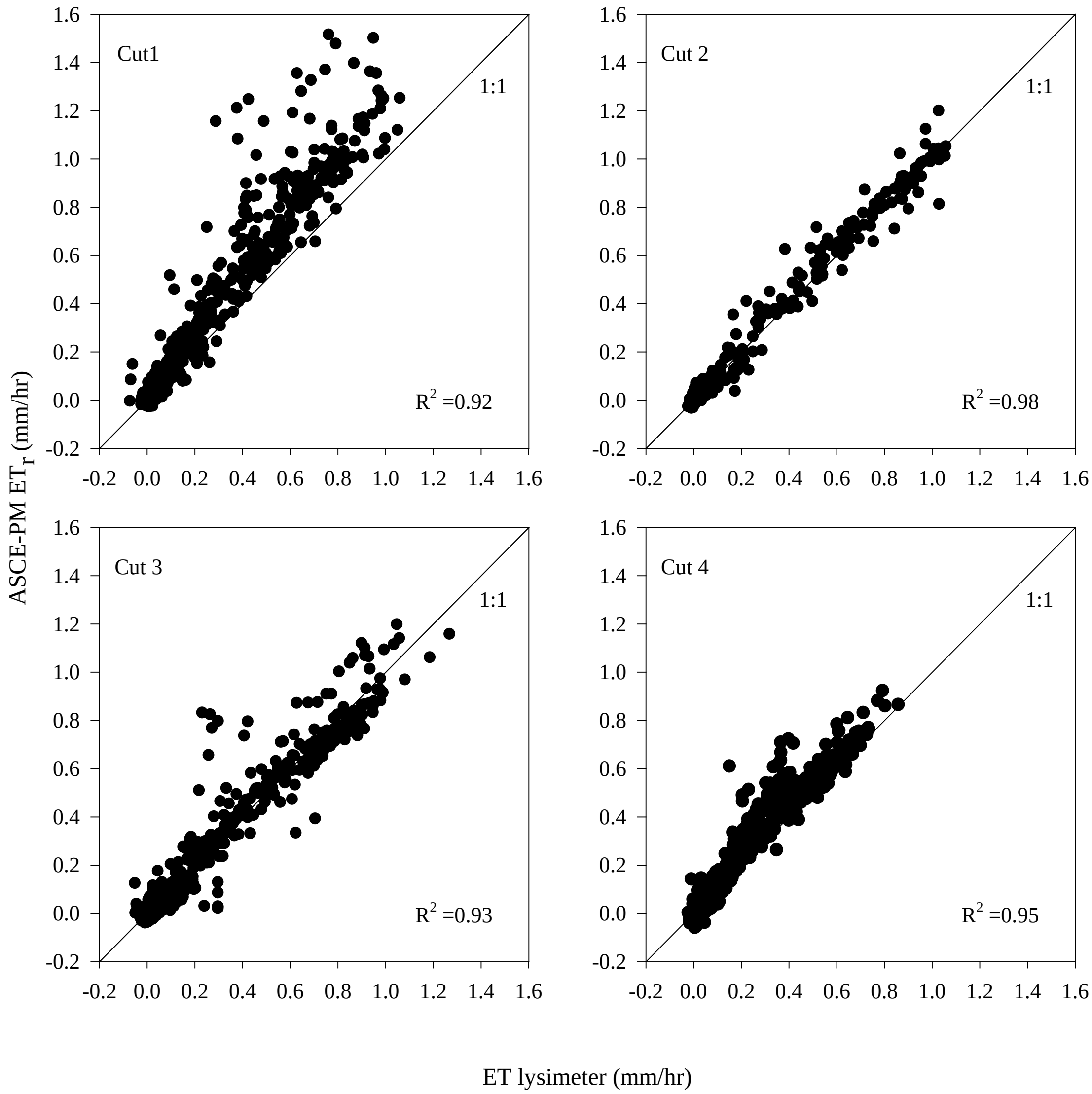


Fig. 6. Hourly ASCE standardized PM ET_{rs} (mm/hr) versus hourly evapotranspiration measured by lysimeter (mm/hr) for the 2008 season. Alfalfa was under water stress at all cuttings cycles.

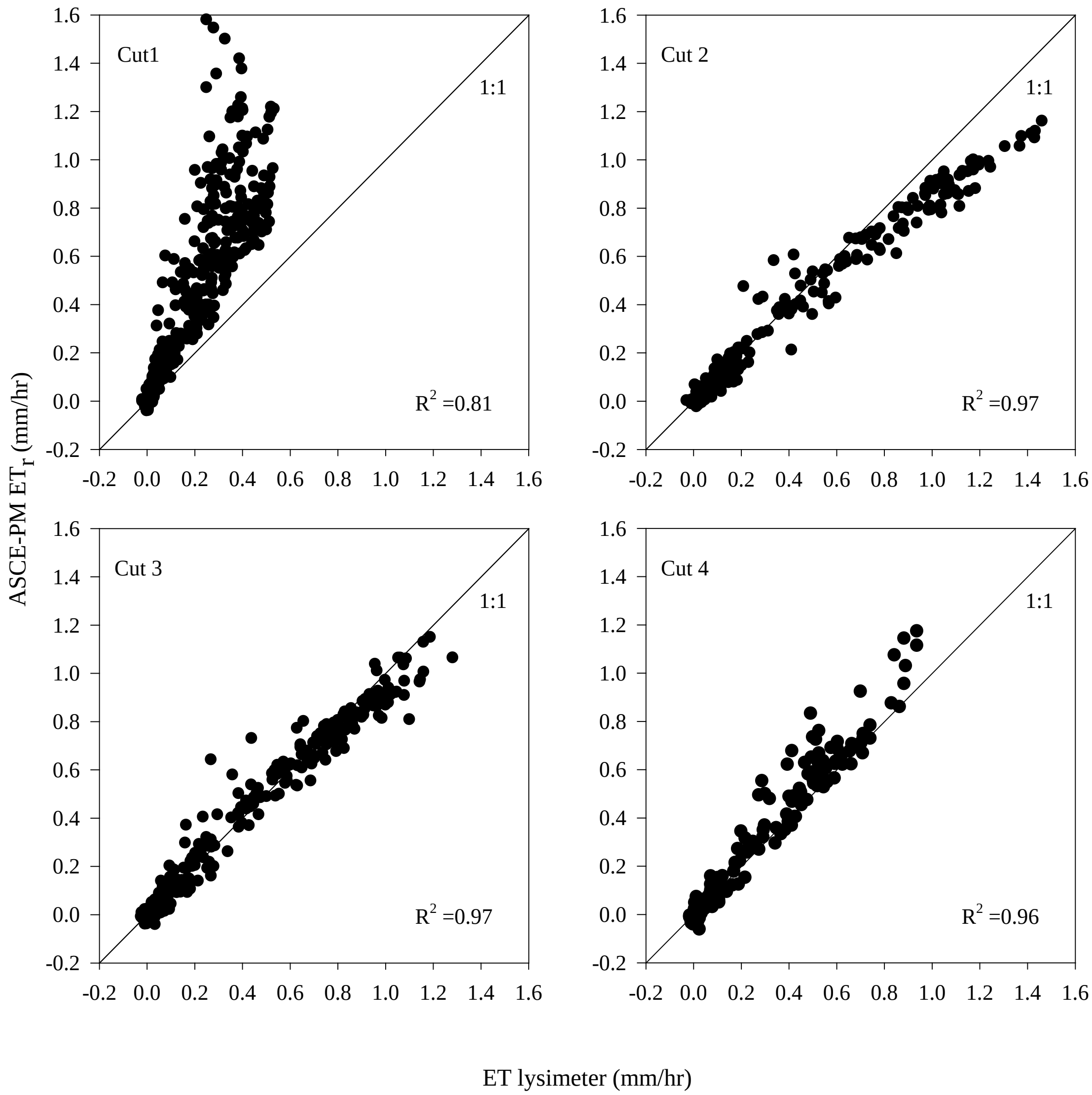


Fig. 7. Hourly ASCE standardized PM ET_{rs} (mm/hr) versus hourly evapotranspiration measured by the lysimeter (mm/hr) when alfalfa was at reference height (50 cm) for the 2009 season. Alfalfa was under water stress at the first cutting cycle.

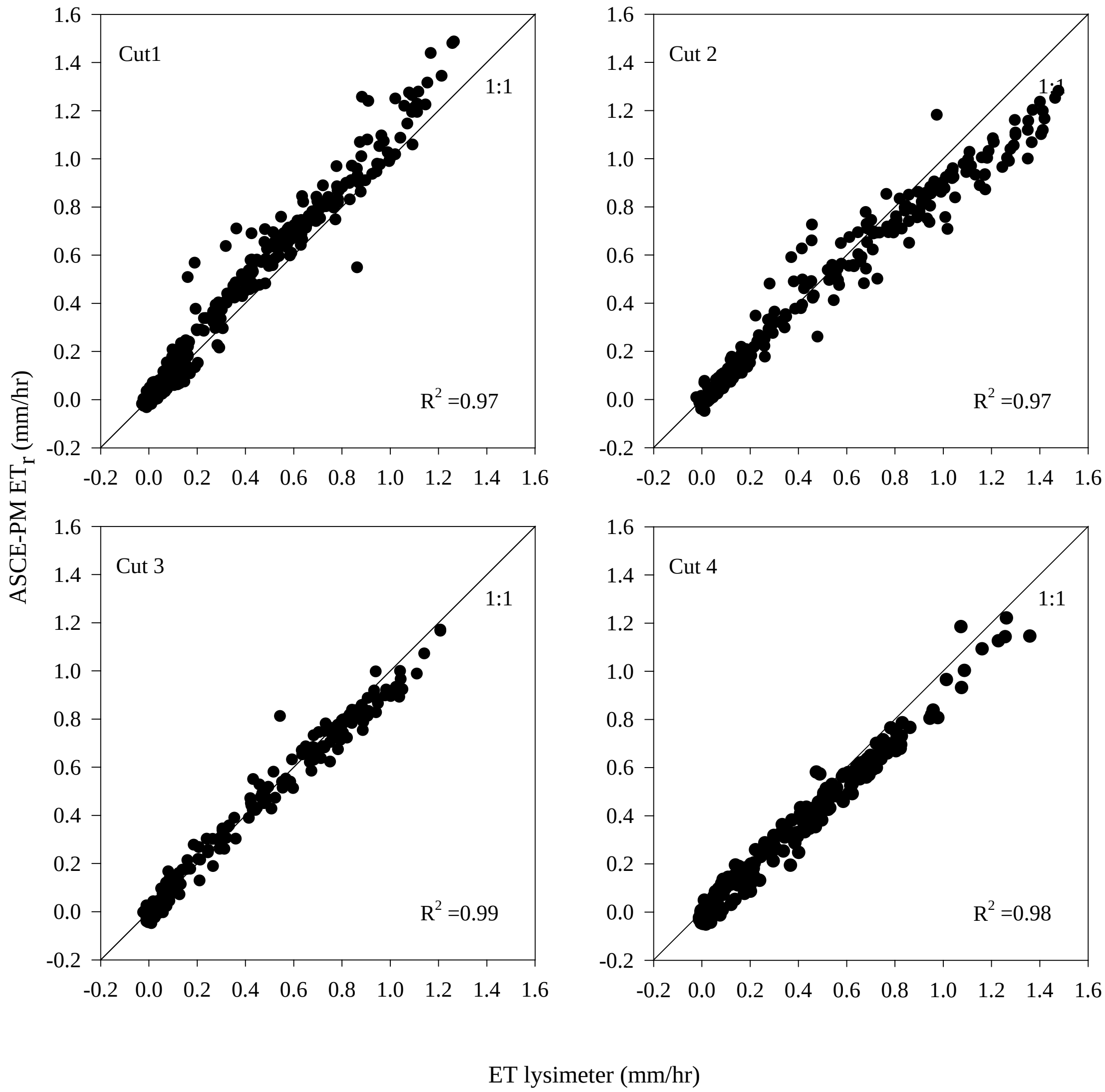


Fig. 8. The Hourly ASCE standardized PM ET_{rs} (mm/hr) versus hourly evapotranspiration measured by lysimeter (mm/hr) when alfalfa was at reference height (50 cm) for the 2010 season.

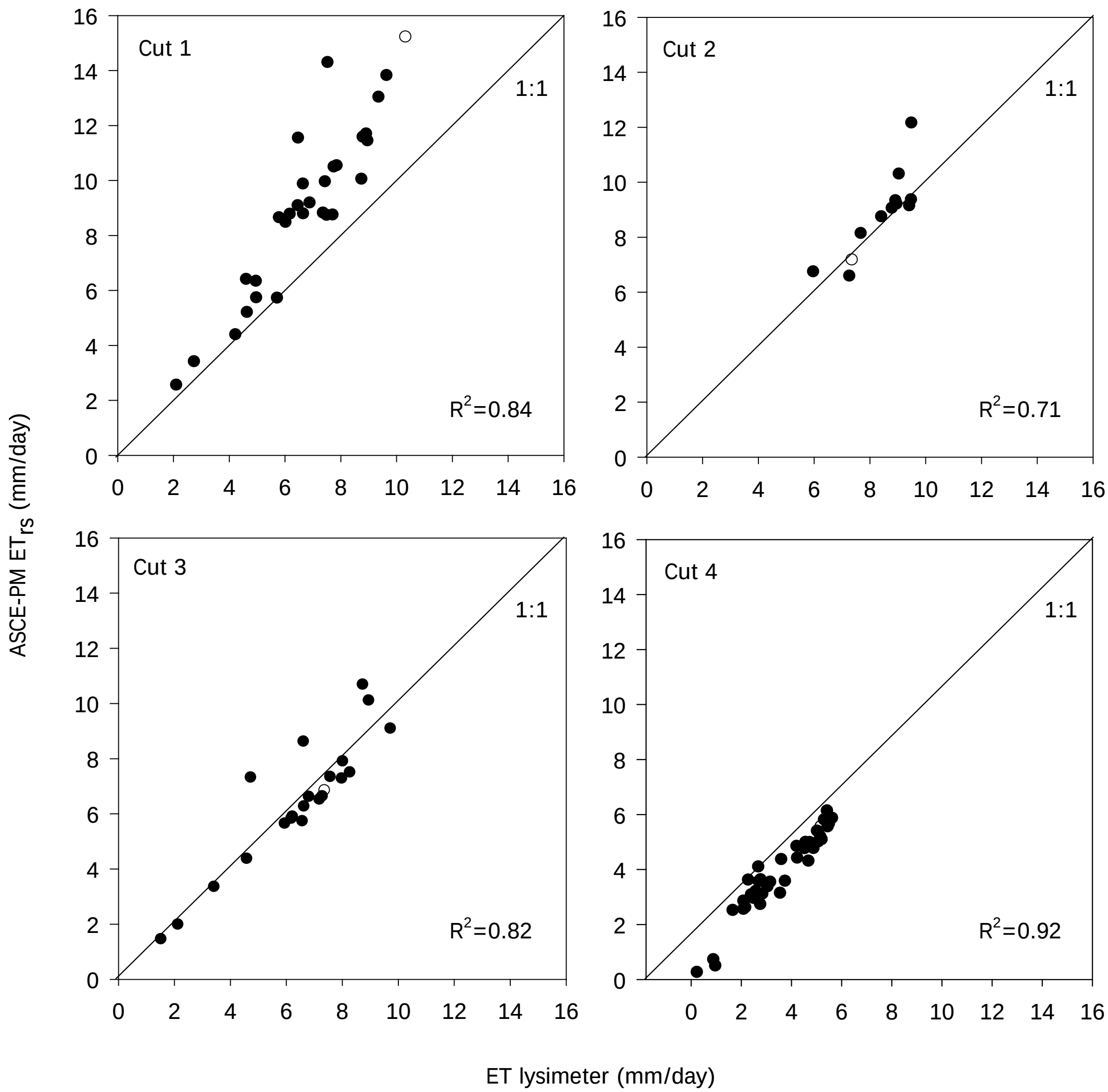


Fig. 9. The relationship between daily evapotranspiration measured by the lysimeter (mm/day) and daily ASCE standardized PM ET_{rs} (mm/day) when alfalfa was at reference height (50 cm) for the 2008 season. Alfalfa was under water stress at all cuttings cycles.

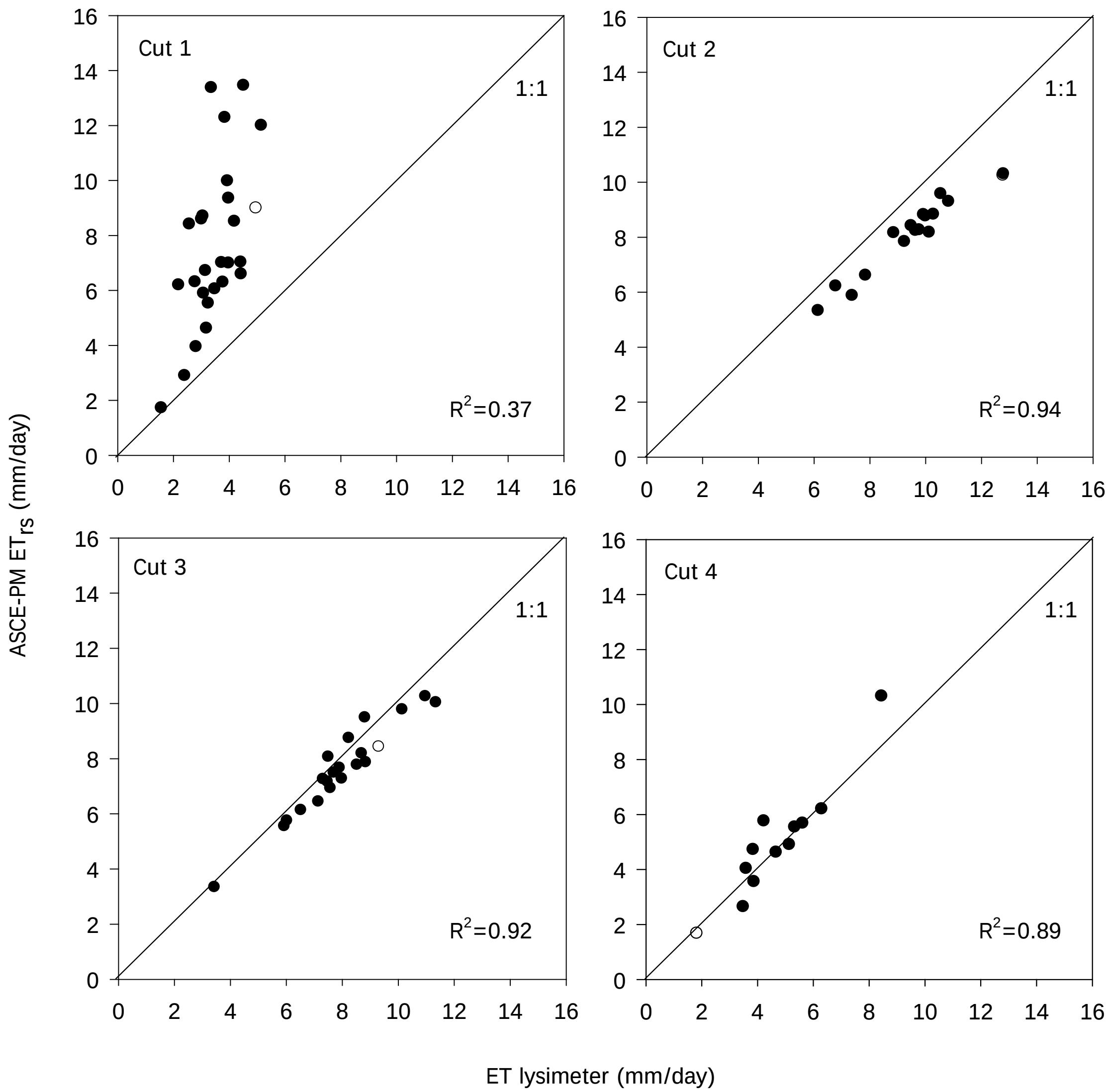


Fig. 10. The relationship between daily evapotranspiration measured by the lysimeter (mm/day) and daily ASCE standardized PM ET_{rs} (mm/day) when alfalfa was at reference height (50 cm) for the 2009 season. Alfalfa was under water stress at the first cutting cycle.

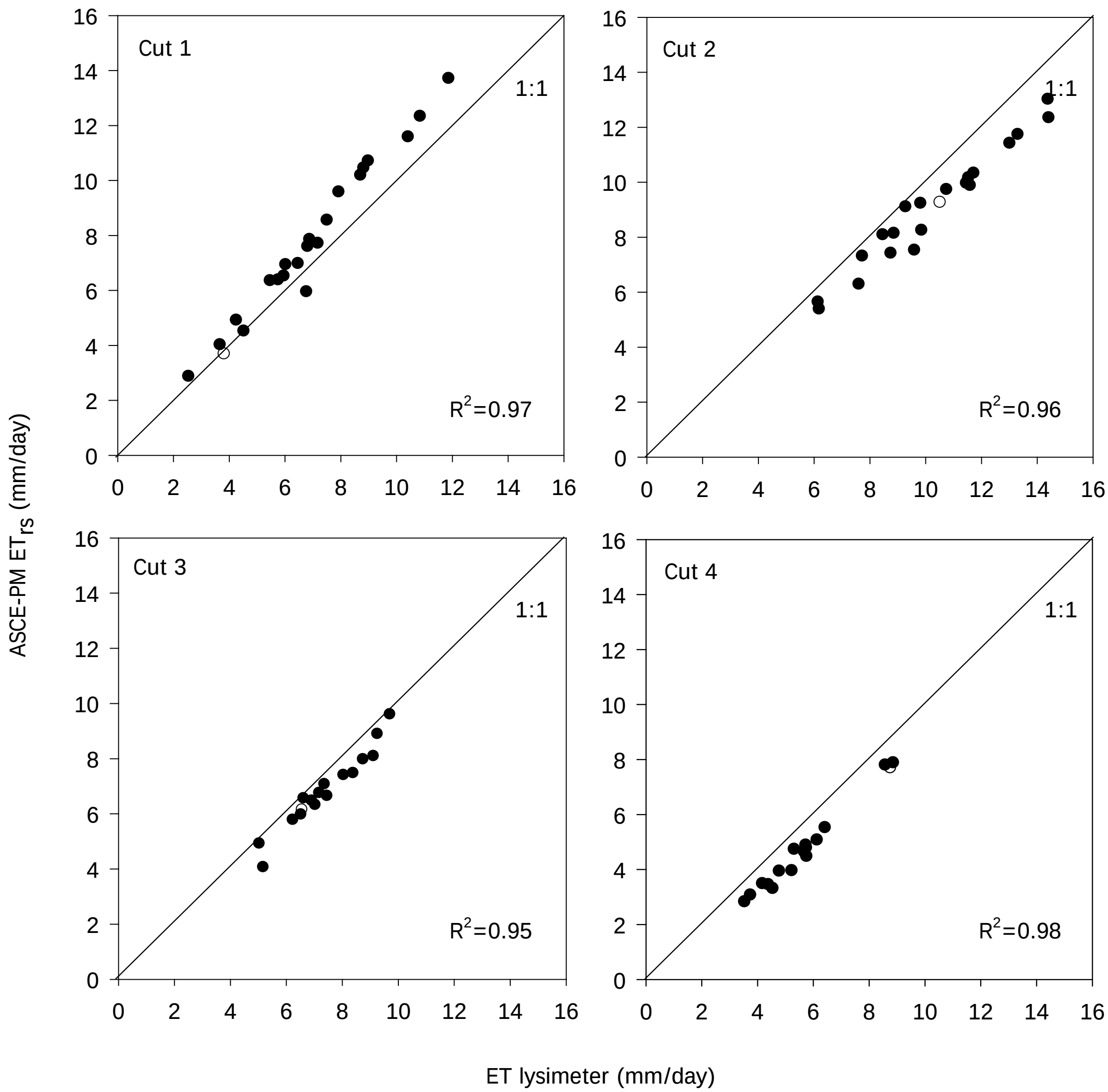


Fig. 11. The relationship between daily evapotranspiration measured by the lysimeter (mm/day) and daily ASCE standardized PM ETrs (mm/day) when alfalfa was at reference height (50 cm) for the 2010 season

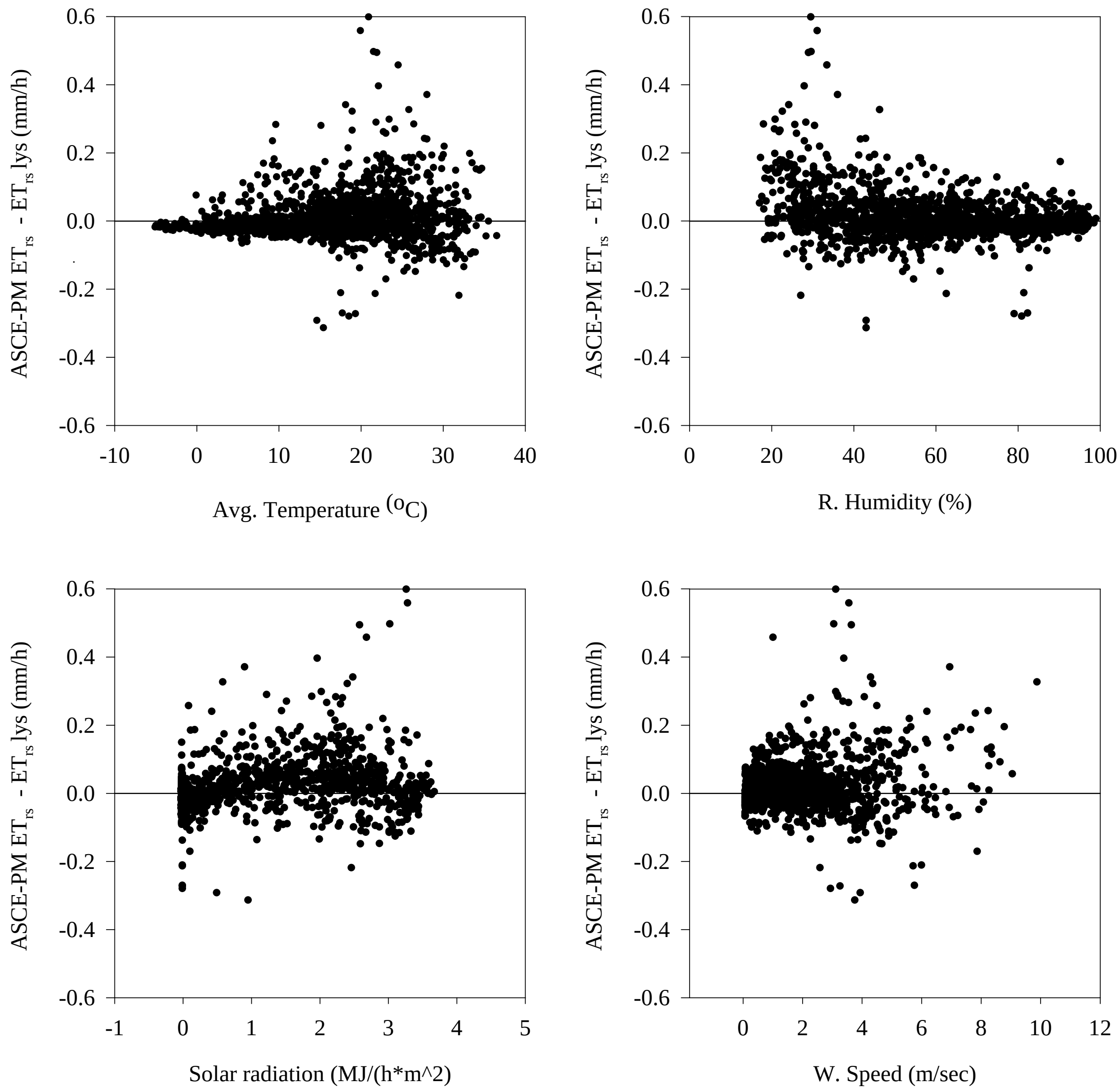


Fig. 12. The residuals (measured ET_{ref} (mm/h) - calculated ET_{rs} (mm/h)) versus climatic variables (temperature, relative humidity, solar radiation and wind speed) for the 2008 season

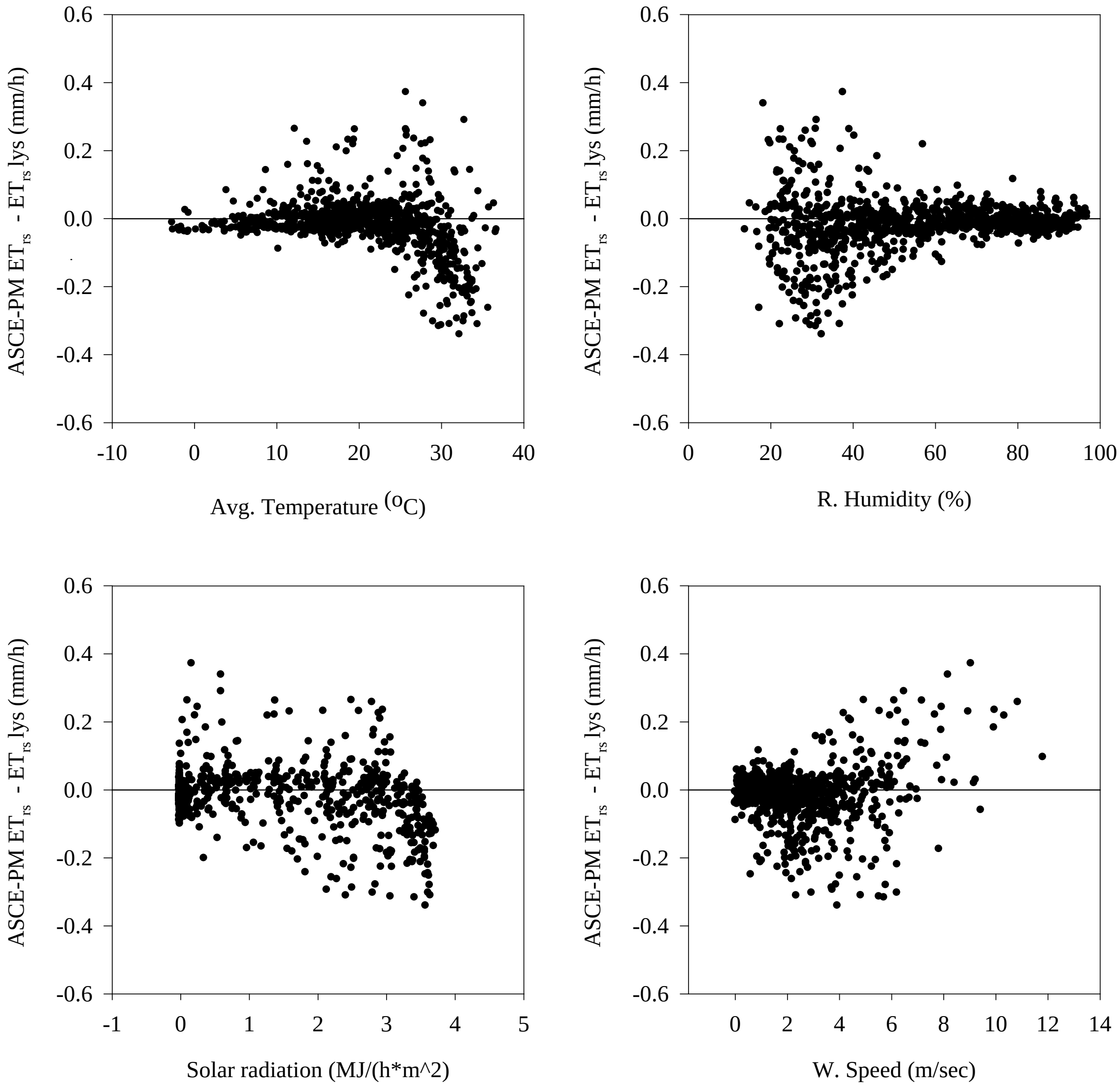


Fig. 13. The residuals (measured ET_{ref} (mm/h) - calculated ET_{rs} (mm/h)) versus climatic variables (temperature, relative humidity, solar radiation and wind speed) for the 2009 season

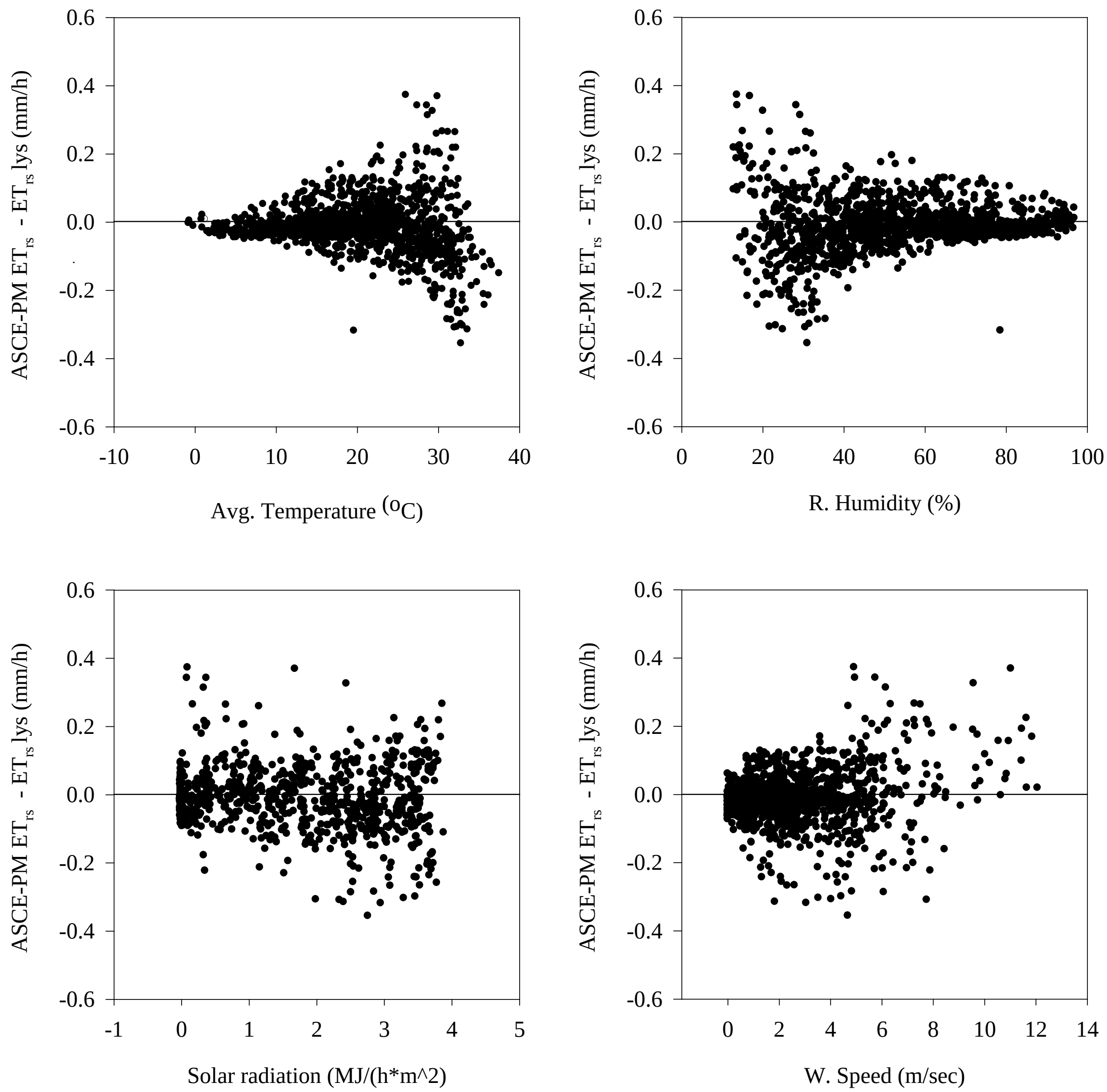


Fig. 14. The residuals (measured ET_{ref} (mm/hr) - calculated ET_{rs} (mm/hr)) versus climatic variables (temperature, relative humidity, solar radiation and wind speed) for the 2010 season

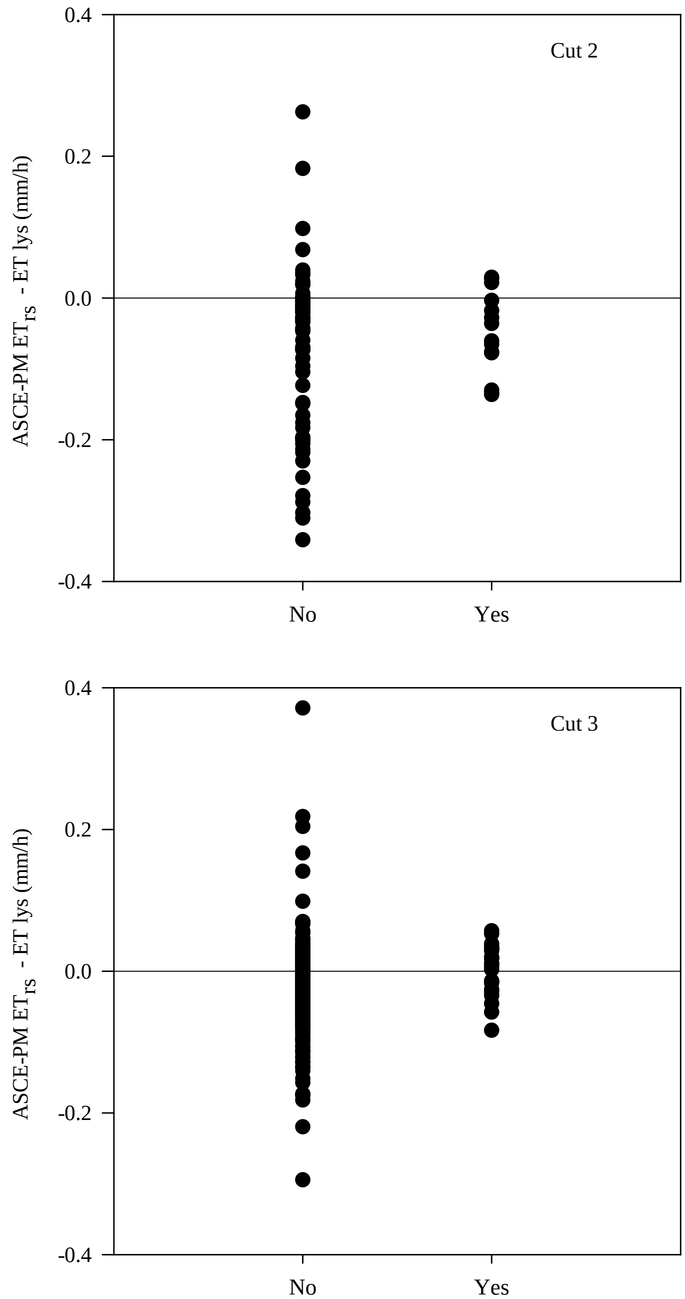


Fig. 15. Residuals classified into "No" and "Yes" categories. "No" means that the existing fetch was less than the required fetch. "Yes" means that the existing fetch was equal or greater than the required fetch. Fetch requirements were determined for cutting cycles 2 and 3 of the 2009 season.

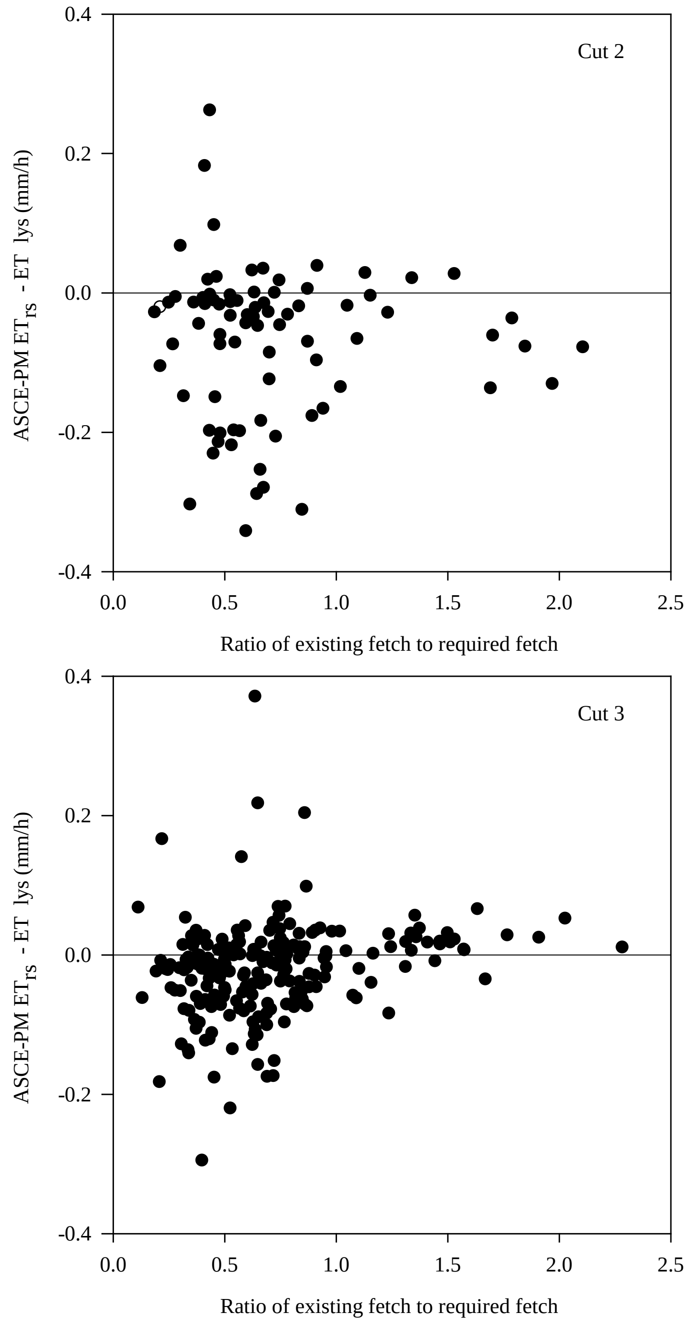
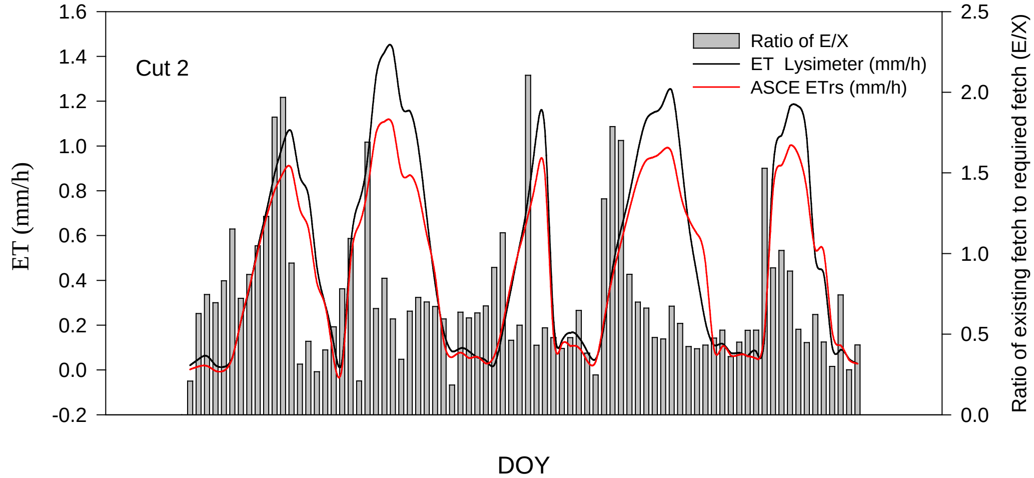


Fig. 16. Residuals versus the ratio of existing fetch to the required fetch. Lower ratios meant that the existing fetch was inadequate while higher ratios meant existing fetch was adequate. Fetch requirements were determined for cutting cycles 2 and 3 for the 2009 season.



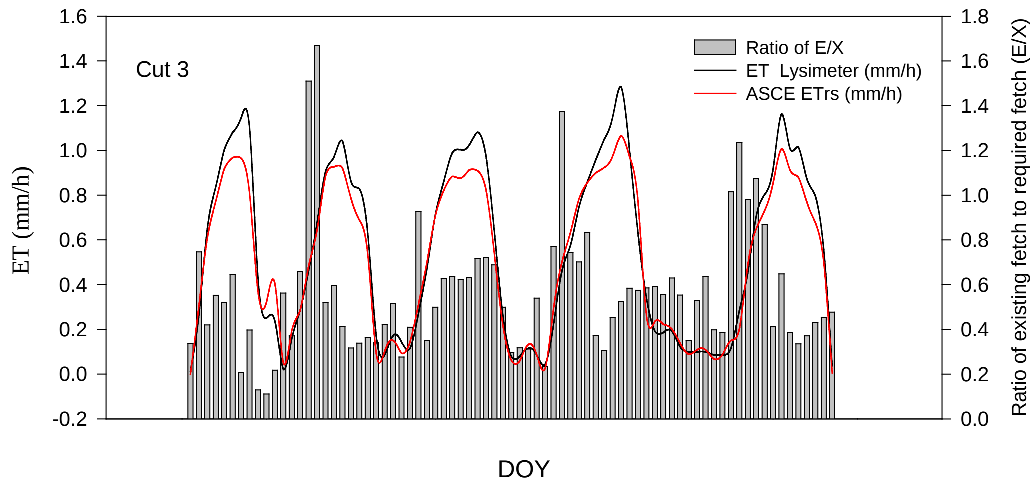


Fig. 17. Relationship between calculated and measured reference ET and the ratio of existing fetch to the required fetch for cutting cycles 2 and 3 of the 2009 season.

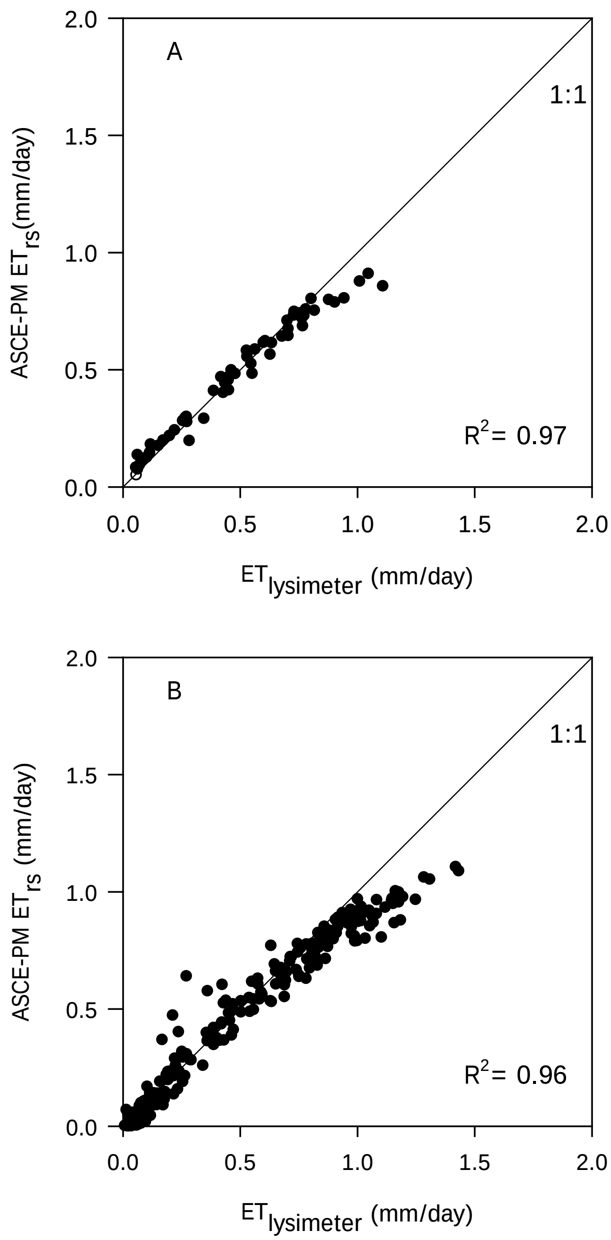


Fig. 18. Relationship between Hourly ASCE standardized PM ET_{rs} (mm/hr) and hourly evapotranspiration measured by lysimeter (mm/hr) when 80% of the footprint length was in the field (A) and when 80 of the footprints length not in the field (B)

Table 3. Statistical evaluation of hourly ASCE-PM ET_{rs} and lysimeter ET_{ref} when 80% of the footprint length in or not in the field for the second and third cutting cycle of 2009 season

	80 % in the field	80 % not in the field
Mean ET lyismeter Mean (mm/h)	0.498	0.449
Mean ASCE standardized ET (mm/h)	0.486	0.412
Relative Error of Mean (%)	-2.327	-8.149
RMSE (mm/h)	0.060	0.093
Index of Agreement (d)	0.987	0.984
Nash-Suttcliffe E	0.956	0.945
No. Obs.	58	262

CHAPTER THREE: ALFALFA CROP COEFFICIENTS DEVELOPED USING A WEIGHING LYSIMETER IN SOUTHEAST COLORADO

ABSTRACT

Weighing lysimeters are precise devices used to measure crop evapotranspiration (ET) and to develop crop coefficients. A weighing lysimeter was installed in the Arkansas River Valley of Colorado in 2006 to measure ET and develop crop coefficients of locally-grown crops. The lysimeter was filled with a 3 m × 3 m undisturbed soil monolith. Alfalfa (*Medicago sativa L.*) was planted in the lysimeter and in 4 ha of surrounding field in August 2007. Climatic data and soil conditions were measured using microclimate and soil sensors installed above and on the lysimeter. Furrow irrigation was applied to the monolith and surrounding field. Reference ET was calculated using the hourly ASCE standardized reference ET equation. Crop coefficients of alfalfa were calculated by dividing daily measured ET from the lysimeter by the corresponding daily ASCE standardized reference ET. Alfalfa was harvested four times in each of the 2008, 2009 and 2010 growing seasons. The results showed that the alfalfa growth, climate, precipitation and soil water content all influenced the shape of the crop coefficient curves. The first cutting cycle, which had slower growth due to cool climate, had lower crop coefficients, whereas later cutting cycles with rapid growth had higher crop coefficients. The maximum crop coefficients were below 1.2 in 2008 and at or above 1.2 in 2009 and 2010. Precipitation interception by the alfalfa canopy increased evaporation and caused outliers in the crop coefficient values.

INTRODUCTION

Irrigation water management is an essential element of conservation and sustainability of water resources. Effective irrigation management depends on accurate estimates of crop water use which is needed for irrigation scheduling and design. Crop water use is defined as the water lost from crop and soil through the processes of transpiration and evaporation which is combined in the term evapotranspiration (ET).

Estimation of ET or water use is the foundation of irrigation scheduling and efficient irrigation water management. Although many methods to determine ET are available, direct measurement using a weighing lysimeter is the standard and the most precise tool for measuring crop water use (Tolk et al., 2005 ; Evett et al., 2009). In a precision weighing lysimeter, ET and other components of the water balance are determined by continuously measuring the change in mass of a soil monolith having an actively growing crop, with an accuracy of a few hundredths of a millimeter (Allen et al., 1998). The crop coefficient (Kc), which represents the effect of plant characteristics on ET, is the ratio of the actual crop evapotranspiration (ETc) to the reference evapotranspiration (ET_{ref}) for non water stress condition.

ET_c (i.e. crop water use) is the total amount of water lost due to transpiration from plant canopies and evaporation from soil and plant surfaces. It can be quantified using a two step approach by adjusting ET_{ref} with Kc. ET_{ref} is defined as the rate of evapotranspiration from a reference crop having uniform height, actively growing, with a full cover and growing on an extended area (Jensen et al., 1990; Allen et al 1998). ASCE standardized Penman Monteith ET (ASCE-PM ET_{ref}) is the recently recommended equation by the American Society of Civil Engineers (ASCE) to determine ET_{ref} (ASCE-EWRI, 2005). Crop coefficients (K_c) represent effects of crop growth (leaf area index or ground cover, crop height, and root depth) on ET. The evolution of these plant characteristics depend on sowing date and crop development rate, and crop management (fertility, soil, climate, planting density, row orientation) (Irmak et al., 2005). They are widely used to estimate crop water use and in determining when and how much water to apply with irrigation (Howell et al., 2006). Even though K_c values for most crops are available in the literature, developing them under local conditions is recommended for more accurate calculation of ET that accounts for local climate, environmental, and crop management factors (Evett et al., 1998). Crop coefficients that have been used by the Colorado Division of Water Resources are estimated from lysimeter data collected at Kimberly, Idaho and Bushland, Texas (Berrada et al., 2008). They were developed using reference ET equations other than the standardized ASCE-PM ET_{ref} equation.

Alfalfa is one of the major and most valuable forage crops and has the highest yield potential in Colorado (Smith et al., 1999). Irrigated alfalfa has one of the highest levels of seasonal water use among irrigated crops (Wright, 1988). Determination of alfalfa water use and subsequent efficient application of irrigation could be a way of saving water. The objective of this research was to develop crop coefficients for alfalfa grown for feed using a weighing lysimeter and the ASCE standardized Penman Monteith ET equation in the Arkansas Valley of Colorado.

MATERIALS AND METHODS

Experiment location

The experiment was conducted in 2008, 2009 and 2010 at the Arkansas Valley Research Center in southeast Colorado (latitude 38^o 2’ 17.30”, longitude 103^o 41’ 17.60”, altitude 1,274 m above sea level). It was carried out using a large weighing lysimeter constructed for evaluating the American Society of Civil Engineers (ASCE) standardized Penman-Monteith (PM) equation and to compute actual evapotranspiration (ETc) and crop coefficients (Kc) for various crops under Arkansas Valley conditions. The lysimeter was built using an undisturbed soil monolith of a Rocky Ford coarse loamy, mixed, superactive, mesic Aridic argiustoll. The soil pH and electrical conductivity (ECe) were 8.2 and 0.78 dS/m, respectively. The soil layers have bulk density and hydraulic conductivity ranges of 1.35-1.45 g/cm^3 and 0.33-1.25 cm/hr, respectively (Table 1).

Lysimeter design

The inner tank of the weighing lysimeter has dimensions of 3.0 m x 3.0 m x 2.4 m depth. Calibration of the weighing mechanism was done according to the procedure developed by USDA-ARS at Bushland, Texas (Berrada et al., 2008) to convert the load cell output in mV/V to equivalent mass of water and water depth evapotranspired. The lysimeter load cell output was recorded every 10 seconds throughout each growing season. Fifteen-minute averages of the load cell outputs were used in the calculation of ET_c. Based on the calibration; a change of 1 mV/V in the load cell output was equivalent to a change of 76 mm of water in the lysimeter. The drainage water was measured by mass change using a separate scale. It was collected in a drainage tank suspended in the lysimeter. Therefore there was no overall weight change as water drained into the drainage tank.

Climate and soil measurements

An automatic weather station was installed directly above the lysimeter to measure climate variables around and within the monolith. Variables included rainfall, horizontal wind speed, air temperature, incoming short wave solar radiation, barometric pressure, soil temperature, and soil heat flux. Berrada et al. (2008) described in detail the sensors and their placement. Climatic data were recorded every 15 minutes. Soil water content was measured by neutron attenuation (CPN 503 DR) at 20 cm increments starting at 10 cm to 190 cm. Two access tubes for neutron probe, were installed inside the monolith and four were installed immediately outside the lysimeter. The neutron probe was calibrated based on the method recommended by Evett et al. (Berrada et al., 2008).

Alfalfa and irrigation management

The soil monolith was irrigated manually to mimic the furrow irrigation of the surrounding field (158.5 m North-South x 256.1 m East-West). When field furrows reached the lysimeter, they were diverted around the lysimeter. The surface of the soil monolith had four furrows with spacing of 76 cm and water was pumped from an irrigation canal and applied to the furrows through a flow meter and hose. Alfalfa (Genoa variety) was planted mechanically in the field and by hand in the lysimeter on 9 August 2007 at a seeding rate of 21.3 kg/ha. Height of the alfalfa canopy was measured weekly. Alfalfa was harvested four times in each of seasons 2008, 2009 and 2010. Alfalfa in the lysimeter was harvested manually on June 11, July 21, September 1 and November 3 in 2008; on June 8, July 15, August 24 and October 5 in 2009; and on June 3 , July 13, August 23 and October 14 in 2010.

Water balance

To calculate the seasonal amount of water used by alfalfa in the lysimeter, seasonal water balance for the 2008, 2009 and 2010 seasons was calculated based on the lysimeter weight data using the water balance equation:

$$\mathrm{ET} = \mathrm{P} + \mathrm{Irr} - \mathrm{D} + \Delta\mathrm{S} \qquad \text{Eq. (1)}$$

where ET is evapotranspiration, P is precipitation , Irr is irrigation , D is drainage and ΔS is seasonal change in soil water content measured by the lysimeter. Runoff and deep percolation were equal to zero during the study period.

The surface area of the lysimeter is 3 m x 3 m (9 m^2). As alfalfa inside the lysimeter grew, it extended outside the lysimeter edges, increasing the area that was subjected to evapotranspiration. The horizontal extension of alfalfa outside the edges was measured weekly in the last cutting cycle of 2010 (by taking the average measurement of alfalfa extended from the four sides of the lysimeter) to adjust and correct the evaporative area. The alfalfa extended outside the lysimeter edge versus number of days after harvest was plotted and the equation was used to correct the evaporative area. The corrected area was used to adjust ET_c values measured from the lysimeter.

Reference ET calculation

The American Society of Civil Engineers (ASCE-PM) standardized ET_{sz} equation was used to estimate tall (alfalfa) reference evapotranspiration on an hourly time step using climatic data obtained from the weather station.

$$\mathrm{ET_{rs}} = \frac{0.408\,\Delta\,(\mathrm{R_n} - \mathrm{G}) + \gamma\,\frac{\mathrm{C_n}}{\mathrm{T} + 273}\,\mathrm{u_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + \mathrm{C_d u_2})} \qquad \text{Eq. (2)}$$

where ET_{rs} is the standardized reference crop evapotranspiration for a tall reference (mm/h),

R_n is calculated net radiation at the crop surface (MJ/m^2/h),

G is soil heat flux density at the soil surface (MJ/m^2/h),

T is mean hourly air temperature at 1.5 to 2.5-m height (°C),

u_2 is mean hourly wind speed at 2-m height (m/s),

e_s is saturation vapor pressure at 1.5 to 2.5-m height (kPa),

e_a is mean actual vapor pressure at 1.5 to 2.5-m height (kPa),

Δ is slope of the saturation vapor pressure-temperature curve (kPa/°C),

γ is psychrometric constant (kPa/ °C),

C_n = 66; a numerator constant for tall reference and hourly time step (K mm s^3 /Mg/h) and

C_d = 0.25 (daytime), 1.7 (nighttime); a denominator constant for tall reference and hourly time step (s/m).

Units for the 0.408 coefficient are m^2 mm / MJ.

The ET_{rs} calculated by ASCE standardized PM ET_{ref} uses wind speed measured at 2 m height over a smooth surface like clipped grass. The wind speed at the lysimeter was measured at 2 m above the ground surface. Alfalfa had variable height during the growing season and at most times was greater than clipped grass. Thus the wind speed adjustment algorithm described by Ley et al. (2009) was used to adjust wind speeds over variable height alfalfa to equivalent wind speeds at 2 m over grass.

Growing Degree Days (GDD)

Growing Degree Days (GDD) were calculated for each cutting cycle of the 2008, 2009 and 2010 seasons. Cumulative GDD was calculated by accumulating positive GDD values after each cutting. The first cutting cycle started from March 1st as recommended by Allen and Beck (1996). The base temperature (T_b) for alfalfa was taken as 5°C (Smeal et al., 1991; Sanerson et al., 1994 and Confalonieri and Bechini, 2004). Cumulative GDD was calculated as follows:

$$\mathrm{CGGD} = \sum \left(\frac{T_{max} + T_{min}}{2}\right) - T_b \qquad \text{Eq. (3)}$$

where CGDD is cumulative growing degree days, , T_{max} is maximum air temperature, T_{min} is minimum air temperature and T_b is base temperature.

Crop coefficient (K_{cr}) calculations

Crop coefficient values based on a tall (alfalfa) reference for the 2008, 2009, and 2010 seasons were calculated on a daily time step as the ratio between measured alfalfa ET_c from the lysimeter and the ASCE standardized ET_{rs}. The daily ET_{rs} values were obtained by summing values, calculated from the hourly version of the standardized equation, for each 24-hour period.

$$K_{cr} = \frac{ET_c}{ET_{rs}} \qquad \text{Eq. (4)}$$

Where ET_c = Actual crop evapotranspiration from lysimeter, alfalfa, (mm/day) ET_{rs} = ASCE standardized reference evapotranspiration for tall crop, alfalfa, (mm/day)

RESULTS AND DISCUSSION

Seasonal Water balance

The seasonal water balances for 2008, 2009, and 2010 are shown in table (2). Alfalfa total ET_c was 1333 mm, 1179 mm, and 1455 mm in 2008, 2009, and 2010, respectively. There was no lysimeter water drainage in any year. The alfalfa consumed 64 mm and 20 mm of soil water beyond what was added by precipitation and irrigation in 2008 and 2010, respectively. In 2009, 202 mm of water added by precipitation and irrigation were stored in the soil and were not used. Alfalfa consumed more water in 2010 than 2009 and 2008. The total growing season was 215 days, 195 days and 197 days in 2008, 2009, and 2010, respectively. Higher water use in 2010 and 2008 compared to 2009 was related to higher yields in those growing seasons. Figure (1) shows the relationships between dry yield and crop evapotranspiration for 2008, 2009, and 2010 seasons. The total yield for four cutting cycles was 19.39 ton/ha, 18.26 ton/ha and 19.21 ton/ha for 2008, 2009 and 2010, respectively (Table 3). The total yield was higher than that found in Bushland, Texas. Evett et al. (1998) found that the yield from four cutting was 16.5 dry ton/ha.

Climatic factors also governed alfalfa water use as reflected in ET_{rs}. Figure (2) shows the average ET_c, temperature, wind speed, solar radiation, relative humidity, and total precipitation by growing season. Temperature, solar radiation and precipitation were higher in 2010 compared to 2009 and 2008 seasons. Average wind speed was larger in 2008 than in 2009 and 2010.

Alfalfa Evapotranspiration

Actual daily alfalfa ET for 2008, 2009, and 2010 is shown in Figure 3. Alfalfa ET fluctuations during the growing season corresponded with similar fluctuations in reference ET (Figure 4). Actual ET in 2010 was larger than in 2008 and 2009 for the first, second and the fourth cutting cycles because of greater atmospheric demand, which is reflected in the higher ET_{rs} values in 2010 for the mentioned cutting cycles. Maximum daily water use of alfalfa was 14.4 mm/day in the second cutting of 2010 season due to high maximum temperature, large solar radiation and high wind speed (Figure 3). Average daily ET for 2008, 2009 and 2010 was 5.7, 6.0, and 6.9 mm/day, respectively. In comparison, Evett et al. (1998) found that lysimeteric measured ET of alfalfa at Bushland, Texas averaged 7.1 mm/day and 6.7 mm/day, 7.3 mm/day, and 6.1 mm/day in 1996 through 1997, respectively for two large weighing lysimeters. They also found that the peak ET reached 16 mm/day in 1996 and 1997, 18 mm/day in 1998, and 13 mm/day in 1999. Wright (1988) also found that alfalfa ET exceeded 10 mm/day at Kimberly, Idaho. He found that average daily alfalfa ET ranged from 4.6 mm/day to 5.9 mm/day. Seasonal alfalfa ET at Kimberly ranged from 904 mm to 1128 mm.

Alfalfa crop coefficients

Crop coefficients based on a tall reference (K_{cr}) which represent the effects of crop growth on ET were developed using a weighing lysimeter. The K_{cr} is small when the crop is in the initial growth stage or after cutting and increases as the crop develops, reaching a maximum value when crop canopy and leaf area is maximum. Figure (5) shows the concurrent development of crop height and the crop coefficient curve. Crop coefficient values increased as the height of alfalfa increased due both to associated increase in leaf area index and, to a lesser extent, the increasing crop surface roughness. Even though alfalfa grew taller than 50 cm in the first cutting cycle of all three seasons, peak crop coefficient values were lower than in later cutting cycles because of other factors such as soil water stress (2008 and 2009; see Figures 2 and 3 in Chapter 2) and cooler weather that resulted in slower growth. It should also be noted that soil water stress also occurred in all cutting cycles of 2008 (Fig. 2 in Chapter 2).

Figure (6) shows the alfalfa crop coefficients versus day of year (DOY) and GDD with all three seasons combined. It is obvious that alfalfa crop coefficients were small in the initial stage and increased as alfalfa growth increased until reaching the maximum when the alfalfa was at full cover (crop canopy and leaf area is maximum). The growth of alfalfa in the first cutting cycle was slower due to cooler weather and reduced solar radiation.

Accumulated GDD's are a better representation of growth time compared to calendar dates or DOY. They can account for differences in weather conditions from year-to-year and may improve the applicability of K_{cr} values across years. Figure (6 and 7) shows that the crop coefficient curves come closer together when plotted against GDD's.

In general, for all cuttings, maximum K_{cr} values were larger in 2010 than in 2008 and 2009. The first cutting cycle in 2008, 2009 and 2010 showed that peak K_{cr} values were lower and less than 1.0 than other cutting cycles. In all years, the second and third cutting cycles had similar lengths of growing periods. In contrast, the fourth growing period in 2008 was longer than in 2009 and 2010 as was reflected in the difference in shape of the K_{cr} curves (Figure 6A). In 2008 the maximum K_{cr} values mostly remained below 1.2 whereas in 2009 and 2010, maximum K_{cr} values were at or above 1.2. The K_{cr} values greater than 1.0 were indicate that ETc values from the lysimeter were larger than ET_{rs} values from the ASCE standardized PM equation. However alfalfa crop coefficients based on ET_{rs} should not persistently exceed 1.0, given the assumption that ET_{rs} represents the theoretical upper limit for ET under standard condition. The peak K_{cr} values reported here were larger than those reported by Howell et al. (2006) and Wright (1982). They found that the peak K_{cr} was near 1.0. However Howell et al. (2006) found that K_{cr} values did exceed 1.0 occasionally.

Figure (8) shows the comparison between K_{cr} developed at Rocky Ford, Colorado (Arkansas Valley) and K_{cr} values developed by Wright in 1981 and later converted to use with the ASCE standardized PM equation. Both K_{cr} values have the same trend. K_{cr} values developed by Wright have a maximum of 1.0 whereas maximum K_{cr} values developed at Rock Ford reached 1.2.

Crop coefficient values increased significantly during precipitation and heavy furrow irrigation days (Figure 9). Crop coefficient curves showed spikes when precipitation and irrigation days were included; and the curves appeared smoother when precipitation and irrigation days were excluded. During precipitation and heavy irrigation days, evaporation tends to increase from bare soil during early growth stages when the alfalfa does not fully cover the ground and causes outliers in crop coefficient values. Precipitation also increases direct evaporation of rainfall that is intercepted by the crop canopy.

Crop coefficients are reduced by high soil water deficits. Figure (10) indicated a reduction in the alfalfa crop coefficients at the end of some cutting cycles which coincided with the reduction in soil water content, even though alfalfa was not under apparent soil water stress. Crop coefficients were also affected by significant soil water stress that occurred in the whole season of 2008 and the first cutting cycle of 2009. Soil water stress increases the crop canopy resistance to transpiration. Effects of water stress on ET can also be expressed using a water stress coefficient, K_s (Allen et al., 1998). The K_{cr} values obtained during periods of water stress cannot be used to estimate potential crop ET. Effectively, these values already include a K_s term. Since all of the 2008 season and the first cutting cycle in 2009 were under soil water stress, lower crop coefficients were observed in the first cutting cycles of both seasons. The lower crop coefficients during first cutting cycle of 2009 are clearly shown in Figure (10). In 2008, only the crop coefficients in the first cutting cycle seemed to be affected by soil water stress. Other cutting cycles in 2008 didn’t seem to show any affects of soil water stress. This could be because the soil water content generally remained adequate in the surface 30 cm layer in 2008 and the alfalfa roots were not yet deep enough to be affected by large soil water deficits in the deeper soil layers, since it was planted in August 2007. In 2010, although there wasn't any soil water stress, the first cutting cycle still showed lower K_{cr} values that remained less than 1.0.

Several factors may have contributed to K_{cr} values that exceeded 1.0, related to alfalfa in the lysimeter or to the ASCE standardized ET_{rs} equation. Alfalfa height in the lysimeter was taller than the surrounded alfalfa during some periods of 2008, 2009, and 2010 seasons. Taller alfalfa in the lysimeter would have received more evaporative energy. This effect is called "clothesline" effect, results because both aerodynamic and radiative transfer of atmospheric energy to the crop in the lysimeter were increased, resulting in larger ET values (Allen et al., 1991)

Alfalfa also extended out beyond the boundary of the lysimeter increasing the evaporative area. This increases the net radiation received and aerodynamic exchange resulting in larger ET from the lysimeter as compared to calculated ET_{rs} causing larger K_{cr} values.

As mentioned earlier, the ASCE standardized ET_{rs} equation did not appear as accurate at high temperature and low relative humidity due to the assumed linear relationship between saturated vapor pressure and temperature. The errors depend on the difference between canopy and air temperatures. It was observed that the difference in temperature was large during the mid-day. Those errors also contributed in larger K_{cr} values. In addition to that, inadequate fetch could also affect ET and hence K_c values. Higher advective energy could influence predicted ET_{rs} by the ASCE standardized equation.

CONCLUSION

In this study, the crop coefficient curves of alfalfa were developed using a precision weighing lysimeter and the ASCE standardized ET_{rs} equation. It was found that climatic parameters, soil water content and the height of alfalfa influenced the crop coefficient values. Soil water stress decreased the crop coefficient values compared to values unaffected by water stress. On the other hand, in all cutting cycles which were not affected by soil water stress, peak crop coefficients were persistently greater than 1.0. Factors related to alfalfa in the lysimeter and related to the ASCE standardized ET_{rs} equation has contributed to larger K_{cr} values. Alfalfa height was taller in the lysimeter and alfalfa coverage extending out of the boundary of the lysimeter and thus received more evaporative energy resulting in larger ET causing larger K_{cr} values. The ASCE standardized ET_{rs} equation which was found less accurate at high temperature and low relative humidity due to the linear relationship between saturated vapor pressure and temperature also contributed to larger K_{cr} values. It is also possible that some advective energy actually available for ET was not being accounted for in the calculated ET_{rs} values. Another possible reason for larger K_{cr} values is the yield of alfalfa. It was found that high alfalfa yield corresponded with high evapotranspiration.

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Table 1. Soil properties of the lysimeter monolith

Depth cm	pH water (1:1)	ECe dS/m	Bulk density g/cm^3	Field Capacity cm^3/cm^3	Wilting point cm^3/cm^3	Hydraulic conductivity cm/hr
0-23	8.1	0.82	1.36	0.291	0.167	0.34
23-36	8.0	0.90	1.36	0.290	0.169	0.33
36-100	8.3	0.58	1.45	0.242	0.112	1.25
100-170	8.3	0.72	1.43	0.252	0.117	1.06
170-230	8.3	0.88	1.35	0.296	0.159	0.42

Table 2. Seasonal water balance of the alfalfa grown in the lysimeter in 2008 (4/1/08 -11/5/08), 2009 (3/24/09 – 10/5/09), and 2010 (3/31/2010 – 10/14/2010). All water balance components determined based on the change in the lysimeter weight.

Season	Irrigation (I) mm	Precipitation (P) mm	Evapotranspiration (ET) mm	Deep percolation (DP) mm	Change in soil (ΔS) mm
2008	1012	257	1333	0	-64
2009	1133	248	1179	0	202
2010	1118	317	1455	0	-20

Table 3. Cutting days, yield, total evapotranspiration (ETc), and water use efficiency (WUE) for each cut in 2008, 2009, and 2010.

Season	Cutting	Cutting date	Cutting date DOY	Cutting date GDD	GDD since last cutting	Days/cut day	Dry yield Kg/ha	Total ETc m^3/ha/cut	WUE Kg/m^3
2008	1	13-Jun	163	727	687	71	7323.1	4780	1.53
	2	23-Jul	205	1453	697	42	5144.2	2934	1.75
	3	3-Sep	247	2196	802	42	4133.3	2996	1.38
	4	4-Nov	309	2766	573	62	2785.5	2597	1.07
2009	1	8-Jun	159	745	735	76	3998.5	3275	1.22
	2	15-Jul	196	1398	663	37	6222.4	3092	2.01
	3	24-Aug	236	2089	671	40	4447.8	3093	1.44
	4	5-Oct	278	2591	523	42	3594.2	2333	1.54
2010	1	3-Jun	154	600	582	64	6424.6	4214	1.53
	2	13-Jul	194	1319	677	40	5256.5	3727	1.41
	3	23-Aug	235	2129	809	41	3998.5	2982	1.34
	4	14-Oct	287	2851	744	52	3526.8	3627	0.97

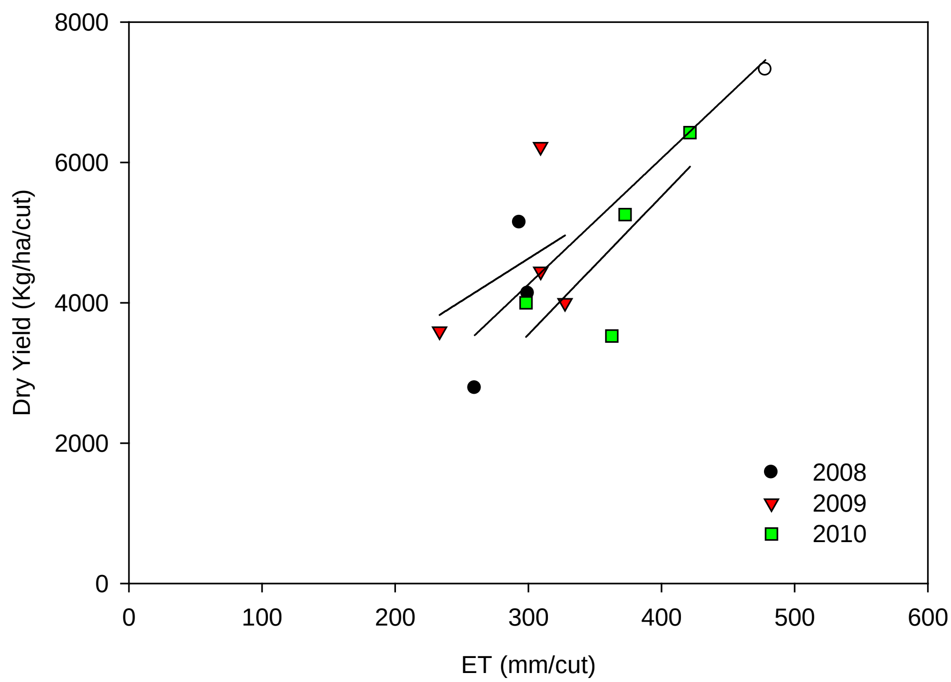


Fig. 1. Relationship between dry yield (Kg/ha/cutting) and crop evapotranspiration for 2008, 2009, and 2010 seasons.

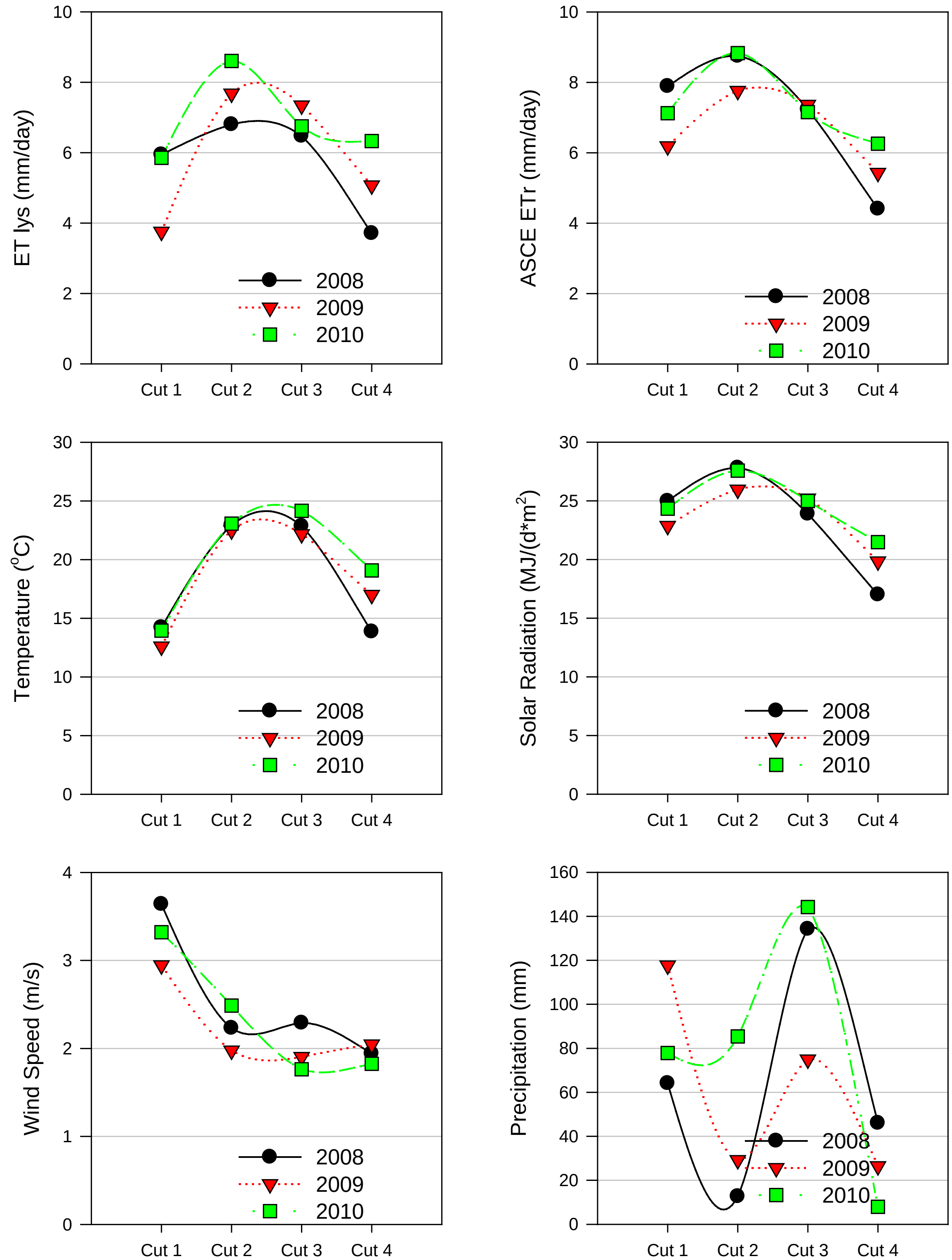


Fig. 2. The relationship between actual and reference evapotranspiration and major climatic factors (average for each cutting cycle) for 2008, 2009, and 2010 seasons.

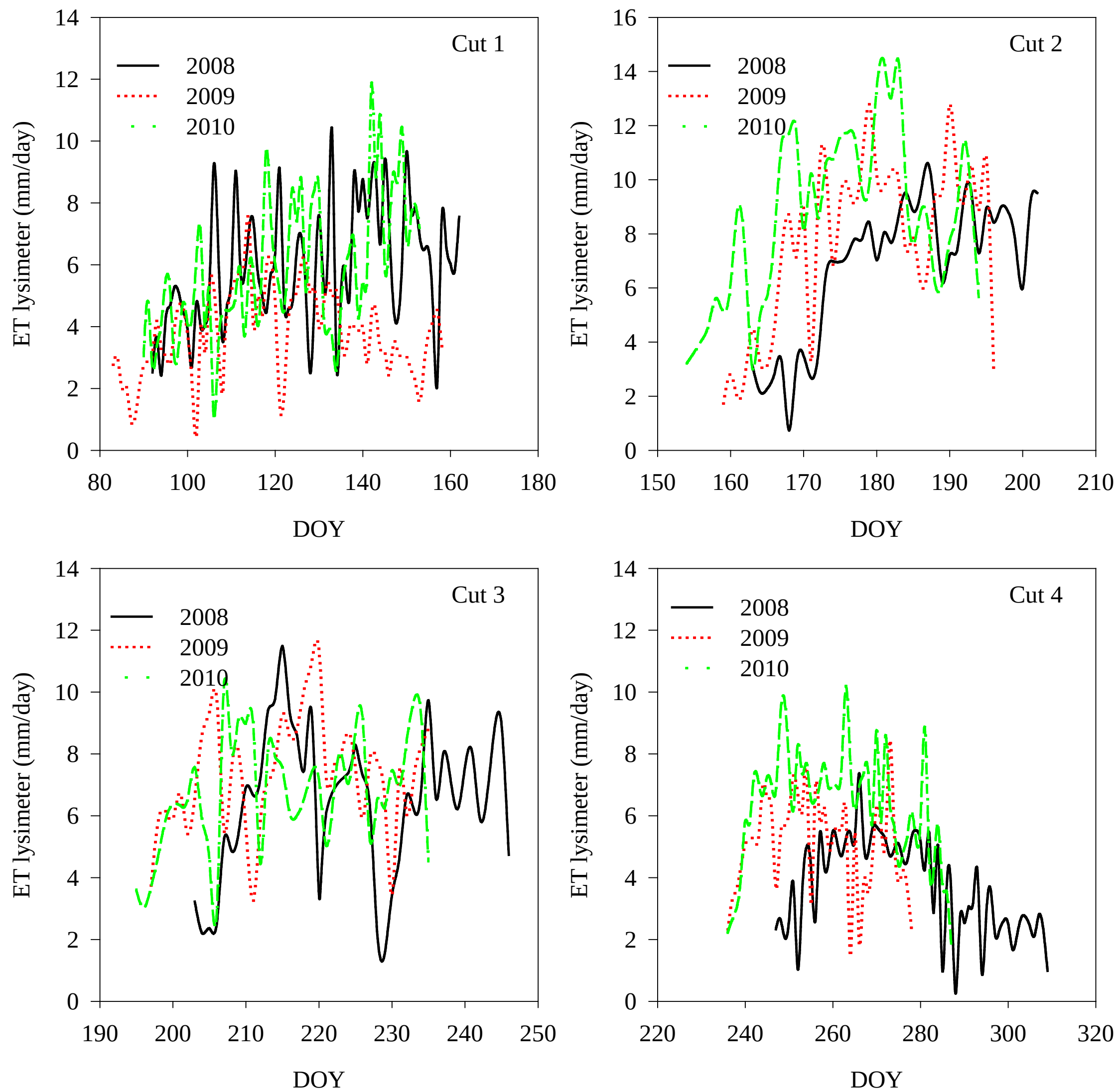


Fig. 3. Actual evapotranspiration of alfalfa measured by lysimeter versus DOY for each cutting cycle for 2008, 2009, and 2010 seasons.

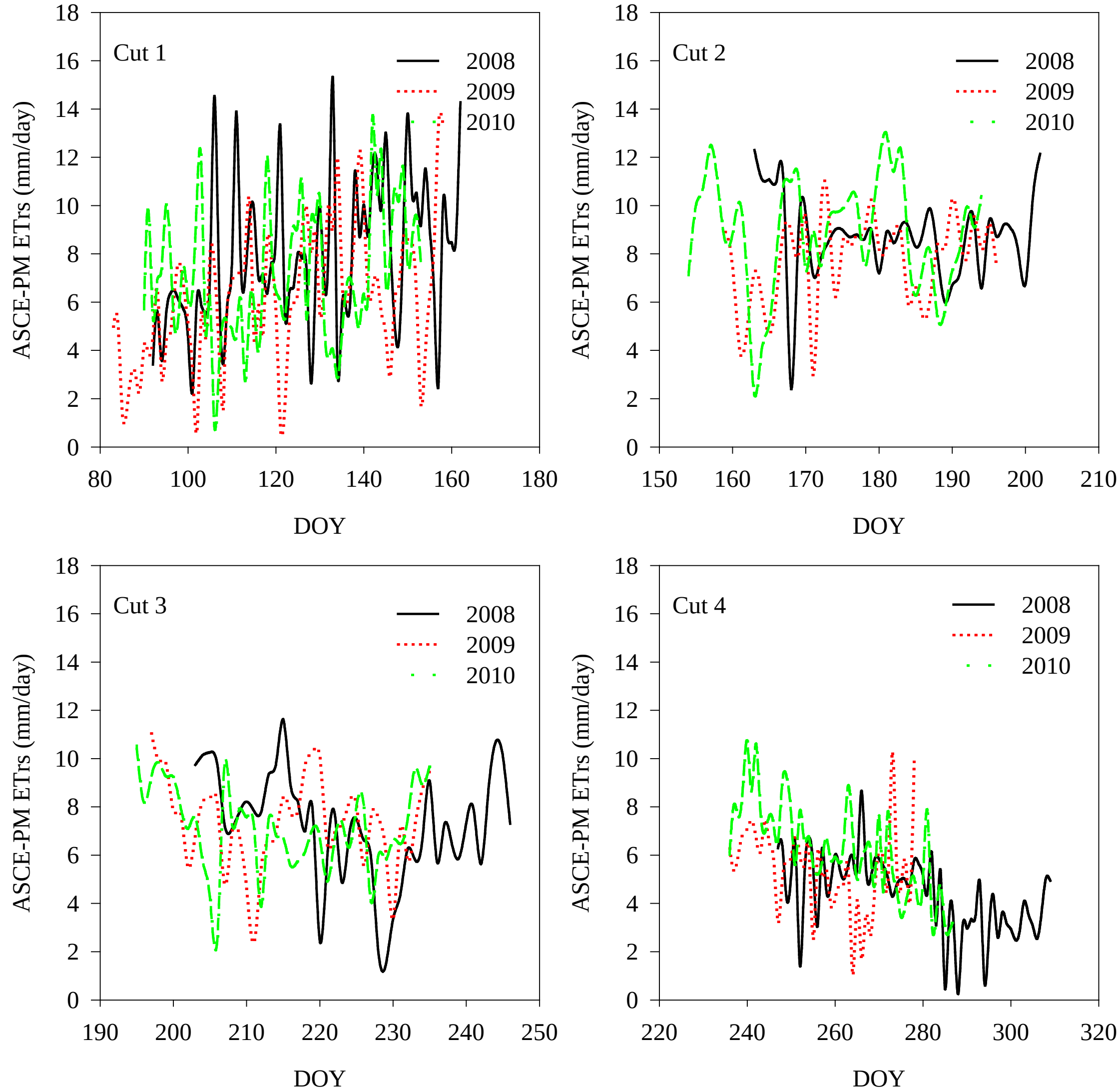


Fig. 4. Reference evapotranspiration calculated using ASCE standardized PM ET equation versus DOY for each cutting cycle for 2008, 2009, and 2010 seasons.

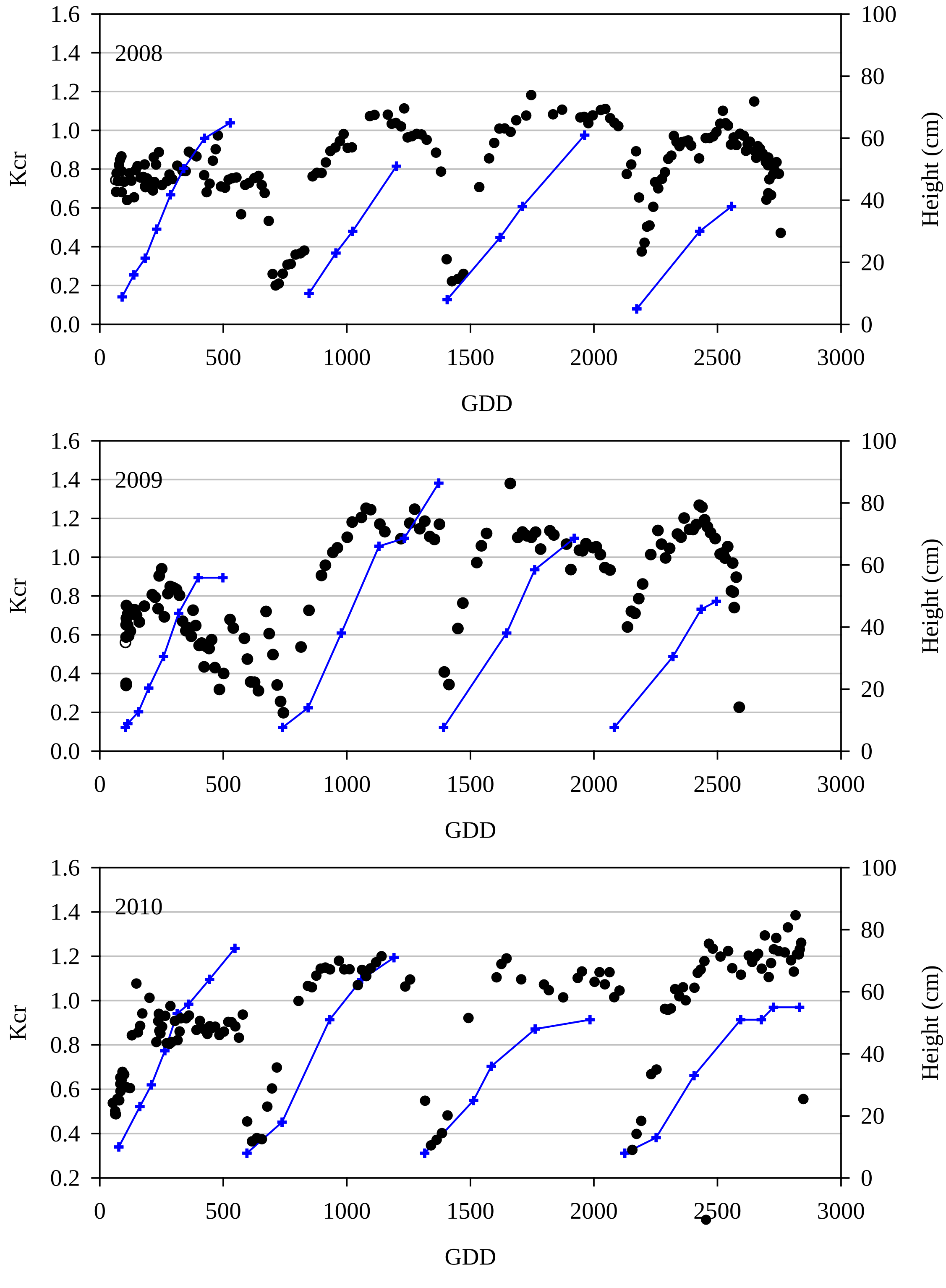


Fig. 5. Crop Coefficient (Kcr) (black data points) and the height of alfalfa (blue trend lines) versus growing degree days for the 2008, 2009, and 2010 seasons. All of the 2008 season and the first cutting cycle in 2009 were under water stress.

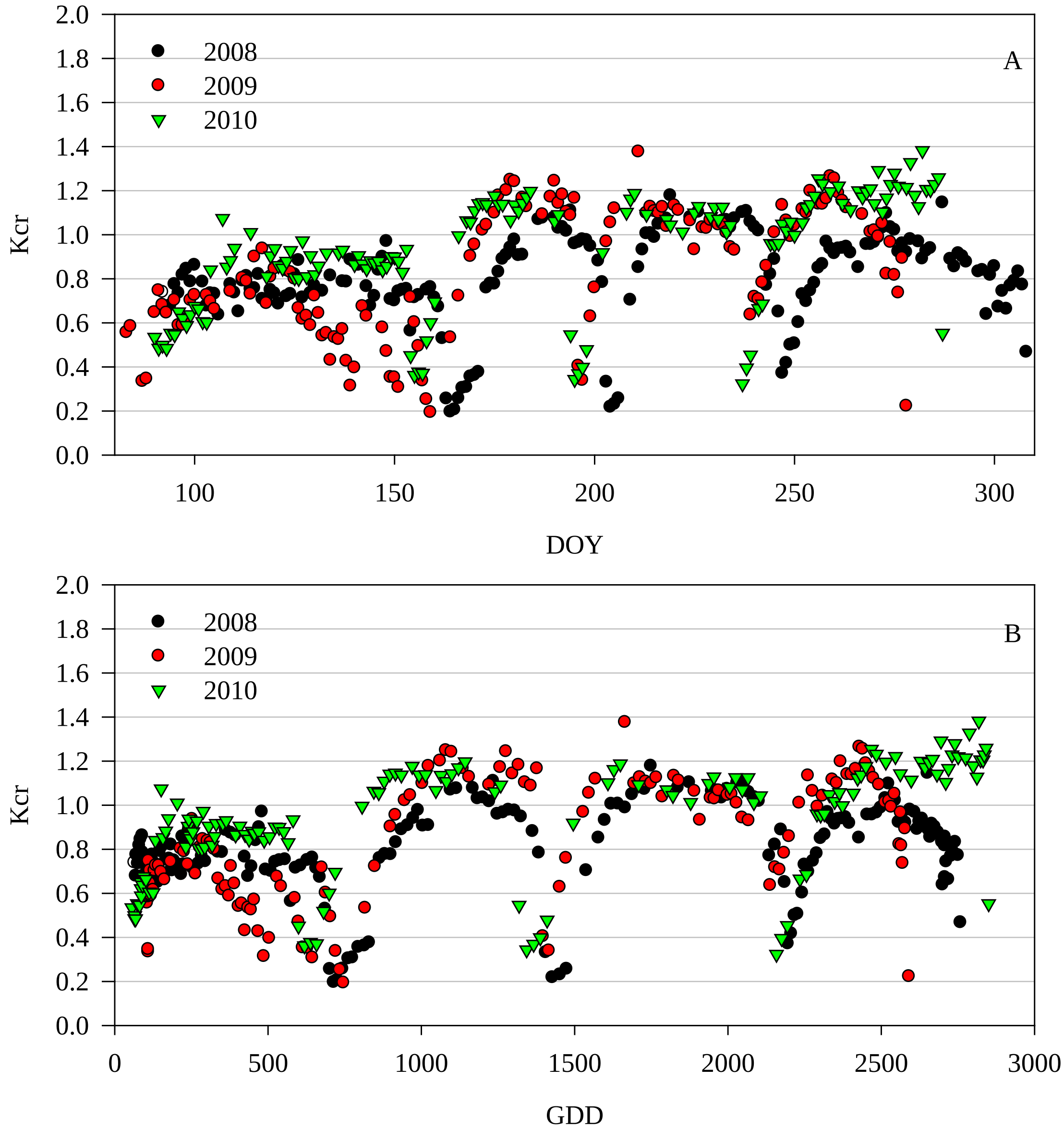


Fig. 6. Alfalfa crop coefficients versus (A) DOY and (B) GDD for 2008, 2009, and 2010 seasons. All of the 2008 season and the first cutting cycle in 2009 were under water stress.

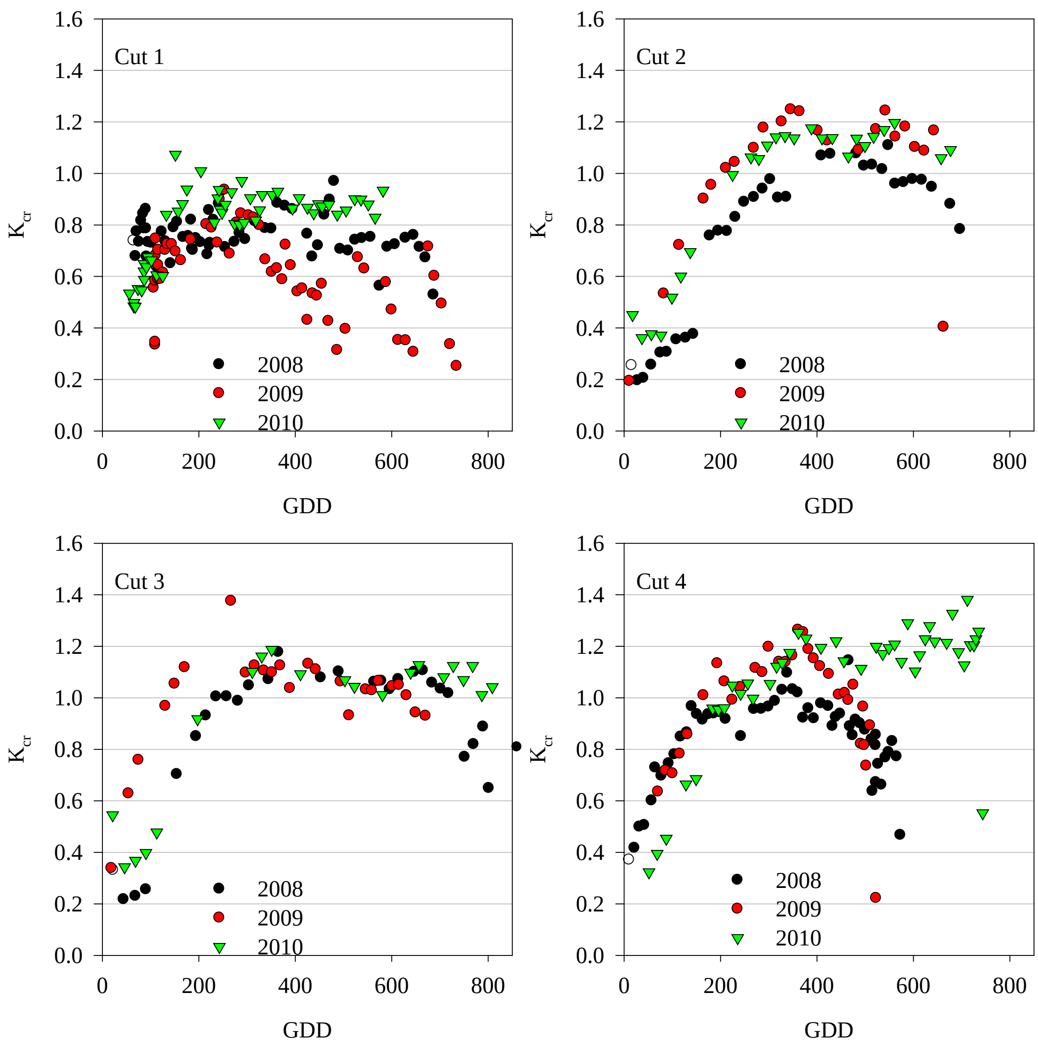


Fig. 7. Alfalfa crop coefficients versus GDD for 2008, 2009, and 2010 seasons. GDD starting from March 1 or after each cut. All of the 2008 season and the first cutting cycle in 2009 were under water stress.

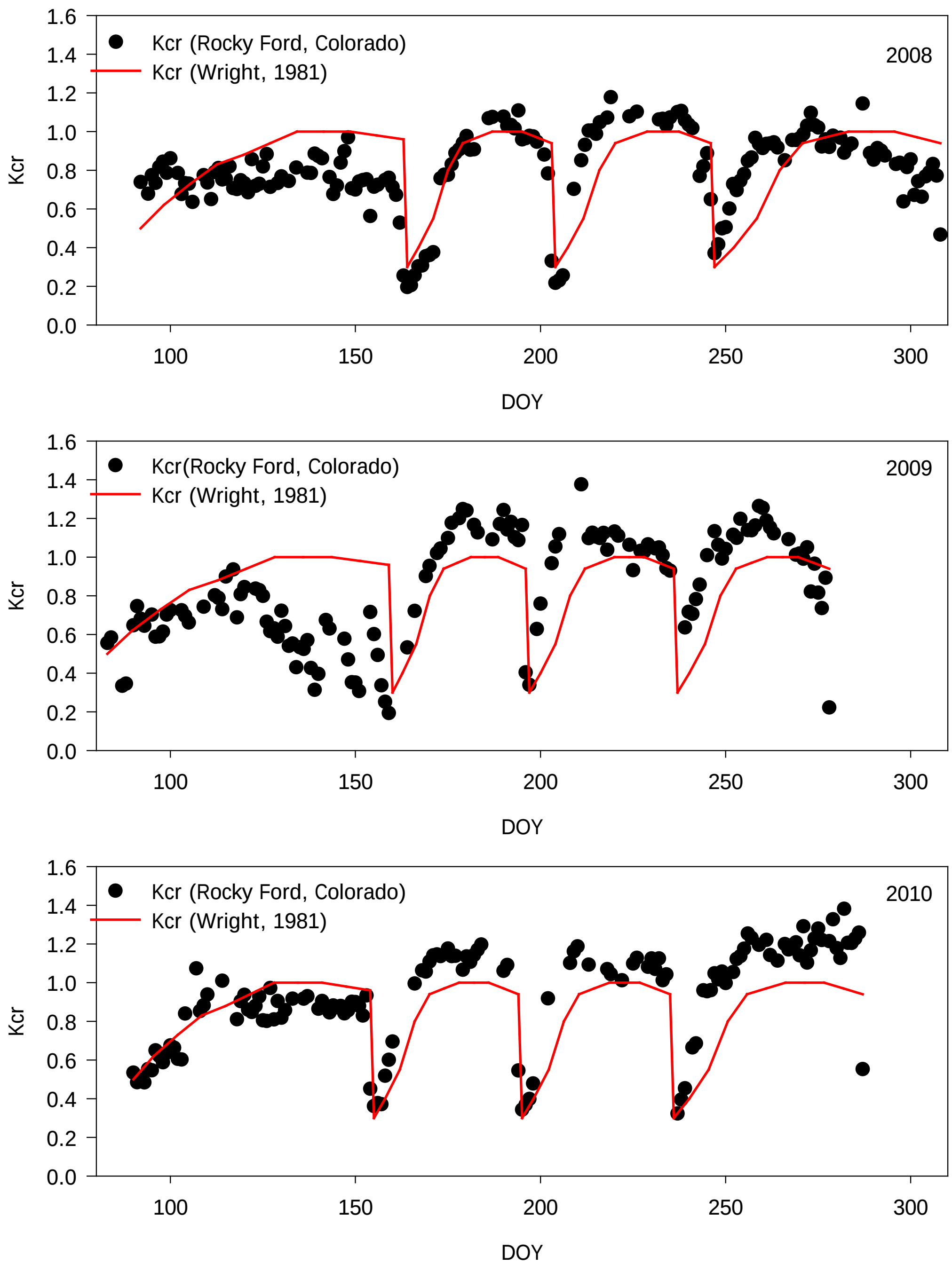
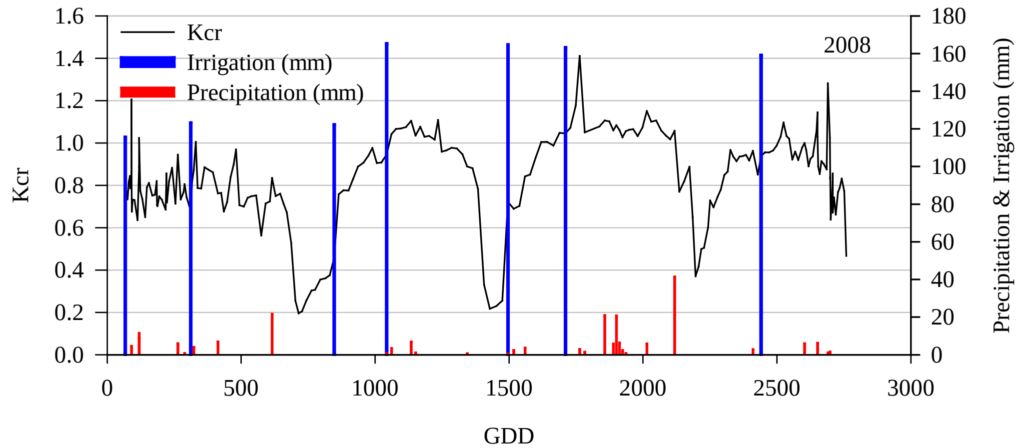
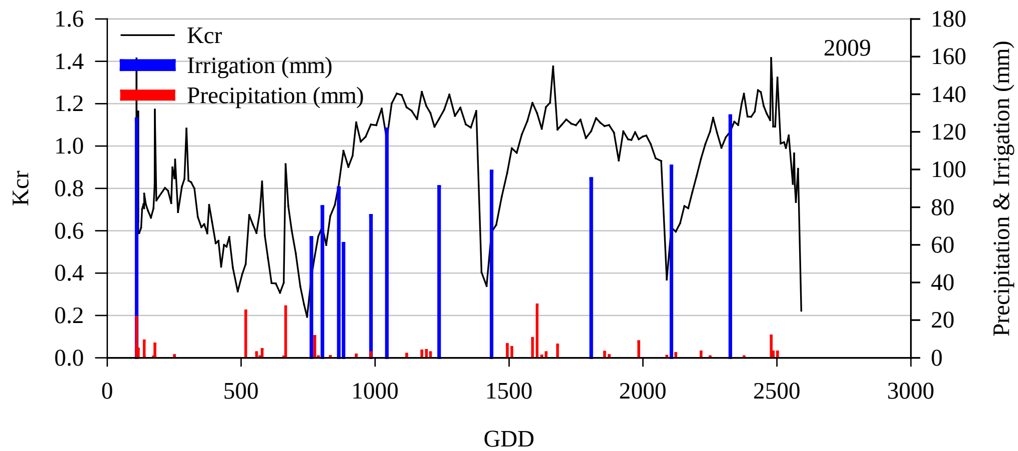


Fig. 8. Alfalfa crop coefficients (Kcr) for 2008, 2009 and 2010 seasons compared with Kcr values developed by Wright in 1981 and converted for use with the ASCE standardized PM equation. All of the 2008 season and the first cutting cycle in 2009 were under water stress.





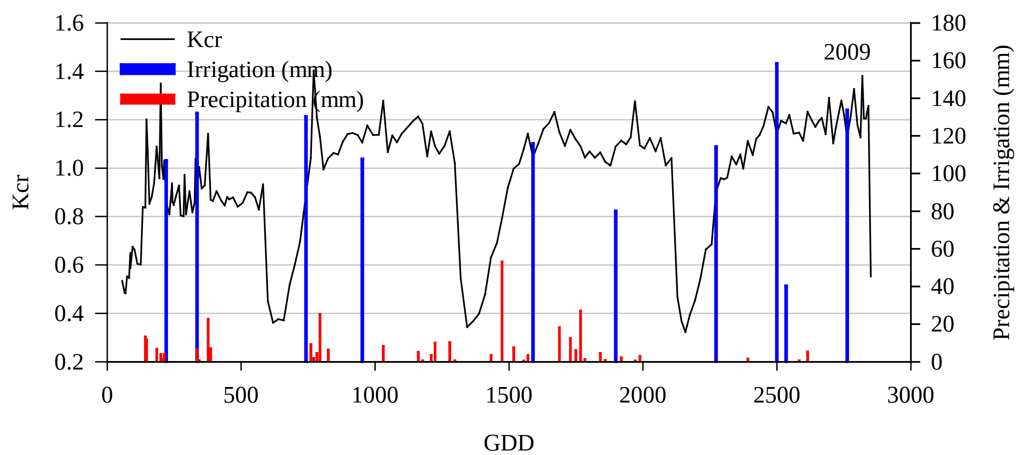


Fig. 9. Effects of precipitation and irrigation on alfalfa crop coefficients for the 2008, 2009, and 2010 seasons. All of the 2008 season and the first cutting cycle in 2009 were under water stress.

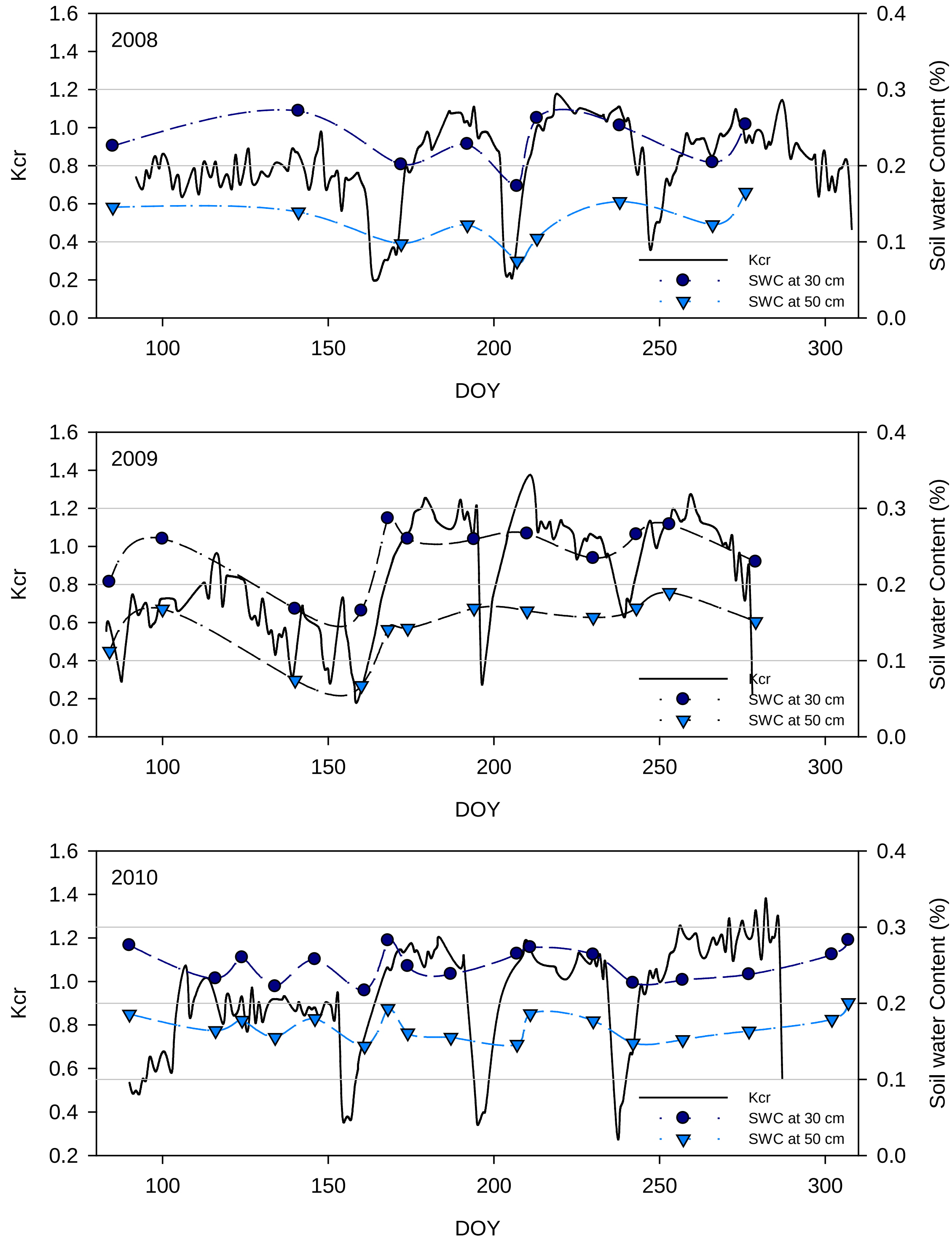


Fig. 10. Correspondence between shapes of K_{cr} and soil water content curves for the 2008, 2009, and 2010 seasons. All of the 2008 season and the first cutting cycle in 2009 were under water stress.

CHAPTER FOUR: COMPARING REFERENCE ET CALCULATED WITH THE FULL VERSION OF THE PENMAN-MONTEITH EQUATION TO THE ASCE STANDARDIZED VERSION

ABSTRACT

Under certain conditions in the field, ET estimated using the ASCE Standardized Penman Monteith equation does not match observed crop ET. Previous studies showed that using the full version of the Penman-Monteith equation could improve reference evapotranspiration (ET_{ref}) estimates. The full version uses calculated aerodynamic (r_a) and surface resistances (r_s) from observed vegetation height and leaf area index rather than using assumed resistance terms. The objective of this study was to compare ET_{ref} using the full and ASCE standardized versions of the Penman-Monteith equation with measured ET using a weighing lysimeter. The comparisons were based on two cutting cycles of alfalfa in the 2010 growing season. The results indicated high correlations between leaf area index (LAI) and alfalfa height but the relationships were not the same as suggested by Allen et al. (1994). Maximum LAI obtained was 5.24. Results also showed that ET_{ref} values calculated by full version of Penman-Monteith did not match ET values measured by the lysimeter as well as values calculated with the ASCE standardized ET_{rs} equation. Index of agreement was 0.946 for ASCE standardized Penman Monteith equation and 0.894 for the full version of Penman-Monteith. However, the full version of Penman-Monteith had good agreement with ASCE standardized ET_{rs}

equation (Index of agreement was 0.973). Both equations underestimated lysimeter ET_{ref}. Thus, errors associated with the assumed resistance terms in the ASCE standardized version of the Penman Monteith equation were not responsible for the deviations in lysimeter measured and predicted ET.

INTRODUCTION

Penman-Monteith is a combination equation (energy balance and aerodynamic) that includes aerodynamic (r_a) and surface (r_s) resistances. Aerodynamic resistance is affected slightly by crop canopy structure whereas surface resistance depends on the biological behavior of the surface of the plant canopy (Howell and Evett, 2004). Penman-Monteith equation has been proven to perform accurately under many climatic conditions (Allen et al., 1998). It gives close estimation of ET_{ref} measured by lysimeters (Temesgen, et al. 2005; Itenfisu et al., 2003). ASCE Standardized ET_{rs} equation was derived from the full version of Penman-Monteith by simplifying and standardizing some terms regarding the aerodynamic and surface resistances. The resistance terms are dependent on crop height and leaf area index (LAI). For tall crop reference (alfalfa), ASCE standardized ET_{rs} assumes that the surface resistance is 30 s/m during the daytime and 200 s/m during the nighttime for calculations using an hourly time step and an average of 45 s/m for calculations using a daily step (ASCE-EWRI, 2005). The full version of Penman-Monteith equation has been shown to give accurate ET_{ref} values by calculating, rather than assuming, standard values for aerodynamic (r_a) and surface resistances (r_s). Allen et al. (1998) found that application of canopy and aerodynamic resistance using measured height and leaf area index into Penman-Monteith equation appeared to improve the calculated ET_{ref}.

The objective of this study was to calculate ET_{ref} using the full version of the Penman-Monteith equation to improve ET_{ref} values as compared to the ASCE standardized ET_{rs} equation for better comparison with lysimeter measured ET_{ref}.

MATERIALS AND METHODS

Location

The study was conducted at Colorado State University's Arkansas Valley Research Center in Southeast Colorado (latitude 38^o 2' 17.30", longitude 103^o 41' 17.60", altitude 1,274 m above sea level). A weighing lysimeter was used for evaluating the ASCE standardized Penman Monteith ET_{rs} equation and to compute actual crop evapotranspiration (ET_c) and crop coefficients (K_c) for various crops under the Arkansas Valley conditions. Alfalfa (*Medicago sativa L.*, Genoa variety) was planted mechanically in the field and manually in the lysimeter on 9 August 2007 at a seeding rate of 21.3 kg/ha. Alfalfa in the lysimeter was irrigated manually to mimic the furrow irrigation of the surrounding field (158.5 m x 256.1 m). The amount of water applied to the monolith was recorded. The height of alfalfa in the lysimeter and surrounding field was measured weekly by taking average measurements from different locations in the lysimeter and the surrounding field.

ET_c measured by Lysimeter

Actual evapotranspiration (ET_c) was measured using the large weighing lysimeter. Berrada et al. (2008) gave a detailed description of the weighing lysimeter. The lysimeter load cell output was sampled every 10 seconds and 15 min averages were recorded throughout each growing season. A calibration was used to convert load cell output to the change in soil water content. The fifteen-minute averages of the load cell outputs were used in the calculation of alfalfa ET_c. Any drainage water was collected and measured in a drainage tank suspended under the lysimeter. Daily ET_c for lysimeter system was computed using water balance equation:

$$\mathrm{ET} = \mathrm{P} + \mathrm{Irr} - \mathrm{D} + \Delta S \qquad \text{Eq. (1)}$$

where ET is the alfalfa evapotranspiration, P is Precipitation, Irr is irrigation, D is drainage, and ΔS is change in soil water content. Runoff and deep percolation were equal to zero for the lysimeter system during the period of study.

As alfalfa grew, it was observed that leaves and stems extended outside the lysimeter edges to a greater extent than plants outside the lysimeter extended inward. This effectively increased the plant surface area that was subjected to evaporation of water from the lysimeter. A measure of the alfalfa that extended beyond the defined lysimeter edges was measured weekly in the last cutting cycle of 2010 (by taking the average horizontal measurement of alfalfa extending from the four sides of the lysimeter) to adjust and correct the evaporative area. The alfalfa extending outside the lysimeter edge versus number of days after harvest was plotted and the equation was used to correct the evaporative area. The corrected area was used to adjust ET_c values measured from the lysimeter.

Computation of ET_{ref} using the Full Penman-Monteith Equation

A complete automatic weather station was installed at the lysimeter site to measure climate variables around and within the monolith. Variables included rainfall, wind speed, air temperature, solar radiation, barometric pressure, soil temperature, and soil heat flux. Average climatic data were recorded every 15 minutes. The details of the sensors and their placement were described in Berrada et al. (2008).

The full Penman Monteith ET equation was used to estimate reference evapotranspiration on a daily time step using climatic data obtained from the weather station:

$$\mathrm{ET} = \left[\frac{\Delta(\mathrm{R_n} - \mathrm{G}) + \rho c_p \ \dfrac{(\mathrm{e_s} - \mathrm{e_a})}{\mathrm{r_a}}}{\Delta + \gamma\left(1 + \dfrac{\mathrm{r_s}}{\mathrm{r_a}}\right)}\right] / \lambda\, \rho_w \qquad \text{Eq. (2)}$$

where ET is reference evapotranspiration (mm d^{-1}); R_n is the net radiation (MJ m^{-2} d^{-1}), G is the soil heat flux (MJ m^{-2} d^{-1}), (e_s - e_a) is the vapor pressure deficit of the air (kPa), ρ_a is the mean air density at constant pressure (kg m^{-3}), c_p is the specific heat of the air (MJ kg^{-1} $°C^{-1}$), Δ represents the slope of the saturation vapor pressure versus temperature line (kPa $°C^{-1}$), γ is the psychrometric constant (kPa $°C^{-1}$), λ is latent heat of vaporization (MJ kg^{-1}), ρ_w is density of water (taken as 1.0 Mg m^{-3}), and r_s and r_a are the bulk surface and aerodynamic resistances (s m^{-1}), respectively.

Canopy resistance (r_s) and aerodynamic resistance (r_a) were calculated using Allen et al. (1994) equations:

$$r_s = \frac{\mathrm{r_l}}{0.5\mathrm{LAI}} \qquad \text{Eq. (3)}$$

where r_s is the canopy resistance (s/m), r_l is the stomatal resistance taken as 100 s/m, and LAI is leaf area index.

$$r_a = \frac{\ln\left[\dfrac{z_m - d}{z_{om}}\right] \ln\left[\dfrac{z_h - d}{z_{oh}}\right]}{k^2\, u_2} \qquad \text{Eq. (4)}$$

where r_a is the aerodynamic resistance (s/m) for neutral atmospheric conditions, z_m is height of wind measurements (m), z_h is height of humidity measurements (m), d is zero plane displacement height (m) = 2/3 hc, hc is the crop height. z_{om} = 0.123hc is roughness length governing momentum transfer (m), z_{oh} = 0.1z_{om} is roughness length governing transfer of heat and vapor (m), k is von Karman's constant = 0.41, and u_z is wind speed at height z (m/s).

Leaf area index (LAI) measurement

Leaf area index (LAI) is the cumulative leaf area of one side of all leaf surfaces expressed per unit of land surface area. Above ground alfalfa biomass from all sides of the lysimeter (4 samples in total) was sampled destructively from a 0.76 m x 0.76 m area and put directly in plastic bags. The fresh samples were weighed and 3 stems were taken from each. Leaves were separated from stems and weighed separately. Leaves of each stem were put on a white board and digital pictures were taken with a Sony camera (14.1 MP) held at a height of approximately 0.4 m. All the samples (fresh samples, leaves and stems) were put in an oven for 24 hours at 60^{o} and were reweighed for dry mass. The area of leaves was measured using digital image analysis (Adobe Photoshop, version 10.0.1).

Wind speed adjustment

The ET_{rs} calculated by ASCE-PM uses wind speed measured at 2 m height over a smooth surface, such as clipped grass. The wind speed at the lysimeter was measured at 2 m above the ground surface in the alfalfa field. The alfalfa had a variable height during the growing season and was generally at a height greater than clipped grass. The wind speed adjustment algorithm described by Ley et al. (2009) was used to adjust wind speeds over variable height alfalfa to equivalent wind speeds at 2 m over grass.

$$u_{z,v} = u_{z,w} \frac{\ln\left(\frac{Z_{IBL,w} - d_w}{Z_{om,w}}\right) \ln\left(\frac{Z_{IBL,v} - d_R}{Z_{om,R}}\right) \ln\left(\frac{Z_v - d_v}{Z_{om,v}}\right)}{\ln\left(\frac{Z_w - d_w}{Z_{om,w}}\right) \ln\left(\frac{Z_{IBL,w} - d_R}{Z_{om,R}}\right) \ln\left(\frac{Z_{IBL,v} - d_v}{Z_{om,w}}\right)} \qquad \text{Eq. (5)}$$

where $u_{z,v}$ is the adjusted wind speed (m/s) at z_v elevation (m) on ground covered with vegetation of type V; $u_{z,w}$ is the measured wind speed (m/s) at z_w elevation (m) above the ground surface; $z_{IBL,w}$ and $z_{IBL,v}$ are the heights (m) of the internal boundary layer (IBL) over the weather measurement surface (W) and over surface (V) to which wind is being translated; d_w , d_R ,and d_v are the zero plane displacement heights (m) taken as 0.67h for the weather measurement vegetation, regional vegetation, and the vegetation surface V; $z_{om,w}$, $z_{om,R}$, $z_{om,v}$ are aerodynamic roughness lengths (m) taken as 0.123h for the weather measurement vegetation, regional vegetation, and the vegetation surface V; and h is the vegetation height (m) for each surface condition (W, R, and V). $Z_{IBL,w}$, $Z_{IBL,R}$, and $Z_{IBL,v}$ are calculated using equation:

$$Z_{IBL} = d + 0.33\, z_{om}{}^{0.125} \times X_f{}^{0.875} \qquad \text{Eq. (6)}$$

where d is the zero plane displacement height (m) and X_f is the horizontal distance downwind.

Alfalfa height was measured weekly to determine the time when alfalfa reached 50 cm in height. Regression lines of the height with day of the year (DOY) were drawn. Calculated wind speed values were used to adjust wind speed using the above equations.

RESULTS AND DISCUSSION

Leaf Area Index (LAI)

LAI was measured for the third and fourth cutting cycles in 2010 season. The results showed that LAI for both cutting cycles increased as alfalfa growth increased (Figure 1). LAI at a height of 50 cm was 4.39 and 4.29 for the third and fourth cutting cycle, respectively. Maximum LAI was 5.24 and 4.62 for the third and fourth cutting cycle, respectively. Larger maximum LAI in the third cutting cycle than fourth could be due to faster growth and taller alfalfa in the third cutting cycle. The maximum height of the alfalfa was 60 cm and 55 cm in the third and fourth cutting cycles, respectively.

Both cutting cycles showed good relationship between LAI and alfalfa height. For the third cutting cycle, there was a curvilinear relationship between plant height and LAI (R^2

= 0.94). Similarly, there was a curvilinear relationship between height and LAI for the fourth cutting cycle (R^2=0.95), although the curves differed between the two cutting cycles (Figure 2). A relationship between plant height and LAI was suggested by Allen et al. (1994) in order to avoid the need for the tedious LAI determinations. LAI predicted according to Allen et al. (1994) did not compare well with the observed data. For both cutting cycles, predicted LAI was larger than observed values at plant heights less than 40 cm. The predicted values were much closer to the observed values when plant height was greater than 40 cm. Evett et al., (2000) also found that the relationship between LAI and plant height was not constant; and did not match observed data. The differences in the relationships between LAI and plant height are likely due to differences in crop variety, crop height, and plant density per unit area.

Reference evapotranspiration ET_{ref}

Alfalfa height and leaf area index measurements were used to calculate aerodynamic and surface resistances and the reference evapotranspiration was determined using the full version of the Penman-Monteith equation. ET_{ref} values were compared with both ASCE standardized ET_{rs} equation and lysimeter ET when alfalfa was at reference condition (alfalfa height = 50 cm). Figure (3) shows the relationships between ASCE-Penman-Monteith, full version of Penman-Monteith and measured lysimeter ET. ET calculated by the ASCE standardized ET_{rs} equation fitted well with lysimeter ET (index of agreement is 0.946) although the calculated values were consistently less than lysimeter values. ET_{ref} calculated using the full version of the Penman-Monteith also fitted well with lysimeter ET_{ref} (index of agreement is 0.894), although the fit was not as good as for the ASCE standardized ET_{rs} values (Figure 3). As observed for the ASCE standardized equation, ET_{ref} calculated with the full equation was consistently below lysimeter ET values. Average daily ET_{ref} calculated over the third and fourth cutting cycles, was 5.81 mm/day and 5.56 mm/day for the ASCE standardized and full versions, respectively, whereas the average daily ET determined from the lysimeter was 6.56 mm/day. Table (2) shows the statistical analysis of the comparisons. The values for index of agreement were 0.946 for the ASCE standardized ET_{rs} and 0.894 for the full version of Penman-Monteith. This indicates that the ASCE standardized ET_{rs} agreed better with the lysimeter ET than the full version of the Penman-Monteith. Lower RMSE (0.821 mm/day) was obtained between ASCE standardized ET_{rs} versus Lysimeter than between full version of Penman Monteith versus lysimeter ET (1.22 mm/day). The lower RMSE also indicates a better fit to the observed ET**.** While ET_{rs} estimates from the ASCE standardized equation fit better with the lysimeter observed ET, both equations under-estimated measured ET_{ref}. Relative error was -11.5 % for ASCE standardized ET_{rs} and -15.2 % for the full version.

The full version of the Penman Monteith showed very good agreement with ASCE standardized ET. RMSE was 0.605 mm/day and the index of agreement was 0.973. The full version of the Penman Monteith underestimated ET_{ref} by 4% compared to ASCE standardized ET_{rs}. Thus, using full version of Penman Monteith equation did not improve the calculations of ET_{ref}. Evett et al, (2004) also found that using curves of LAI and alfalfa height to estimate aerodynamic and surface resistances did not improve ET values. Using predicted LAI formula (Allen et al., 1994) in calculating ET_{ref} with the full equation gave almost the same results as measured LAI (data is not shown).

CONCLUSION

This study sought to improve ET_{ref} values from the ASCE standardized ET_{rs} equation by using the full version of the Penman-Monteith equation. The results indicated high correlations between LAI and alfalfa height but the relationships were not the same as suggested by Allen et al. (1994). ET_{rs} values calculated by the ASCE standardized equation fitted better with lysimeter ET values than that calculated by the full version of Penman-Monteith. Both ASCE standardized and full version of Penman-Monteith equations underestimated ET_{ref}, but no advantage to using the full version was observed.

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Table 1. pH, electrical conductivity (ECe), bulk density, water content at field capacity and wilting point, and the hydraulic conductivity for soil within the lysimeter.

Depth cm	pH water (1:1)	ECe dS/m	Bulk density g/cm^3	Field Capacity cm^3/cm^3	Wilting point cm^3/cm^3	Hydraulic conductivity cm/hr
0-23	8.1	0.82	1.36	0.291	0.167	0.34
23-36	8.0	0.90	1.36	0.290	0.169	0.33
36-100	8.3	0.58	1.45	0.242	0.112	1.25
100-170	8.3	0.72	1.43	0.252	0.117	1.06
170-230	8.3	0.88	1.35	0.296	0.159	0.42

Table 2. The average daily evapotranspiration (ET) estimated by the ASCE standardized Penman-Monteith equation or the full Penman-Monteith equation and a statistical evaluation of their relationship to lysimeter ET and to each other. Statistical evaluations include root mean square error (RMSE), relative error (RE), and the index of agreement.

Equation	Average ET mm/day	RMSE mm/day	RE %	Index of agreement
Lysimeter	6.56	-	-	-
ASCE standardized PM	5.81	0.821	-11.47	0.946
Full PM equation	5.56	1.22	-15.19	0.894
Full PM equation versus ASCE standardized PM		0.605	-4.2	0.973

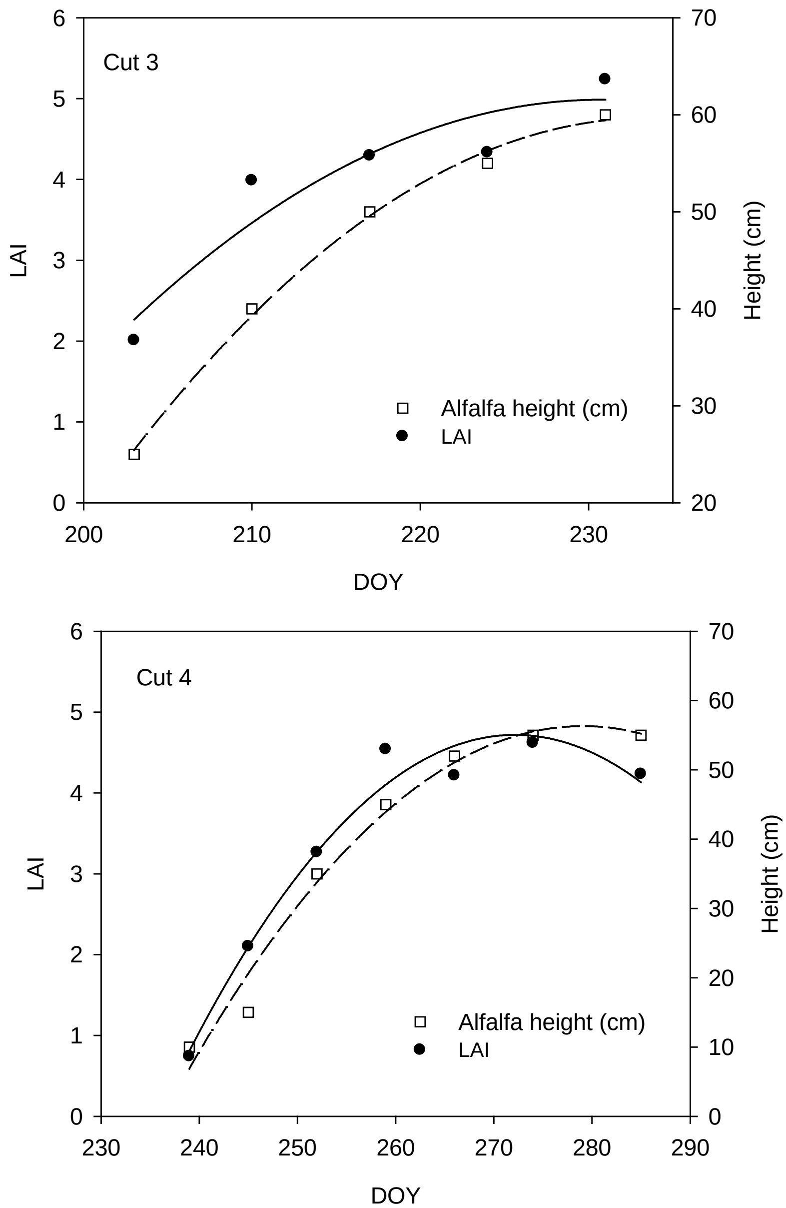

Fig. 1. Leaf area index and alfalfa height (cm) versus day of the year for the third and forth cutting cycle in 2010

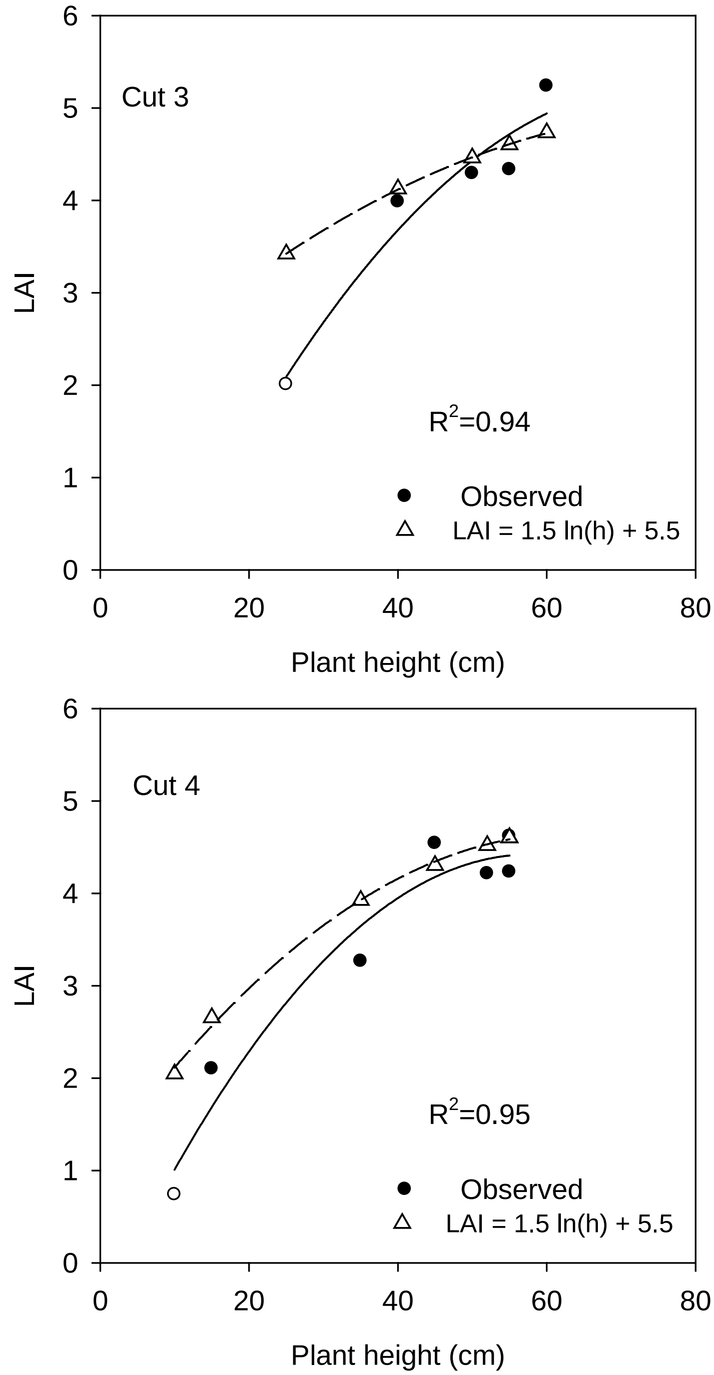

Fig. 2. Measured and calculated leaf area index versus alfalfa height for the third and fourth cutting cycles in 2010. Calculated leaf area index was from the function given by Allen et al. (1994).

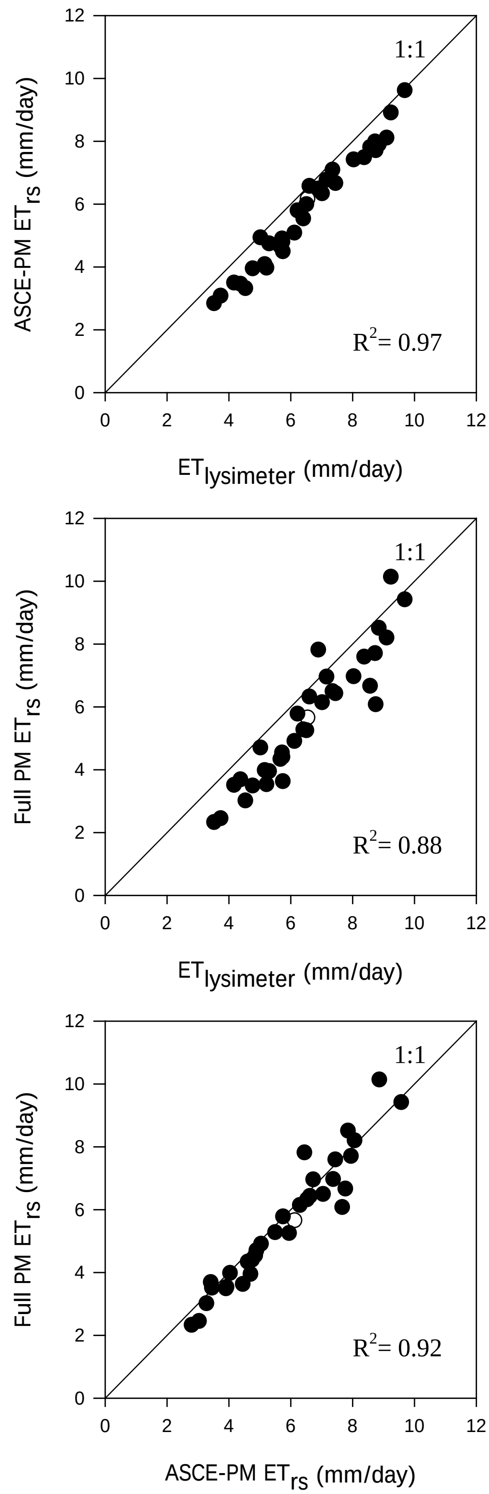

Fig. 3. The relationships between ASCE-Penman-Monteith, full version of Penman-Monteith and measured ET using lysimeter.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

Conclusion

The objectives of this study were to use a precise weighing lysimeter to measure alfalfa ET to test the performance of the ASCE standardized ET_{rs} equation and to develop compatible local crop coefficients of alfalfa under southeast Colorado conditions. A corollary objective was to determine if the full version of the Penman-Monteith equation could better match measured alfalfa ET from the lysimeter when reference conditions were satisfied.

Even though some challenges were encountered, this study has provided significant results regarding the performance of the ASCE standardized ET_{rs} equation, alfalfa crop coefficients, and alfalfa water use. From this study, it can be concluded that:

- Both climatic factors and crop growth impact alfalfa water use. Alfalfa ET ranged from 1179 mm to 1455 mm. The average total yield was 18.95 Mg/ha. Maximum daily water use of alfalfa was 14.4 mm/day in 2010. Average daily ET for 2008, 2009 and 2010 was 5.7 mm/day, 6.0 mm/day and 6.9 mm/day, respectively.
- Hourly ET_{rs} values calculated by the ASCE standardized PM equation agreed well with measured ET of well irrigated alfalfa.
- Residuals (differences between calculated ETrs and measured ET from the lysimeter) increased with higher temperatures and lower relative humidity, indicating that the ASCE standardized ET_{rs} was less accurate under these conditions.

- Greater residuals were obtained when less than 80 % of the footprint length was in the field, indicating that the lack of fetch contributed to the differences between the ASCE standardized PM ET_{rs} and lysimeter ET. Residuals also increased as the ratio of existing fetch to the required fetch decreased.
- Alfalfa crop coefficient curves obtained in this study were similar in shape to those reported in the literature. Alfalfa growth, climate, precipitation and soil water content influenced the shape of the crop coefficient curves. Maximum crop coefficients were above 1.2 in some cutting cycles. The K_{cr} values greater than 1.0 were due to ET_c values from the lysimeter being higher than ET_{rs} values from the ASCE standardized PM equation. Peak crop coefficient values greater than 1.0 led us to believe that uncertainties related to both alfalfa ET in the lysimeter and the ASCE standardized ET_{rs} equation contributed to this. The height difference between alfalfa inside and outside the lysimeter and the extension of alfalfa outside the lysimeter boundary resulted in higher ET; likely causing higher K_{cr} values. The ASCE standardized ET_{rs} equation, which deviated more from lysimeter ET under conditions of high temperature and low relative humidity may have also contributed to higher K_{cr} values.
- Average LAI at a height of 50 cm was 4.34. There were good correlations between LAI and alfalfa height, but the relationships were different from those suggested by Allen et al. (1994). Crop height, crop variety, and planting density affected the measurements of LAI.
- Using the full version of the Penman-Monteith equation did not seem to improve the calculations of ET_{ref}. ET_{ref} values calculated by the ASCE standardized ET_{rs} equation fit better with lysimeter ET values than that

calculated by full version of Penman-Monteith. Both equations underestimated observed ET_{ref} from the lysimeter.

- Due to difference in height between alfalfa in the lysimeter and surrounding field, the alfalfa canopy extended beyond the edges of the lysimeter and the evaporative area increased from 9 m^2 from the beginning of growth or after cutting to an average of 10.6 m^2. Soil settling after lysimeter construction and increased foot traffic from maintenance and harvest events may have resulted in stunted growth in the immediate vicinity of the lysimeter.

Recommendations

- Soil water content measurements indicated that alfalfa was under soil water stress in some portions of the season. Timely irrigation applications based on measured soil water deficits should be done to eliminate soil water stress. To have more uniform distribution of irrigation in the field, it is recommended that furrow irrigation be replaced with a sprinkler irrigation system.
- Soil compaction due to lysimeter construction and crop and soil measurements around the lysimeter affects the growth of alfalfa around the lysimeter. It is better to minimize working around the lysimeter.
- It is difficult sometimes to control the growth of alfalfa that extends outside the lysimeter edges. The extent of alfalfa canopy extending outside the lysimeter should be measured regularly. It may also be possible to eliminate the problem by fixing a string on sticks (i.e., fence) at the edge of the lysimeter and raising this string as alfalfa height increases.
- Lack of fetch contributed to the differences between the ASCE standardized PM ET_{rs} and lysimeter ET. The residuals increased as the ratio of existing fetch to the required fetch decreased. More studies should be concentrated on

the effect of footprint on the lysimeter ET and include footprint analysis in the placement of weather stations that will be used for calculating ASCE standardized PM ET_{rs}.

- The ASCE standardized ET_{rs} equation lacked sensitivity to conditions of high temperature and low relative humidity. This could be due to the linear relationship between temperature and saturation vapor pressure assumed in the derivation. It is recommended to use recursive calculation proposed by Lascano and van Bavel (2007) to determine ET_{ref} to include canopy temperature in the calculations.
- The relationship between LAI and alfalfa height was not the same as suggested by Allen et al. (1994). More studies should be focused on the estimation of LAI and its effect on surface resistance (r_s) to vapor transport.

APPENDIX

A. Water Stress Coefficient (Ks)

Ks values were calculated based on Allen et al. (1998)

$$K_s = \frac{TAW - D_r}{(1 - P)TAW}$$

where K_s is the reduction factor dependent on available soil water (0-1), TAW is the total available water in the root zone (mm) = water content at field capacity (FC) – water content at wilting point (PWP), D_r is the root zone depletion (mm), and P is a fraction of TAW that crop can extract from the root zone without suffering water stress.

Figure (1) shows water stress coefficient (K_s) and soil water content (SWC) versus DOY for 2009 season. It is clear that alfalfa was under water stress during the first cutting cycle of 2009 season. K_s values reduced below 1.0.

Lysimeter ET_c values, which were under water stress at the first cutting cycle of 2009, were close to adjusted ET_c (stressed). Calculated ET_c values (K_c x ET_r) are above the water stress lysimeter ET_c (figure 2). The calculations of K_s and soil water content (SWC) are shown in the next following table.

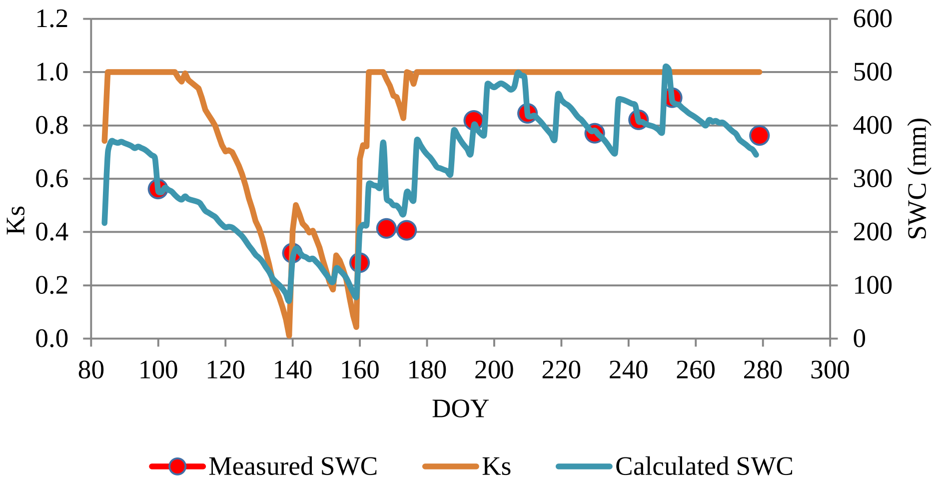

Fig. 1. Water Stress Coefficient (Ks) and soil water content (SWC) versus DOY for 2009 showing water stress at the beginning of the season (first cutting cycle)

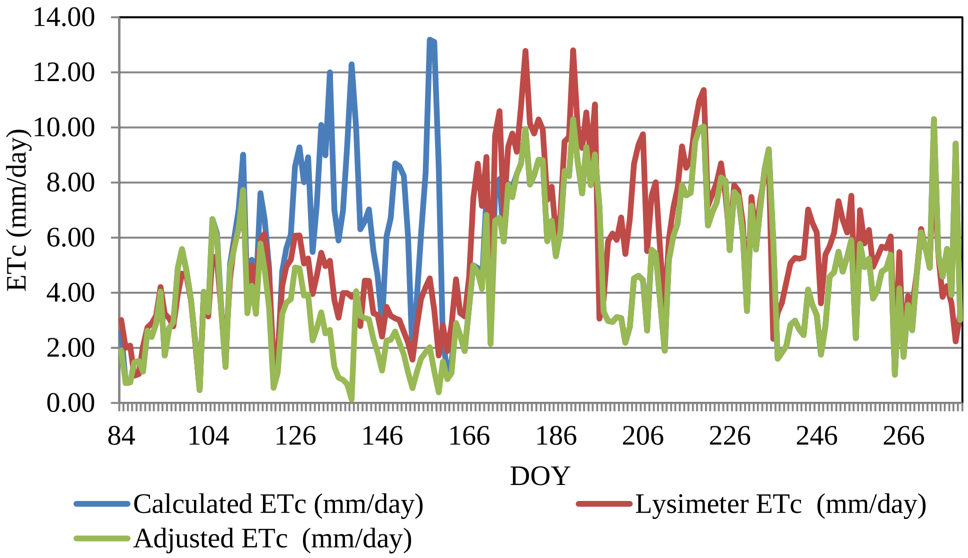

Fig. 2. Calculated ETc (Kc x ETr), Lysimeter ET and adjusted ETc versus DOY for 2009 showing water stress at the beginning of the season (first cutting cycle)

Soil water content and water stress coefficient (Ks) calculation for 2009 season

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
84	219.49	0.50	5.15	2.57	0.00	0.00	3.00	216.92	293.1	0.7	1.91
85		0.50	1.44	0.72	126.80	6.46	2.00	349.46	160.5	1.0	0.72
86		0.50	1.48	0.74	0.00	21.60	2.08	370.32	139.7	1.0	0.74
87		0.50	2.94	1.47	0.00	0.00	0.98	368.85	141.1	1.0	1.47
88		0.50	3.03	1.52	0.00	0.00	1.05	367.34	142.7	1.0	1.52
89		0.50	2.27	1.14	0.00	3.20	2.04	369.40	140.6	1.0	1.14
90		0.62	4.24	2.63	0.00	0.00	2.74	366.77	143.2	1.0	2.63
91		0.62	3.86	2.39	0.00	0.00	2.88	364.38	145.6	1.0	2.39
92		0.62	4.65	2.88	0.00	0.00	3.16	361.50	148.5	1.0	2.88
93		0.62	6.53	4.05	0.00	0.00	4.20	357.45	152.5	1.0	4.05
94		0.62	2.78	1.72	0.00	4.59	3.23	360.32	149.7	1.0	1.72
95		0.62	4.38	2.71	0.00	0.00	3.07	357.61	152.4	1.0	2.71
96		0.62	4.73	2.93	0.00	0.00	2.78	354.68	155.3	1.0	2.93
97		0.73	6.71	4.90	0.00	0.00	3.95	349.78	160.2	1.0	4.90
98		0.73	7.64	5.58	0.00	0.00	4.69	344.21	165.8	1.0	5.58
99		0.73	6.56	4.79	0.00	0.00	4.61	339.41	170.6	1.0	4.79
100	280.28	0.73	5.13	3.74	0.00	0.00	3.72	276.53	233.5	1.0	3.74
101		0.73	3.12	2.28	0.00	0.45	2.20	274.70	235.3	1.0	2.28
102		0.73	0.63	0.46	0.00	9.09	0.49	283.33	226.7	1.0	0.46
103		0.73	5.52	4.03	0.00	0.00	4.00	279.30	230.7	1.0	4.03
104		0.73	4.51	3.29	0.00	0.00	3.14	276.01	234.0	1.0	3.29
105		0.83	8.04	6.67	0.00	0.00	5.32	269.33	240.7	1.0	6.67

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
106		0.83	7.40	6.14	0.00	0.46	5.22	263.65	246.3	1.0	6.01
107		0.83	4.07	3.38	0.00	0.67	3.33	260.94	249.1	1.0	3.26
108		0.83	1.58	1.31	0.00	7.42	1.85	267.05	243.0	1.0	1.30
109		0.83	6.06	5.03	0.00	0.00	4.50	262.01	248.0	1.0	4.88
112		0.83	7.20	5.98	0.00	0.00	5.78	256.04	254.0	0.9	5.62
113		0.88	7.98	7.02	0.00	0.00	6.30	249.01	261.0	0.9	6.35
114		0.88	10.24	9.01	0.00	0.00	7.48	240.01	270.0	0.9	7.73
115		0.88	4.41	3.88	0.00	0.00	3.96	236.13	273.9	0.8	3.26
116		0.88	5.90	5.19	0.00	1.25	5.00	232.19	277.8	0.8	4.25
117		0.88	4.60	4.04	0.00	0.00	4.30	228.14	281.9	0.8	3.23
118		0.88	8.65	7.61	0.00	0.00	5.94	220.53	289.5	0.8	5.79
119		0.88	7.60	6.68	0.00	0.00	6.13	213.85	296.2	0.7	4.86
120		0.88	5.58	4.91	0.00	0.00	4.71	208.94	301.1	0.7	3.45
121		0.94	0.82	0.77	0.00	1.85	1.47	210.02	300.0	0.7	0.54
122		0.94	1.67	1.57	0.00	0.16	1.80	208.62	301.4	0.7	1.10
123		0.94	5.08	4.77	0.00	0.00	4.25	203.84	306.2	0.7	3.23
124		0.94	5.97	5.61	0.00	0.00	4.95	198.23	311.8	0.6	3.64
125		0.94	6.50	6.11	0.00	0.00	5.19	192.12	317.9	0.6	3.77
126		0.94	9.13	8.58	0.00	0.00	6.07	183.54	326.5	0.6	4.92
127		0.94	9.86	9.27	0.00	0.00	6.08	174.27	335.7	0.5	4.88
128		1.00	8.01	8.01	0.00	0.00	5.06	166.26	343.7	0.5	3.89
129		1.00	8.91	8.91	0.00	0.00	5.24	157.35	352.7	0.4	3.93

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
130		1.00	5.47	5.47	0.00	0.00	3.95	151.88	358.1	0.4	2.26
131		1.00	7.19	7.19	0.00	0.00	4.62	144.70	365.3	0.4	2.71
132		1.00	10.09	10.09	0.00	0.00	5.45	134.61	375.4	0.3	3.29
133		1.00	8.99	8.99	0.00	0.00	4.96	125.62	384.4	0.3	2.52
134		1.00	12.00	12.00	0.00	0.00	5.16	113.62	396.4	0.2	2.64
135		1.00	7.00	7.00	0.00	0.00	3.73	106.62	403.4	0.2	1.30
136		1.00	5.89	5.89	0.00	0.00	3.09	100.73	409.3	0.2	0.91
137		1.00	6.99	6.99	0.00	0.00	3.98	93.74	416.3	0.1	0.84
138		1.00	9.35	9.35	0.00	0.00	3.98	84.40	425.6	0.1	0.68
139		1.00	12.28	12.28	0.00	0.00	3.85	72.11	437.9	0.0	0.13
140	160.46	1.00	9.98	9.98	0.00	0.00	3.95	150.48	359.5	0.4	4.05
141		1.00	6.30	6.30	0.00	25.01	2.78	169.19	340.8	0.5	3.16
142		1.00	6.59	6.59	0.00	0.00	4.44	162.60	347.4	0.5	3.08
143		1.00	7.02	7.02	0.00	0.00	4.42	155.58	354.4	0.4	3.04
144		1.00	5.53	5.53	0.00	2.79	3.25	152.84	357.2	0.4	2.31
145		1.00	4.62	4.62	0.00	0.56	3.19	148.79	361.2	0.4	1.84
146		1.00	2.89	2.89	0.00	4.47	2.41	150.37	359.6	0.4	1.17
147		1.00	6.04	6.04	0.00	0.00	3.49	144.32	365.7	0.4	2.27
148		1.00	6.71	6.71	0.00	0.00	3.16	137.61	372.4	0.3	2.29
149		1.00	8.70	8.70	0.00	0.00	3.07	128.91	381.1	0.3	2.59
150		1.00	8.59	8.59	0.00	0.00	3.01	120.32	389.7	0.3	2.18
151		0.98	8.40	8.24	0.00	0.00	2.58	112.09	397.9	0.2	1.75

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
152		0.98	6.20	6.07	0.00	0.47	2.19	106.49	403.5	0.2	1.12
153		0.98	1.72	1.69	0.00	27.14	1.57	131.94	378.1	0.3	0.53
154		0.98	3.94	3.86	0.00	0.00	2.82	128.08	381.9	0.3	1.13
155		0.98	6.29	6.16	0.00	0.00	3.78	121.91	388.1	0.3	1.62
156		0.98	8.51	8.34	0.00	0.00	4.20	113.58	396.4	0.2	1.83
157		0.98	13.45	13.18	0.00	0.00	4.52	100.40	409.6	0.2	2.02
158		0.98	13.37	13.10	0.00	0.00	3.37	87.29	422.7	0.1	1.14
159		0.96	8.91	8.56	0.00	0.00	1.72	78.73	431.3	0.0	0.38
160	142.21	0.30	7.41	2.22	63.66	0.00	2.81	203.64	306.4	0.7	1.50
161		0.30	3.93	1.18	0.00	11.42	1.88	213.88	296.1	0.7	0.86
162		0.30	4.96	1.49	0.00	0.56	2.84	212.96	297.0	0.7	1.07
163		0.40	7.24	2.90	80.16	0.00	4.48	290.22	219.8	1.0	2.90
164		0.40	6.13	2.45	0.00	0.00	3.26	287.77	222.2	1.0	2.45
165		0.40	4.70	1.88	0.00	0.67	3.14	286.55	223.4	1.0	1.88
166		0.55	6.35	3.49	0.00	0.00	4.58	283.06	226.9	1.0	3.49
167		0.55	9.08	5.00	90.14	0.00	7.41	368.20	141.8	1.0	5.00
168	206.53	0.55	8.89	4.89	60.59	0.00	8.68	262.23	247.8	1.0	4.74
169		0.55	7.93	4.36	0.00	0.00	7.14	257.87	252.1	0.9	4.14
170		0.80	9.36	7.48	0.00	0.00	8.93	250.39	259.6	0.9	6.82
171		0.80	2.95	2.36	0.00	1.56	3.27	249.60	260.4	0.9	2.14
172		0.80	9.52	7.61	0.00	0.00	9.71	241.98	268.0	0.9	6.61
173		0.80	10.15	8.12	0.00	0.00	10.59	233.86	276.1	0.8	6.72

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
174	202.72	0.94	6.23	5.86	75.47	2.71	6.86	275.05	234.9	1.0	5.86
175		0.94	8.46	7.95	0.00	0.00	9.29	267.10	242.9	1.0	7.92
176		0.94	8.31	7.81	0.00	0.00	9.77	259.29	250.7	1.0	7.46
177		0.94	8.84	8.30	121.41	0.00	9.11	372.39	137.6	1.0	8.30
178		0.97	8.95	8.68	0.00	0.00	10.75	363.71	146.3	1.0	8.68
179		0.97	10.24	9.94	0.00	0.00	12.78	353.77	156.2	1.0	9.94
180		0.97	8.17	7.93	0.00	0.00	10.14	345.85	164.2	1.0	7.93
181		1.00	8.26	8.26	0.00	1.90	9.77	339.49	170.5	1.0	8.26
182		1.00	8.83	8.83	0.00	0.00	10.29	330.66	179.3	1.0	8.83
183		1.00	8.82	8.82	0.00	0.00	9.93	321.84	188.2	1.0	8.82
184		1.00	5.87	5.87	0.00	3.63	7.37	319.60	190.4	1.0	5.87
185		1.00	6.61	6.61	0.00	4.00	7.85	316.99	193.0	1.0	6.61
186		1.00	5.32	5.32	0.00	2.77	6.15	314.43	195.6	1.0	5.32
187		1.00	6.22	6.22	0.00	0.00	6.78	308.21	201.8	1.0	6.22
188		1.00	8.41	8.41	90.72	0.00	9.49	390.52	119.5	1.0	8.41
189		1.00	8.24	8.24	0.00	0.00	9.64	382.29	127.7	1.0	8.24
190		1.00	10.30	10.30	0.00	0.00	12.80	371.99	138.0	1.0	10.30
191		1.00	8.76	8.76	0.00	0.00	10.00	363.23	146.8	1.0	8.76
192		0.97	7.83	7.60	0.00	0.00	9.25	355.64	154.4	1.0	7.60
193		0.97	9.57	9.28	0.00	0.00	10.55	346.35	163.6	1.0	9.28
194	408.99	0.97	8.15	7.91	0.00	0.00	8.86	401.08	108.9	1.0	7.91
195		0.97	9.29	9.02	0.00	0.00	10.83	392.06	117.9	1.0	9.02

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
196		0.94	7.58	7.12	0.00	0.00	3.06	384.94	125.1	1.0	7.12
197		0.30	11.04	3.31	0.00	0.00	3.74	381.63	128.4	1.0	3.31
198		0.30	9.90	2.97	98.92	0.00	5.87	477.58	32.4	1.0	2.97
199		0.30	9.79	2.94	0.00	0.00	6.14	474.64	35.4	1.0	2.94
200		0.40	7.80	3.12	0.00	0.00	5.91	471.52	38.5	1.0	3.12
201		0.40	7.70	3.08	0.00	7.04	6.73	475.48	34.5	1.0	3.08
202		0.40	5.47	2.19	0.00	5.57	5.41	478.86	31.1	1.0	2.19
203		0.40	6.89	2.76	0.00	0.00	6.67	476.11	33.9	1.0	2.76
204		0.55	8.23	4.52	0.00	0.00	8.67	471.58	38.4	1.0	4.52
205		0.55	8.38	4.61	0.00	0.00	9.37	466.97	43.0	1.0	4.61
206		0.55	8.10	4.46	0.00	10.28	9.76	472.79	37.2	1.0	4.46
207		0.55	4.76	2.62	0.00	28.14	5.50	498.31	11.7	1.0	2.62
208		0.80	6.95	5.56	0.00	0.94	7.52	493.69	16.3	1.0	5.56
209		0.80	6.77	5.42	0.00	2.73	8.01	491.00	19.0	1.0	5.42
210	422.09	0.80	4.56	3.65	0.00	0.25	5.50	418.69	91.3	1.0	3.65
211		0.80	2.37	1.89	0.00	0.00	3.26	416.80	93.2	1.0	1.89
212		0.94	5.52	5.19	0.00	6.81	5.95	418.41	91.6	1.0	5.19
213		0.94	6.46	6.07	0.00	0.00	7.09	412.34	97.7	1.0	6.07
214		0.94	6.92	6.50	0.00	0.00	7.78	405.84	104.2	1.0	6.50
215		0.94	8.43	7.92	0.00	0.00	9.31	397.92	112.1	1.0	7.92
216		0.97	7.77	7.53	0.00	0.00	8.53	390.39	119.6	1.0	7.53
217		0.97	7.86	7.63	0.00	0.00	8.84	382.76	127.2	1.0	7.63

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
218		0.97	9.78	9.49	0.00	0.00	10.15	373.27	136.7	1.0	9.49
219		0.97	10.25	9.95	94.95	0.00	10.97	458.28	51.7	1.0	9.95
220		1.00	10.03	10.03	0.00	0.00	11.35	448.25	61.8	1.0	10.03
221		1.00	6.44	6.44	0.00	0.00	7.15	441.81	68.2	1.0	6.44
222		1.00	6.93	6.93	0.00	3.06	7.58	437.93	72.1	1.0	6.93
223		1.00	7.27	7.27	0.00	1.18	7.99	431.84	78.2	1.0	7.27
224		1.00	8.19	8.19	0.00	0.00	8.70	423.66	86.3	1.0	8.19
225		1.00	8.06	8.06	0.00	0.00	7.51	415.60	94.4	1.0	8.06
226		1.00	5.55	5.55	0.00	0.31	5.93	410.36	99.6	1.0	5.55
227		1.00	7.66	7.66	0.00	0.00	7.91	402.70	107.3	1.0	7.66
228		1.00	7.49	7.49	0.00	0.00	7.70	395.21	114.8	1.0	7.49
229		1.00	6.13	6.13	0.00	0.00	6.53	389.08	120.9	1.0	6.13
230	385.20	1.00	3.33	3.33	0.00	8.62	3.44	390.49	119.5	1.0	3.33
231		1.00	7.16	7.16	0.00	0.00	7.48	383.33	126.7	1.0	7.16
232		0.97	5.74	5.57	0.00	0.00	6.03	377.76	132.2	1.0	5.57
233		0.97	7.25	7.04	0.00	0.00	7.32	370.72	139.3	1.0	7.04
234		0.97	8.74	8.48	0.00	0.00	8.24	362.24	147.8	1.0	8.48
235		0.97	9.49	9.20	0.00	0.00	8.82	353.04	157.0	1.0	9.20
236		0.94	6.28	5.91	0.00	0.82	2.32	347.95	162.1	1.0	5.91
237		0.30	5.33	1.60	101.69	0.19	3.28	448.23	61.8	1.0	1.60
238		0.30	6.09	1.83	0.00	2.27	3.63	448.67	61.3	1.0	1.83
239		0.30	6.90	2.07	0.00	0.00	4.39	446.60	63.4	1.0	2.07

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
240		0.40	7.09	2.84	0.00	0.00	5.08	443.77	66.2	1.0	2.84
241		0.40	7.45	2.98	0.00	0.00	5.26	440.79	69.2	1.0	2.98
242		0.40	6.69	2.67	0.00	0.00	5.23	438.11	71.9	1.0	2.67
243	410.22	0.40	6.16	2.46	0.00	0.00	5.28	407.76	102.2	1.0	2.46
244		0.55	7.48	4.11	0.00	3.16	7.02	406.80	103.2	1.0	4.11
245		0.55	6.49	3.57	0.00	0.00	6.55	403.24	106.8	1.0	3.57
246		0.55	5.78	3.18	0.00	0.61	6.18	400.66	109.3	1.0	3.18
247		0.55	3.19	1.75	0.00	0.00	3.62	398.91	111.1	1.0	1.75
248		0.55	5.07	2.79	0.00	0.00	5.38	396.12	113.9	1.0	2.79
249		0.80	5.73	4.58	0.00	0.00	5.68	391.54	118.5	1.0	4.58
250		0.80	5.93	4.75	0.00	0.00	6.18	386.79	123.2	1.0	4.75
251		0.80	6.85	5.48	128.34	0.00	7.32	509.65	0.3	1.0	5.48
252		0.80	5.96	4.77	0.00	0.00	6.65	504.88	5.1	1.0	4.77
253	451.57	0.94	5.63	5.29	0.00	0.00	6.19	446.27	63.7	1.0	5.29
254		0.94	6.29	5.91	0.00	0.00	7.52	440.36	69.6	1.0	5.91
255		0.94	2.50	2.35	0.00	0.62	3.11	438.63	71.4	1.0	2.35
256		0.94	6.14	5.78	0.00	0.00	7.00	432.86	77.1	1.0	5.78
257		0.97	5.08	4.93	0.00	0.00	5.79	427.93	82.1	1.0	4.93
258		0.97	5.40	5.24	0.00	0.00	6.28	422.69	87.3	1.0	5.24
259		0.97	3.91	3.79	0.00	0.00	4.94	418.90	91.1	1.0	3.79
260		0.97	4.23	4.11	0.00	0.00	5.31	414.80	95.2	1.0	4.11
261		1.00	4.77	4.77	0.00	0.00	5.67	410.03	100.0	1.0	4.77

DOY	SWC (measured) mm	Kc Wright 1981	ETr mm/day	calculated ETc mm/day	Irrigation mm	Precip. mm	lysimeter ETc mm/day	SWC (calculated) mm	Dr mm	Ks	ETc adjusted mm/day
262		1.00	4.87	4.87	0.00	0.00	5.61	405.16	104.8	1.0	4.87
263		1.00	5.39	5.39	0.00	0.00	6.04	399.77	110.2	1.0	5.39
264		1.00	1.03	1.03	0.00	11.66	1.45	410.41	99.6	1.0	1.03
265		1.00	4.16	4.16	0.00	0.87	5.47	407.12	102.9	1.0	4.16
266		1.00	1.67	1.67	0.00	3.15	1.83	408.60	101.4	1.0	1.67
267		1.00	3.55	3.55	0.00	0.00	3.88	405.04	105.0	1.0	3.55
268		1.00	2.64	2.64	0.00	3.09	3.49	405.50	104.5	1.0	2.64
269		1.00	4.62	4.62	0.00	0.00	4.68	400.87	109.1	1.0	4.62
270		1.00	6.20	6.20	0.00	0.00	6.31	394.67	115.3	1.0	6.20
271		1.00	5.68	5.68	0.00	0.00	5.62	389.00	121.0	1.0	5.68
272		1.00	4.90	4.90	0.00	0.00	5.15	384.10	125.9	1.0	4.90
273		1.00	10.30	10.30	0.00	0.00	8.46	373.80	136.2	1.0	10.30
274		0.97	5.53	5.37	0.00	0.00	5.34	368.43	141.6	1.0	5.37
275		0.97	4.72	4.58	0.00	0.00	3.85	363.85	146.2	1.0	4.58
276		0.97	5.76	5.59	0.00	0.00	4.24	358.26	151.7	1.0	5.59
277		0.97	4.03	3.91	0.00	0.00	3.60	354.35	155.6	1.0	3.91
278		0.94	10.02	9.42	0.00	0.00	2.22	344.93	165.1	1.0	9.42
279	380.73	0.30	10.02	3.01	0.00	0.00	3.22	377.73	132.3	1.0	3.01

B. Water Balance

- 2008 season

Julian Date	Begin Load Cell (mV/v)	Irrigation (mV/v)	Precip (mV/v)	Fill in Holes (mV/v)	Plant Cutting (mV/v)	Adjust Counter Wt (mV/v)	End Load Cell (mV/v)	Measured ET (mm)
92	0.28893						0.25578	2.52
93	0.25578	1.519909					1.72760	3.65
94	1.72760						1.69550	2.44
95	1.69550						1.63930	4.27
96	1.63930						1.57710	4.73
97	1.57710						1.50650	5.37
98	1.50650						1.43800	5.21
99	1.43800						1.37780	4.58
100	1.37780						1.32480	4.03
101	1.32480		0.060042				1.34820	2.78
102	1.34820						1.28350	4.92
103	1.28350						1.22920	4.13
104	1.22920						1.17310	4.26
105	1.17310						1.10130	5.46
106	1.10130						0.97389	9.68
107	0.97389		0.149223				1.03200	6.92
108	1.03200		0.116118				1.09910	3.73
109	1.09910						1.03400	4.95
110	1.03400						0.95589	5.94
111	0.95589						0.82921	9.63
112	0.82921						0.74383	6.49
113	0.74383						0.66350	6.11
114	0.66350						0.56343	7.61
115	0.56343						0.45786	8.02
116	0.45786					1.390723	1.76610	6.27
117	1.76610						1.69390	5.49
118	1.69390						1.62990	4.86
119	1.62990						1.54780	6.24
120	1.54780						1.45580	6.99

Julian Date	Begin Load Cell (mV/v)	Irrigation (mV/v)	Precip (mV/v)	Fill in Holes (mV/v)	Plant Cutting (mV/v)	Adjust Counter Wt (mV/v)	End Load Cell (mV/v)	Measured ET (mm)
121	1.45580						1.32360	10.05
122	1.32360						1.25170	5.46
123	1.25170						1.18520	5.05
124	1.18520						1.11470	5.36
125	1.11470						1.01820	7.33
126	1.01820						0.91669	7.71
127	0.91669						0.84045	5.79
128	0.84045		0.07771				0.88109	2.82
129	0.88109						0.80682	5.64
130	0.80682					0.435577	1.12910	8.61
131	1.12910		0.009071				1.05550	6.28
132	1.05550						0.96102	7.18
133	0.96102	1.619147					2.42450	11.83
134	2.42450						2.38280	3.17
135	2.38280		0.052895				2.36010	5.75
136	2.36010		0.0025				2.27540	6.63
137	2.27540						2.19950	5.77
138	2.19950						2.06220	10.43
139	2.06220						1.94360	9.01
140	1.94360						1.80870	10.25
141	1.80870						1.69270	8.82
142	1.69270		0.091158			0.433635	2.08100	10.37
143	2.08100						1.94220	10.55
144	1.94220						1.83830	7.90
145	1.83830						1.69170	11.14
146	1.69170						1.57590	8.80
147	1.57590						1.50260	5.57
148	1.50260						1.43560	5.09
149	1.43560						1.33760	7.45
150	1.33760						1.18420	11.66
151	1.18420						1.06040	9.41
152	1.06040						0.93456	9.56
153	0.93456						0.82389	8.41
154	0.82389						0.71955	7.93
155	0.71955						0.61508	7.94
156	0.61508						0.54020	5.69
157	0.54020		0.284202				0.78995	2.62
158	0.78995						0.66866	9.22
159	0.66866						0.55977	8.28
160	0.55977						0.46084	7.52
161	0.46084						0.36542	7.25

Julian Date	Begin Load Cell (mV/v)	Irrigation (mV/v)	Precip (mV/v)	Fill in Holes (mV/v)	Plant Cutting (mV/v)	Adjust Counter Wt (mV/v)	End Load Cell (mV/v)	Measured ET (mm)
162	0.36542						0.24102	9.45
163	0.24102					1.069133	1.25840	3.93
164	1.25840						1.22980	2.17
165	1.22980						1.19980	2.28
166	1.19980						1.16250	2.83
167	1.16250						1.11910	3.30
168	1.11910						1.10930	0.74
169	1.10930						1.06700	3.21
170	1.06700						1.02020	3.56
171	1.02020						0.98402	2.75
172	0.98402	1.606757					2.54280	3.65
173	2.54280						2.45610	6.59
174	2.45610						2.36110	7.22
175	2.36110						2.26590	7.24
176	2.26590						2.16700	7.52
177	2.16700						2.05960	8.16
178	2.05960						1.95190	8.19
179	1.95190						1.83540	8.85
180	1.83540						1.73780	7.42
181	1.73780						1.62580	8.51
182	1.62580						1.51860	8.15
183	1.51860	2.174119	0.009859				3.58120	9.22
184	3.58120		0.043836				3.49110	10.18
185	3.49110		0.0022				3.36840	9.49
186	3.36840						3.23400	10.21
187	3.23400						3.08330	11.45
188	3.08330		0.089624				3.04830	9.47
189	3.04830		0.01323				2.97290	6.74
190	2.97290						2.86940	7.87
191	2.86940						2.76330	8.06
192	2.76330						2.62710	10.35
193	2.62710						2.48950	10.46
194	2.48950						2.38360	8.05
195	2.38360						2.25330	9.90
196	2.25330						2.13000	9.37
197	2.13000						1.99820	10.02
198	1.99820						1.86850	9.86
199	1.86850						1.75490	8.63
200	1.75490		0.007595				1.67380	6.74
201	1.67380						1.53910	10.24
202	1.53910						1.39730	10.78

Julian Date	Begin Load Cell (mV/v)	Irrigation (mV/v)	Precip (mV/v)	Fill in Holes (mV/v)	Plant Cutting (mV/v)	Adjust Counter Wt (mV/v)	End Load Cell (mV/v)	Measured ET (mm)
203	1.39730				0.028771		1.32030	3.67
204	1.32030			0.021148			1.30840	2.51
205	1.30840						1.27290	2.70
206	1.27290						1.24010	2.49
207	1.24010	2.165718	0.007578				3.34430	5.25
208	3.34430		0.029965				3.30960	4.91
209	3.30960						3.23710	5.51
210	3.23710		0.046189				3.19110	7.01
211	3.19110						3.10190	6.78
212	3.10190						3.00450	7.40
213	3.00450						2.87820	9.60
214	2.87820						2.74580	10.06
215	2.74580						2.59000	11.84
216	2.59000						2.46290	9.66
217	2.46290	2.146065				1.640175	2.85140	8.92
218	2.85140						2.74860	7.81
219	2.74860						2.62010	9.77
220	2.62010		0.037101				2.60990	3.59
221	2.60990		0.018302				2.54380	6.41
222	2.54380		0.1147				2.47300	14.10
223	2.47300		0.146197				2.61110	0.62
224	2.61110						2.50800	7.84
225	2.50800		0.2741				2.66590	8.83
226	2.66590						2.56320	7.81
227	2.56320		0.075657				2.55080	6.69
228	2.55080		0.271596				2.79210	2.30
229	2.79210		0.083475				2.85380	1.65
230	2.85380		0.030534				2.83540	3.72
231	2.83540		0.009812				2.77940	5.00
232	2.77940						2.68410	7.24
233	2.68410						2.59490	6.78
234	2.59490						2.49640	7.49
235	2.49640						2.35540	10.72
236	2.35540		0.076337				2.33600	7.28
237	2.33600						2.21940	8.86
238	2.21940						2.11410	8.00
239	2.11410						2.02270	6.95
240	2.02270						1.91110	8.48
241	1.91110						1.79250	9.01
242	1.79250		0.543649				2.24790	6.71
243	2.24790						2.14940	7.49

Julian Date	Begin Load Cell (mV/v)	Irrigation (mV/v)	Precip (mV/v)	Fill in Holes (mV/v)	Plant Cutting (mV/v)	Adjust Counter Wt (mV/v)	End Load Cell (mV/v)	Measured ET (mm)
244	2.14940						2.01900	9.91
245	2.01900						1.88490	10.19
246	1.88490				0.005777		1.80800	5.41
247	1.80800						1.77290	2.67
248	1.77290						1.73790	2.66
249	1.73790						1.71050	2.08
250	1.71050						1.67600	2.62
251	1.67600						1.62550	3.84
252	1.62550						1.61170	1.05
253	1.61170						1.56490	3.56
254	1.56490						1.49810	5.08
255	1.49810						1.43920	4.48
256	1.43920						1.40420	2.66
257	1.40420						1.33090	5.57
258	1.33090						1.27120	4.54
259	1.27120						1.20960	4.68
260	1.20960						1.13430	5.72
261	1.13430						1.06380	5.36
262	1.06380						0.99887	4.93
263	0.99887					0.467427	1.39350	5.53
264	1.39350						1.31790	5.75
265	1.31790		0.035605				1.28060	5.54
266	1.28060						1.17760	7.83
267	1.17760	2.092409					3.19710	5.54
268	3.19710						3.13030	5.08
269	3.13030						3.05180	5.97
270	3.05180						2.97190	6.07
271	2.97190						2.89420	5.91
272	2.89420						2.81970	5.66
273	2.81970						2.75240	5.11
274	2.75240						2.68200	5.35
275	2.68200						2.60870	5.57
276	2.60870						2.54250	5.03
277	2.54250						2.47660	5.01
278	2.47660						2.39920	5.88
279	2.39920						2.31870	6.12
280	2.31870		0.0779				2.32090	5.75
281	2.32090						2.25840	4.75
282	2.25840						2.17820	6.10
283	2.17820						2.13590	3.21
284	2.13590						2.06110	5.68

Julian Date	Begin Load Cell (mV/v)	Irrigation (mV/v)	Precip (mV/v)	Fill in Holes (mV/v)	Plant Cutting (mV/v)	Adjust Counter Wt (mV/v)	End Load Cell (mV/v)	Measured ET (mm)
285	2.06110		0.37375				2.42010	1.12
286	2.42010		0.0038				2.36770	4.27
287	2.36770						2.31420	4.07
288	2.31420		0.081046				2.39140	0.29
289	2.39140						2.35110	3.06
290	2.35110						2.31280	2.91
291	2.31280						2.26630	3.53
292	2.26630						2.21800	3.67
293	2.21800						2.15350	4.90
294	2.15350		0.0133				2.15290	1.06
295	2.15290		0.019887				2.13010	3.24
296	2.13010						2.07440	4.23
297	2.07440						2.04070	2.56
298	2.04070						2.00510	2.71
299	2.00510						1.96470	3.07
300	1.96470						1.92550	2.98
301	1.92550						1.89920	2.00
302	1.89920						1.86610	2.52
303	1.86610						1.82360	3.23
304	1.82360						1.78060	3.27
305	1.78060						1.74230	2.91
306	1.74230						1.70870	2.55
307	1.70870						1.66420	3.38
308	1.66420				0.008214		1.61830	2.86
309	1.61830						1.60250	1.20
310	1.60250						1.59150	0.84

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Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Remove Tank (mV/V)	Plant Cutting (mV/V)	Adjust Counter Wt (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
83	0.66214						0.62577	2.76
84	0.62577						0.58612	3.01
85	0.58612	1.66839	0.08506				2.31310	2.01
86	2.31310		0.28420				2.56960	2.11
87	2.56960						2.55650	1.00
88	2.55650						2.54250	1.06
89	2.54250		0.04208				2.55720	2.08
90	2.55720						2.52030	2.80
91	2.52030						2.48140	2.96
92	2.48140						2.43850	3.26
93	2.43850						2.38130	4.35
94	2.38130		0.06045				2.39760	3.36
95	2.39760						2.35550	3.20
96	2.35550						2.31730	2.90
97	2.31730						2.26280	4.14
98	2.26280						2.19790	4.93
99	2.19790			-0.01724			2.11670	4.86
100	2.11670						2.06490	3.94
101	2.06490		0.00588				2.04000	2.34
102	2.04000		0.11955				2.15270	0.52
103	2.15270						2.09640	4.28
104	2.09640						2.05210	3.37
105	2.05210						1.97680	5.72
106	1.97680		0.00606				1.90870	5.64
107	1.90870		0.00880				1.87010	3.60
108	1.87010		0.09762				1.94130	2.01
109	1.94130						1.87670	4.91
110	1.87670							
111							1.72670	11.40
112	1.72670						1.64300	6.36
113	1.64300						1.55150	6.95
114	1.55150						1.44250	8.28
115	1.44250						1.38450	4.41
116	1.38450		0.01649				1.32760	5.58
117	1.32760						1.26430	4.81
118	1.26430						1.17650	6.67
119	1.17650						1.08560	6.91
120	1.08560						1.01560	5.32
121	1.01560		0.02437				1.01800	1.67

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Remove Tank (mV/V)	Plant Cutting (mV/V)	Adjust Counter Wt (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
122	1.01800		0.00210				0.99315	2.05
123	0.99315						0.92941	4.84
124	0.92941						0.85493	5.66
125	0.85493						0.77650	5.96
126	0.77650						0.68450	6.99
127	0.68450						0.59204	7.03
128	0.59204					1.13195	1.64690	5.86
129	1.64690						1.56680	6.09
130	1.56680						1.50620	4.61
131	1.50620						1.43510	5.40
132	1.43510						1.35090	6.40
133	1.35090						1.27400	5.84
134	1.27400						1.19380	6.10
135	1.19380						1.13560	4.42
136	1.13560						1.08730	3.67
137	1.08730						1.02480	4.75
138	1.02480						0.96210	4.77
139	0.96210						0.90134	4.62
140	0.90134						0.83886	4.75
141	0.83886		0.32910			1.27916	2.40290	3.36
142	2.40290						2.33220	5.37
143	2.33220						2.26150	5.37
144	2.26150		0.03667				2.24600	3.96
145	2.24600		0.00740				2.20210	3.90
146	2.20210		0.05885				2.22210	2.95
147	2.22210						2.16570	4.29
148	2.16570						2.11450	3.89
149	2.11450						2.06460	3.79
150	2.06460						2.01540	3.74
151	2.01540						1.97320	3.21
152	1.97320		0.00619				1.94340	2.73
153	1.94340		0.35710				2.27460	1.97
154	2.27460						2.22800	3.54
155	2.22800						2.16530	4.77
156	2.16530						2.09550	5.30
157	2.09550						2.02010	5.73
158	2.02010						1.96380	4.28
159	1.96380				0.01439		1.92050	2.20
160	1.92050	0.83764					2.72120	2.81
161	2.72120		0.15022				2.84660	1.89
162	2.84660		0.00737				2.81640	2.86

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Remove Tank (mV/V)	Plant Cutting (mV/V)	Adjust Counter Wt (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
163	2.81640	1.05470				-2.03621	1.77530	4.53
164	1.77530						1.73180	3.31
165	1.73180		0.00875				1.69850	3.20
166	1.69850						1.63700	4.67
167	1.63700	1.18606					2.72320	7.59
168	2.72320	0.79727					3.40310	8.92
169	3.40310						3.30620	7.36
170	3.30620						3.18470	9.23
171	3.18470		0.02059				3.16060	3.40
172	3.16060						3.02760	10.11
173	3.02760						2.88200	11.07
174	2.88200	0.99308	0.03567				3.81610	7.19
175	3.81610						3.68750	9.77
176	3.68750						3.55180	10.31
177	3.55180	1.59745				-1.01259	4.00970	9.65
178	4.00970						3.85950	11.42
179	3.85950						3.68030	13.62
180	3.68030						3.53770	10.84
181	3.53770		0.02500				3.42480	10.48
182	3.42480						3.27910	11.07
183	3.27910						3.13800	10.72
184	3.13800		0.04772				3.08060	7.99
185	3.08060		0.05257				3.02090	8.53
186	3.02090		0.03638				2.96900	6.71
187	2.96900						2.87140	7.42
188	2.87140	1.19370					3.92810	10.41
189	3.92810						3.78840	10.62
190	3.78840						3.60240	14.14
191	3.60240					-1.63275	1.82380	11.08
192	1.82380						1.68850	10.28
193	1.68850						1.53370	11.76
194	1.53370						1.40320	9.92
195	1.40320						1.24320	12.16
196	1.24320				0.04193		1.15600	3.44
197	1.15600						1.10680	3.74
198	1.10680	1.30152					2.33080	5.89
199	2.33080						2.24940	6.19
200	2.24940						2.17080	5.97
201	2.17080		0.09262				2.17360	6.83
202	2.17360		0.07329				2.17450	5.50
203	2.17450						2.08490	6.81

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Remove Tank (mV/V)	Plant Cutting (mV/V)	Adjust Counter Wt (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
204	2.08490						1.96810	8.88
205	1.96810						1.84150	9.62
206	1.84150		0.13524				1.84440	10.06
207	1.84440		0.37022				2.13970	5.69
208	2.13970		0.01234				2.04940	7.80
209	2.04940		0.03589				1.97550	8.34
210	1.97550		0.00326				1.90320	5.74
211	1.90320						1.85830	3.41
212	1.85830		0.08960				1.86560	6.25
213	1.86560						1.76720	7.48
214	1.76720						1.65880	8.24
215	1.65880						1.52870	9.89
216	1.52870						1.40910	9.09
217	1.40910						1.28470	9.45
218	1.28470						1.14150	10.88
219	1.14150	1.24937					2.23550	11.81
220	2.23550						2.07420	12.26
221	2.07420						1.97230	7.74
222	1.97230		0.04022				1.90410	8.24
223	1.90410		0.01553				1.80500	8.71
224	1.80500						1.67980	9.52
225	1.67980						1.57140	8.24
226	1.57140		0.00406				1.48950	6.53
227	1.48950						1.37460	8.73
228	1.37460						1.26230	8.53
229	1.26230						1.16680	7.26
230	1.16680		0.11346				1.22980	3.83
231	1.22980						1.11970	8.37
232	1.11970						1.03070	6.76
233	1.03070						0.92222	8.24
234	0.92222						0.79974	9.31
235	0.79974						0.66826	9.99
236	0.66826		0.01074		0.03074		0.61358	2.64
237	0.61358	1.33809	0.00246				1.91100	3.28
238	1.91100		0.02989				1.89300	3.64
239	1.89300						1.83490	4.42
240	1.83490						1.76740	5.13
241	1.76740						1.69720	5.34
242	1.69720						1.62720	5.32
243	1.62720						1.55630	5.39
244	1.55630		0.04152				1.50330	7.18

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Remove Tank (mV/V)	Plant Cutting (mV/V)	Adjust Counter Wt (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
245	1.50330						1.41480	6.73
246	1.41480		0.00799				1.33900	6.37
247	1.33900						1.28980	3.74
248	1.28980						1.21630	5.59
249	1.21630						1.13850	5.91
250	1.13850						1.05360	6.45
251	1.05360	1.68871					2.64140	7.67
252	2.64140						2.54940	6.99
253	2.54940						2.46350	6.53
254	2.46350						2.35870	7.96
255	2.35870		0.00810				2.32330	3.31
256	2.32330						2.22520	7.46
257	2.22520						2.14380	6.19
258	2.14380						2.05520	6.73
259	2.05520						1.98530	5.31
260	1.98530						1.90990	5.73
261	1.90990						1.82910	6.14
262	1.82910						1.74890	6.10
263	1.74890						1.66220	6.59
264	1.66220		0.15340				1.79470	1.59
265	1.79470		0.01144				1.72710	6.01
266	1.72710		0.04147				1.74210	2.01
267	1.74210						1.68570	4.29
268	1.68570		0.04071				1.67550	3.87
269	1.67550						1.60710	5.20
270	1.60710						1.51450	7.04
271	1.51450						1.43170	6.29
272	1.43170						1.35570	5.78
273	1.35570						1.23040	9.52
274	1.23040						1.15100	6.03
275	1.15100						1.09360	4.36
276	1.09360						1.03020	4.82
277	1.03020						0.97622	4.10
278	0.97622				0.02036		0.92237	2.55

- 2010 season

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Drain Tanks (mV/V)	Plant Cutting (mV/V)	Maintain Sensors (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
90	3.08900						3.04890	3.05
91	3.04890						2.98540	4.83
92	2.98540						2.94990	2.70
93	2.94990						2.90570	3.36
94	2.90570						2.85150	4.12
95	2.85150						2.77830	5.56
96	2.77830			0.09084			2.61690	5.36
97	2.61690						2.57630	3.09
98	2.57630						2.53100	3.44
99	2.53100						2.46630	4.92
100	2.46630						2.41040	4.25
101	2.41040						2.35230	4.42
102	2.35230						2.26910	6.32
103	2.26910						2.17040	7.50
104	2.17040			0.08361		0.00641	2.03840	4.16
105	2.03840		0.17509			-0.00156	2.13960	5.50
106	2.13960		0.15377				2.27850	1.13
107	2.27850						2.23350	3.42
108	2.23350						2.17180	4.69
109	2.17180						2.10840	4.82
110	2.10840						2.04380	4.91
111	2.04380		0.08800				2.06110	5.37
112	2.06110		0.00330				1.98140	6.31
113	1.98140		0.05157				1.98060	3.98
114	1.98060						1.89760	6.31
115	1.89760		0.01578				1.83170	6.21
116	1.83170		0.05220				1.82590	4.41
117	1.82590	1.40462					3.14450	6.54
118	3.14450						3.00350	10.72
119	3.00350						2.89270	8.42
120	2.89270						2.80460	6.70
121	2.80460						2.72920	5.73
122	2.72920						2.66350	4.99
123	2.66350						2.56880	7.20
124	2.56880						2.44370	9.51
125	2.44370						2.33430	8.31
126	2.33430						2.20430	9.88
127	2.20430						2.12780	5.81
128	2.12780						2.01590	8.50

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Drain Tanks (mV/V)	Plant Cutting (mV/V)	Maintain Sensors (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
129	2.01590						1.88980	9.58
130	1.88980						1.76250	9.67
131	1.76250						1.69410	5.20
132	1.69410		0.00278				1.63910	4.39
133	1.63910						1.58330	4.24
134	1.58330	1.73558	0.08506				3.36510	2.95
135	3.36510		0.00750				3.30350	5.25
136	3.30350						3.21220	6.94
137	3.21220						3.11280	7.55
138	3.11280		0.29737				3.30580	7.93
139	3.30580		0.09150				3.33140	5.01
140	3.33140						3.24650	6.45
141	3.24650						3.15690	6.81
142	3.15690						2.97170	14.08
143	2.97170						2.83360	10.50
144	2.83360						2.66330	12.94
145	2.66330						2.56830	7.22
146	2.56830						2.45950	8.27
147	2.45950						2.31710	10.82
148	2.31710						2.17860	10.53
149	2.17860						2.01250	12.62
150	2.01250						1.90350	8.28
151	1.90350						1.78300	9.16
152	1.78300						1.65540	9.70
153	1.65540						1.53940	8.82
154	1.53940				0.03670	0.00590	1.45670	3.94
155	1.45670						1.40920	3.61
156	1.40920						1.35580	4.06
157	1.35580						1.29440	4.67
158	1.29440						1.21970	5.68
159	1.21970						1.15140	5.19
160	1.15140						1.06950	6.22
161	1.06950	1.71278					2.66180	9.16
162	2.66180		0.12061				2.68520	7.39
163	2.68520		0.02398				2.66840	3.10
164	2.66840		0.06038				2.66260	5.03
165	2.66260		0.33198				2.91740	5.87
166	2.91740						2.80980	8.18
167	2.80980		0.08273				2.73670	11.84
168	2.73670						2.57590	12.22
169	2.57590						2.41260	12.41

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Drain Tanks (mV/V)	Plant Cutting (mV/V)	Maintain Sensors (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
170	2.41260						2.30060	8.51
171	2.30060						2.15860	10.79
172	2.15860						2.03910	9.08
173	2.03910						1.89200	11.18
174	1.89200	1.41519					3.15630	11.47
175	3.15630						2.99300	12.41
176	2.99300						2.82740	12.59
177	2.82740						2.66390	12.43
178	2.66390		0.10862				2.63600	10.38
179	2.63600						2.49590	10.65
180	2.49590						2.30550	14.47
181	2.30550						2.09890	15.70
182	2.09890						1.91140	14.25
183	1.91140						1.70310	15.83
184	1.70310						1.56020	10.86
185	1.56020		0.06632				1.51580	8.41
186	1.51580		0.00729				1.39530	9.71
187	1.39530		0.00219				1.27350	9.42
188	1.27350		0.04555				1.22820	6.90
189	1.22820		0.13105				1.26870	6.88
190	1.26870						1.15440	8.69
191	1.15440						1.02290	9.99
192	1.02290		0.13391				0.98631	12.96
193	0.98631		0.00825				0.85598	10.53
194	0.85598				0.03212		0.73911	6.44
195	0.73911						0.69158	3.61
196	0.69158					0.00482	0.65665	3.02
197	0.65665						0.60794	3.70
198	0.60794						0.54550	4.75
199	0.54550		0.04475				0.51217	5.93
200	0.51217		0.00317				0.42997	6.49
201	0.42997		0.69888				1.04370	6.47
202	1.04370						0.95589	6.67
203	0.95589		0.09862				0.95219	7.78
204	0.95219		0.00192				0.87474	6.03
205	0.87474		0.00503				0.81665	4.80
206	0.81665		0.04393				0.82298	2.86
207	0.82298	1.52330					2.20620	10.65
208	2.20620						2.09520	8.44
209	2.09520						1.96830	9.64
210	1.96830						1.84400	9.45

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Drain Tanks (mV/V)	Plant Cutting (mV/V)	Maintain Sensors (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
211	1.84400		0.00406				1.72340	9.47
212	1.72340		0.23840				1.89990	4.70
213	1.89990						1.78660	8.61
214	1.78660		0.16269				1.83830	8.44
215	1.83830		0.07879				1.81090	8.07
216	1.81090		0.35442				2.07950	6.52
217	2.07950		0.01646				2.01090	6.46
218	2.01090						1.91760	7.09
219	1.91760						1.81250	7.99
220	1.81250		0.05983				1.76960	7.81
221	1.76960		0.00973				1.70700	5.50
222	1.70700						1.61160	7.25
223	1.61160	1.05110					2.54640	8.84
224	2.54640		0.02945				2.47390	7.75
225	2.47390						2.34670	9.67
226	2.34670						2.21370	10.11
227	2.21370		0.00710				2.14500	5.76
228	2.14500		0.03826				2.08740	7.29
229	2.08740						1.99550	6.98
230	1.99550						1.88520	8.38
231	1.88520						1.78270	7.79
232	1.78270						1.65790	9.48
233	1.65790						1.51310	11.00
234	1.51310						1.37450	10.53
235	1.37450		0.00116		0.02627		1.28140	5.17
236	1.28140		0.00176			0.00369	1.25770	2.22
237	1.25770						1.22320	2.62
238	1.22320						1.18350	3.02
239	1.18350						1.13110	3.98
240	1.13110		0.00462				1.05820	5.89
241	1.05820						0.98138	5.84
242	0.98138						0.88365	7.43
243	0.88365	1.50080					2.28820	7.31
244	2.28820						2.19830	6.83
245	2.19830						2.10000	7.47
246	2.10000						2.00460	7.25
247	2.00460						1.91170	7.06
248	1.91170						1.78600	9.55
249	1.78600						1.65220	10.17
250	1.65220						1.54530	8.12
251	1.54530		0.02057				1.48040	6.50

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Drain Tanks (mV/V)	Plant Cutting (mV/V)	Maintain Sensors (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
252	1.48040						1.36550	8.73
253	1.36550						1.26300	7.79
254	1.26300						1.15540	8.18
255	1.15540						1.06350	6.98
256	1.06350						0.97165	6.98
257	0.97165						0.87330	7.47
258	0.87330	2.08386					2.84810	8.29
259	2.84810						2.74980	7.47
260	2.74980	0.52856					3.17820	7.61
261	3.17820						3.07910	7.53
262	3.07910						2.97120	8.20
263	2.97120		0.00795				2.83240	11.15
264	2.83240						2.71980	8.56
265	2.71980		0.06931				2.69960	6.80
266	2.69960						2.59900	7.65
267	2.59900						2.49200	8.13
268	2.49200						2.38180	8.38
269	2.38180						2.29770	6.39
270	2.29770						2.16860	9.81
271	2.16860						2.08340	6.48
272	2.08340						1.95610	9.67
273	1.95610						1.86050	7.27
274	1.86050						1.77570	6.44
275	1.77570						1.70990	5.00
276	1.70990						1.63800	5.46
277	1.63800	1.75807					3.31590	6.09
278	3.31590						3.22310	7.05
279	3.22310						3.14370	6.03
280	3.14370						3.05640	6.63
281	3.05640						2.92110	10.28
282	2.92110						2.85140	5.30
283	2.85140						2.78710	4.89
284	2.78710						2.69850	6.73
285	2.69850						2.64050	4.41
286	2.64050						2.58560	4.17
287	2.58560				0.02139		2.53510	2.21
288	2.53510						2.51340	1.65
289	2.51340						2.49210	1.62
290	2.49210						2.47460	1.33
291	2.47460						2.45920	1.17
292	2.45920						2.44350	1.19

Julian Date	Begin Load Cell (mV/V)	Irrigation (mV/V)	Precip (mV/V)	Drain Tanks (mV/V)	Plant Cutting (mV/V)	Maintain Sensors (mV/V)	End Load Cell (mV/V)	Measured ET (mm)
293	2.44350						2.42530	1.38
294	2.42530						2.41300	0.93
295	2.41300						2.39690	1.22
296	2.39690						2.38220	1.12
297	2.38220						2.36170	1.56
298	2.36170		0.01752				2.35460	1.87
299	2.35460						2.33260	1.67
300	2.33260						2.31590	1.27
301	2.31590						2.30450	0.87

C. Area Correction

- 2008 season

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
92	1	0.00	9.00	2.52	2.52
93	2	0.01	9.03	3.65	3.64
94	3	0.01	9.06	2.44	2.42
95	4	0.02	9.09	4.27	4.23
96	5	0.02	9.12	4.73	4.66
97	6	0.03	9.15	5.37	5.28
98	7	0.03	9.18	5.21	5.10
99	8	0.04	9.22	4.58	4.47
100	9	0.04	9.25	4.03	3.92
101	10	0.05	9.28	2.78	2.70
102	11	0.05	9.31	4.92	4.75
103	12	0.06	9.34	4.13	3.98
104	13	0.06	9.37	4.26	4.09
105	14	0.07	9.40	5.46	5.22
106	15	0.07	9.43	9.68	9.24
107	16	0.08	9.47	6.92	6.58
108	17	0.08	9.50	3.73	3.53
109	18	0.09	9.53	4.95	4.67
110	19	0.09	9.56	5.94	5.59
111	20	0.10	9.59	9.63	9.03
112	21	0.10	9.62	6.49	6.07
113	22	0.11	9.65	6.11	5.69
114	23	0.11	9.69	7.61	7.07
115	24	0.12	9.72	8.02	7.43
116	25	0.12	9.75	6.27	5.79
117	26	0.13	9.78	5.49	5.05
118	27	0.13	9.81	4.86	4.46
119	28	0.14	9.85	6.24	5.70
120	29	0.14	9.88	6.99	6.37
121	30	0.15	9.91	10.05	9.12
122	31	0.15	9.94	5.46	4.95
123	32	0.16	9.97	5.05	4.56
124	33	0.16	10.01	5.36	4.82
125	34	0.17	10.04	7.33	6.58
126	35	0.17	10.07	7.71	6.89
127	36	0.18	10.10	5.79	5.16
128	37	0.18	10.14	2.82	2.50
129	38	0.19	10.17	5.64	5.00
130	39	0.19	10.20	8.61	7.60

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
131	40	0.20	10.23	6.28	5.53
132	41	0.20	10.27	7.18	6.29
133	42	0.21	10.30	11.83	10.34
134	43	0.21	10.33	3.17	2.76
135	44	0.22	10.36	5.75	4.99
136	45	0.22	10.40	6.63	5.74
137	46	0.23	10.43	5.77	4.98
138	47	0.23	10.46	10.43	8.98
139	48	0.24	10.50	9.01	7.73
140	49	0.24	10.53	10.25	8.76
141	50	0.25	10.56	8.82	7.51
142	51	0.26	10.60	10.37	8.81
143	52	0.26	10.63	10.55	8.93
144	53	0.27	10.66	7.90	6.67
145	54	0.27	10.70	11.14	9.38
146	55	0.28	10.73	8.80	7.38
147	56	0.28	10.76	5.57	4.66
148	57	0.29	10.80	5.09	4.24
149	58	0.29	10.83	7.45	6.19
150	59	0.30	10.86	11.66	9.66
151	60	0.30	10.90	9.41	7.77
152	61	0.31	10.93	9.56	7.87
153	62	0.31	10.96	8.41	6.90
154	63	0.32	11.00	7.93	6.49
155	64	0.32	11.03	7.94	6.48
156	65	0.33	11.07	5.69	4.63
157	66	0.33	11.10	2.62	2.12
158	67	0.34	11.13	9.22	7.45
159	68	0.34	11.17	8.28	6.67
160	69	0.35	11.20	7.52	6.04
161	70	0.35	11.24	7.25	5.81
162	71	0.36	11.27	9.45	7.55
163	72	0.36	11.30	3.93	3.13
164	1	0.00	9.00	2.17	2.17
165	2	0.01	9.03	2.28	2.27
166	3	0.01	9.06	2.83	2.82
167	4	0.02	9.09	3.30	3.26
168	5	0.02	9.12	0.74	0.73
169	6	0.03	9.15	3.21	3.16
170	7	0.03	9.18	3.56	3.49

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
171	8	0.04	9.22	2.75	2.69
172	9	0.04	9.25	3.65	3.55
173	10	0.05	9.28	6.59	6.39
174	11	0.05	9.31	7.22	6.98
175	12	0.06	9.34	7.24	6.97
176	13	0.06	9.37	7.52	7.22
177	14	0.07	9.40	8.16	7.81
178	15	0.07	9.43	8.19	7.81
179	16	0.08	9.47	8.85	8.42
180	17	0.08	9.50	7.42	7.03
181	18	0.09	9.53	8.51	8.04
182	19	0.09	9.56	8.15	7.67
183	20	0.10	9.59	9.22	8.66
184	21	0.10	9.62	10.18	9.52
185	22	0.11	9.65	9.49	8.85
186	23	0.11	9.69	10.21	9.49
187	24	0.12	9.72	11.45	10.61
188	25	0.12	9.75	9.47	8.74
189	26	0.13	9.78	6.74	6.20
190	27	0.13	9.81	7.87	7.21
191	28	0.14	9.85	8.06	7.37
192	29	0.14	9.88	10.35	9.43
193	30	0.15	9.91	10.46	9.50
194	31	0.15	9.94	8.05	7.29
195	32	0.16	9.97	9.90	8.94
196	33	0.16	10.01	9.37	8.43
197	34	0.17	10.04	10.02	8.98
198	35	0.17	10.07	9.86	8.81
199	36	0.18	10.10	8.63	7.69
200	37	0.18	10.14	6.74	5.99
201	38	0.19	10.17	10.24	9.06
202	39	0.19	10.20	10.78	9.51
203	40	0.20	10.23	3.67	3.22
204	41	0.20	10.27	2.51	2.20
205	42	0.21	10.30	2.70	2.36
206	1	0.00	9.00	2.49	2.49
207	2	0.01	9.03	5.25	5.23
208	3	0.01	9.06	4.91	4.88
209	4	0.02	9.09	5.51	5.45
210	5	0.02	9.12	7.01	6.91
211	6	0.03	9.15	6.78	6.67
212	7	0.03	9.18	7.40	7.25

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
213	8	0.04	9.22	9.60	9.37
214	9	0.04	9.25	10.06	9.79
215	10	0.05	9.28	11.84	11.49
216	11	0.05	9.31	9.66	9.34
217	12	0.06	9.34	8.92	8.60
218	13	0.06	9.37	7.81	7.50
219	14	0.07	9.40	9.77	9.35
220	15	0.07	9.43	3.59	3.43
221	16	0.08	9.47	6.41	6.10
222	17	0.08	9.50	14.10	13.36
223	18	0.09	9.53	0.62	0.58
224	19	0.09	9.56	7.84	7.38
225	20	0.10	9.59	8.83	8.29
226	21	0.10	9.62	7.81	7.30
227	22	0.11	9.65	6.69	6.24
228	23	0.11	9.69	2.30	2.14
229	24	0.12	9.72	1.65	1.53
230	25	0.12	9.75	3.72	3.43
231	26	0.13	9.78	5.00	4.60
232	27	0.13	9.81	7.24	6.64
233	28	0.14	9.85	6.78	6.20
234	29	0.14	9.88	7.49	6.82
235	30	0.15	9.91	10.72	9.73
236	31	0.15	9.94	7.28	6.59
237	32	0.16	9.97	8.86	8.00
238	33	0.16	10.01	8.00	7.20
239	34	0.17	10.04	6.95	6.23
240	35	0.17	10.07	8.48	7.58
241	36	0.18	10.10	9.01	8.03
242	37	0.18	10.14	6.71	5.96
243	38	0.19	10.17	7.49	6.63
244	39	0.19	10.20	9.91	8.74
245	40	0.20	10.23	10.19	8.96
246	41	0.20	10.27	5.41	4.74
247	42	0.21	10.30	2.67	2.33
248	1	0.00	9.00	2.66	2.66
249	2	0.01	9.03	2.08	2.08
250	3	0.01	9.06	2.62	2.60
251	4	0.02	9.09	3.84	3.80
252	5	0.02	9.12	1.05	1.03
253	6	0.03	9.15	3.56	3.50
254	7	0.03	9.18	5.08	4.97

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
255	8	0.04	9.22	4.48	4.37
256	9	0.04	9.25	2.66	2.59
257	10	0.05	9.28	5.57	5.40
258	11	0.05	9.31	4.54	4.39
259	12	0.06	9.34	4.68	4.51
260	13	0.06	9.37	5.72	5.50
261	14	0.07	9.40	5.36	5.13
262	15	0.07	9.43	4.93	4.71
263	16	0.08	9.47	5.53	5.26
264	17	0.08	9.50	5.75	5.45
265	18	0.09	9.53	5.54	5.23
266	19	0.09	9.56	7.83	7.37
267	20	0.10	9.59	5.54	5.20
268	21	0.10	9.62	5.08	4.75
269	22	0.11	9.65	5.97	5.56
270	23	0.11	9.69	6.07	5.64
271	24	0.12	9.72	5.91	5.47
272	25	0.12	9.75	5.66	5.23
273	26	0.13	9.78	5.11	4.71
274	27	0.13	9.81	5.35	4.91
275	28	0.14	9.85	5.57	5.09
276	29	0.14	9.88	5.03	4.58
277	30	0.15	9.91	5.01	4.55
278	31	0.15	9.94	5.88	5.33
279	32	0.16	9.97	6.12	5.52
280	33	0.16	10.01	5.75	5.17
281	34	0.17	10.04	4.75	4.26
282	35	0.17	10.07	6.10	5.45
283	36	0.18	10.10	3.21	2.86
284	37	0.18	10.14	5.68	5.05
285	38	0.19	10.17	1.12	0.99
286	39	0.19	10.20	4.27	3.77
287	40	0.20	10.23	4.07	3.58
288	41	0.20	10.27	0.29	0.26
289	42	0.21	10.30	3.06	2.68
290	43	0.21	10.33	2.91	2.54
291	44	0.22	10.36	3.53	3.07
292	45	0.22	10.40	3.67	3.18
293	46	0.23	10.43	4.90	4.23
294	47	0.23	10.46	1.06	0.91
295	48	0.24	10.50	3.24	2.78
296	49	0.24	10.53	4.23	3.62

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
297	50	0.25	10.56	2.56	2.18
298	51	0.26	10.60	2.71	2.30
299	52	0.26	10.63	3.07	2.60
300	53	0.27	10.66	2.98	2.51
301	54	0.27	10.70	2.00	1.68
302	55	0.28	10.73	2.52	2.11
303	56	0.28	10.76	3.23	2.70
304	57	0.29	10.80	3.27	2.72
305	58	0.29	10.83	2.91	2.42
306	59	0.30	10.86	2.55	2.12
307	60	0.30	10.90	3.38	2.79
308	61	0.31	10.93	2.86	2.36
309	62	0.31	10.96	1.20	0.99

- 2009 season

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
83	1	0.000	9.00	2.76	2.76
84	2	0.005	9.03	3.01	3.00
85	3	0.010	9.06	2.01	2.00
86	4	0.015	9.09	2.11	2.08
87	5	0.020	9.12	1.00	0.98
88	6	0.026	9.15	1.06	1.05
89	7	0.031	9.18	2.08	2.04
90	8	0.036	9.22	2.80	2.74
91	9	0.041	9.25	2.96	2.88
92	10	0.046	9.28	3.26	3.16
93	11	0.051	9.31	4.35	4.20
94	12	0.056	9.34	3.36	3.23
95	13	0.061	9.37	3.20	3.07
96	14	0.066	9.40	2.90	2.78
97	15	0.071	9.43	4.14	3.95
98	16	0.077	9.47	4.93	4.69
99	17	0.082	9.50	4.86	4.61
100	18	0.087	9.53	3.94	3.72
101	19	0.092	9.56	2.34	2.20
102	20	0.097	9.59	0.52	0.49
103	21	0.102	9.62	4.28	4.00
104	22	0.107	9.65	3.37	3.14
105	23	0.112	9.69	5.72	5.32
106	24	0.117	9.72	5.64	5.22
107	25	0.122	9.75	3.60	3.33
108	26	0.128	9.78	2.01	1.85
109	27	0.133	9.81	4.91	4.50
	28	0.138	9.85		0.00
	29	0.143	9.88		0.00
112	30	0.148	9.91	6.36	5.78
113	31	0.153	9.94	6.95	6.30
114	32	0.158	9.97	8.28	7.48
115	33	0.163	10.01	4.41	3.96
116	34	0.168	10.04	5.58	5.00
117	35	0.173	10.07	4.81	4.30
118	36	0.179	10.10	6.67	5.94
119	37	0.184	10.14	6.91	6.13
120	38	0.189	10.17	5.32	4.71
121	39	0.194	10.20	1.67	1.47
122	40	0.199	10.23	2.05	1.80

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
123	41	0.204	10.27	4.84	4.25
124	42	0.209	10.30	5.66	4.95
125	43	0.214	10.33	5.96	5.19
126	44	0.219	10.36	6.99	6.07
127	45	0.224	10.40	7.03	6.08
128	46	0.230	10.43	5.86	5.06
129	47	0.235	10.46	6.09	5.24
130	48	0.240	10.50	4.61	3.95
131	49	0.245	10.53	5.40	4.62
132	50	0.250	10.56	6.40	5.45
133	51	0.255	10.60	5.84	4.96
134	52	0.260	10.63	6.10	5.16
135	53	0.265	10.66	4.42	3.73
136	54	0.270	10.70	3.67	3.09
137	55	0.276	10.73	4.75	3.98
138	56	0.281	10.76	4.77	3.98
139	57	0.286	10.80	4.62	3.85
140	58	0.291	10.83	4.75	3.95
141	59	0.296	10.86	3.36	2.78
142	60	0.301	10.90	5.37	4.44
143	61	0.306	10.93	5.37	4.42
144	62	0.311	10.96	3.96	3.25
145	63	0.316	11.00	3.90	3.19
146	64	0.321	11.03	2.95	2.41
147	65	0.327	11.07	4.29	3.49
148	66	0.332	11.10	3.89	3.16
149	67	0.337	11.13	3.79	3.07
150	68	0.342	11.17	3.74	3.01
151	69	0.347	11.20	3.21	2.58
152	70	0.352	11.24	2.73	2.19
153	71	0.357	11.27	1.97	1.57
154	72	0.362	11.30	3.54	2.82
155	73	0.367	11.34	4.77	3.78
156	74	0.372	11.37	5.30	4.20
157	75	0.378	11.41	5.73	4.52
158	76	0.383	11.44	4.28	3.37
159	77	0.388	11.48	2.20	1.72
160	1	0.000	9.00	2.81	2.81
161	2	0.005	9.03	1.89	1.88
162	3	0.010	9.06	2.86	2.84
163	4	0.015	9.09	4.53	4.48

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
164	5	0.020	9.12	3.31	3.26
165	6	0.026	9.15	3.20	3.14
166	7	0.031	9.18	4.67	4.58
167	8	0.036	9.22	7.59	7.41
168	9	0.041	9.25	8.92	8.68
169	10	0.046	9.28	7.36	7.14
170	11	0.051	9.31	9.23	8.93
171	12	0.056	9.34	3.40	3.27
172	13	0.061	9.37	10.11	9.71
173	14	0.066	9.40	11.07	10.59
174	15	0.071	9.43	7.19	6.86
175	16	0.077	9.47	9.77	9.29
176	17	0.082	9.50	10.31	9.77
177	18	0.087	9.53	9.65	9.11
178	19	0.092	9.56	11.42	10.75
179	20	0.097	9.59	13.62	12.78
180	21	0.102	9.62	10.84	10.14
181	22	0.107	9.65	10.48	9.77
182	23	0.112	9.69	11.07	10.29
183	24	0.117	9.72	10.72	9.93
184	25	0.122	9.75	7.99	7.37
185	26	0.128	9.78	8.53	7.85
186	27	0.133	9.81	6.71	6.15
187	28	0.138	9.85	7.42	6.78
188	29	0.143	9.88	10.41	9.49
189	30	0.148	9.91	10.62	9.64
190	31	0.153	9.94	14.14	12.80
191	32	0.158	9.97	11.08	10.00
192	33	0.163	10.01	10.28	9.25
193	34	0.168	10.04	11.76	10.55
194	35	0.173	10.07	9.92	8.86
195	36	0.179	10.10	12.16	10.83
196	37	0.184	10.14	3.44	3.06
197	1	0.000	9.00	3.74	3.74
198	2	0.005	9.03	5.89	5.87
199	3	0.010	9.06	6.19	6.14
200	4	0.015	9.09	5.97	5.91
201	5	0.020	9.12	6.83	6.73
202	6	0.026	9.15	5.50	5.41
203	7	0.031	9.18	6.81	6.67
204	8	0.036	9.22	8.88	8.67

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
205	9	0.041	9.25	9.62	9.37
206	10	0.046	9.28	10.06	9.76
207	11	0.051	9.31	5.69	5.50
208	12	0.056	9.34	7.80	7.52
209	13	0.061	9.37	8.34	8.01
210	14	0.066	9.40	5.74	5.50
211	15	0.071	9.43	3.41	3.26
212	16	0.077	9.47	6.25	5.95
213	17	0.082	9.50	7.48	7.09
214	18	0.087	9.53	8.24	7.78
215	19	0.092	9.56	9.89	9.31
216	20	0.097	9.59	9.09	8.53
217	21	0.102	9.62	9.45	8.84
218	22	0.107	9.65	10.88	10.15
219	23	0.112	9.69	11.81	10.97
220	24	0.117	9.72	12.26	11.35
221	25	0.122	9.75	7.74	7.15
222	26	0.128	9.78	8.24	7.58
223	27	0.133	9.81	8.71	7.99
224	28	0.138	9.85	9.52	8.70
225	29	0.143	9.88	8.24	7.51
226	30	0.148	9.91	6.53	5.93
227	31	0.153	9.94	8.73	7.91
228	32	0.158	9.97	8.53	7.70
229	33	0.163	10.01	7.26	6.53
230	34	0.168	10.04	3.83	3.44
231	35	0.173	10.07	8.37	7.48
232	36	0.179	10.10	6.76	6.03
233	37	0.184	10.14	8.24	7.32
234	38	0.189	10.17	9.31	8.24
235	39	0.194	10.20	9.99	8.82
236	40	0.199	10.23	2.64	2.32
237	1	0.000	9.00	3.28	3.28
238	2	0.005	9.03	3.64	3.63
239	3	0.010	9.06	4.42	4.39
240	4	0.015	9.09	5.13	5.08
241	5	0.020	9.12	5.34	5.26
242	6	0.026	9.15	5.32	5.23
243	7	0.031	9.18	5.39	5.28
244	8	0.036	9.22	7.18	7.02
245	9	0.041	9.25	6.73	6.55

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
246	10	0.046	9.28	6.37	6.18
247	11	0.051	9.31	3.74	3.62
248	12	0.056	9.34	5.59	5.38
249	13	0.061	9.37	5.91	5.68
250	14	0.066	9.40	6.45	6.18
251	15	0.071	9.43	7.67	7.32
252	16	0.077	9.47	6.99	6.65
253	17	0.082	9.50	6.53	6.19
254	18	0.087	9.53	7.96	7.52
255	19	0.092	9.56	3.31	3.11
256	20	0.097	9.59	7.46	7.00
257	21	0.102	9.62	6.19	5.79
258	22	0.107	9.65	6.73	6.28
259	23	0.112	9.69	5.31	4.94
260	24	0.117	9.72	5.73	5.31
261	25	0.122	9.75	6.14	5.67
262	26	0.128	9.78	6.10	5.61
263	27	0.133	9.81	6.59	6.04
264	28	0.138	9.85	1.59	1.45
265	29	0.143	9.88	6.01	5.47
266	30	0.148	9.91	2.01	1.83
267	31	0.153	9.94	4.29	3.88
268	32	0.158	9.97	3.87	3.49
269	33	0.163	10.01	5.20	4.68
270	34	0.168	10.04	7.04	6.31
271	35	0.173	10.07	6.29	5.62
272	36	0.179	10.10	5.78	5.15
273	37	0.184	10.14	9.52	8.46
274	38	0.189	10.17	6.03	5.34
275	39	0.194	10.20	4.36	3.85
276	40	0.199	10.23	4.82	4.24
277	41	0.204	10.27	4.10	3.60
278	42	0.209	10.30	2.55	2.22

- 2010 season

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
90	1	0.000	9.00	3.05	3.05
91	2	0.005	9.03	4.83	4.81
92	3	0.010	9.06	2.70	2.68
93	4	0.015	9.09	3.36	3.33
94	5	0.020	9.12	4.12	4.06
95	6	0.026	9.15	5.56	5.47
96	7	0.031	9.18	5.36	5.26
97	8	0.036	9.22	3.09	3.01
98	9	0.041	9.25	3.44	3.35
99	10	0.046	9.28	4.92	4.77
100	11	0.051	9.31	4.25	4.11
101	12	0.056	9.34	4.42	4.25
102	13	0.061	9.37	6.32	6.07
103	14	0.066	9.40	7.50	7.18
104	15	0.071	9.43	4.16	3.97
105	16	0.077	9.47	5.50	5.23
106	17	0.082	9.50	1.13	1.07
107	18	0.087	9.53	3.42	3.23
108	19	0.092	9.56	4.69	4.41
109	20	0.097	9.59	4.82	4.52
110	21	0.102	9.62	4.91	4.59
111	22	0.107	9.65	5.37	5.01
112	23	0.112	9.69	6.31	5.86
113	24	0.117	9.72	3.98	3.69
114	25	0.122	9.75	6.31	5.82
115	26	0.128	9.78	6.21	5.71
116	27	0.133	9.81	4.41	4.04
117	28	0.138	9.85	6.54	5.98
118	29	0.143	9.88	10.72	9.76
119	30	0.148	9.91	8.42	7.65
120	31	0.153	9.94	6.70	6.06
121	32	0.158	9.97	5.73	5.17
122	33	0.163	10.01	4.99	4.49
123	34	0.168	10.04	7.20	6.45
124	35	0.173	10.07	9.51	8.50
125	36	0.179	10.10	8.31	7.41
126	37	0.184	10.14	9.88	8.77
127	38	0.189	10.17	5.81	5.15
128	39	0.194	10.20	8.50	7.50
129	40	0.199	10.23	9.58	8.43
130	41	0.204	10.27	9.67	8.48

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
131	42	0.209	10.30	5.20	4.54
132	43	0.214	10.33	4.39	3.83
133	44	0.219	10.36	4.24	3.68
134	45	0.224	10.40	2.95	2.55
135	46	0.230	10.43	5.25	4.53
136	47	0.235	10.46	6.94	5.97
137	48	0.240	10.50	7.55	6.48
138	49	0.245	10.53	7.93	6.78
139	50	0.250	10.56	5.01	4.27
140	51	0.255	10.60	6.45	5.48
141	52	0.260	10.63	6.81	5.77
142	53	0.265	10.66	14.08	11.88
143	54	0.270	10.70	10.50	8.83
144	55	0.276	10.73	12.94	10.86
145	56	0.281	10.76	7.22	6.04
146	57	0.286	10.80	8.27	6.89
147	58	0.291	10.83	10.82	8.99
148	59	0.296	10.86	10.53	8.72
149	60	0.301	10.90	12.62	10.43
150	61	0.306	10.93	8.28	6.82
151	62	0.311	10.96	9.16	7.52
152	63	0.316	11.00	9.70	7.94
153	64	0.321	11.03	8.82	7.19
154	65	0.327	11.07	3.94	3.21
155	1	0.000	9.00	3.61	3.61
156	2	0.005	9.03	4.06	4.04
157	3	0.010	9.06	4.67	4.63
158	4	0.015	9.09	5.68	5.62
159	5	0.020	9.12	5.19	5.12
160	6	0.026	9.15	6.22	6.12
161	7	0.031	9.18	9.16	8.97
162	8	0.036	9.22	7.39	7.22
163	9	0.041	9.25	3.10	3.02
164	10	0.046	9.28	5.03	4.88
165	11	0.051	9.31	5.87	5.67
166	12	0.056	9.34	8.18	7.88
167	13	0.061	9.37	11.84	11.37
168	14	0.066	9.40	12.22	11.70
169	15	0.071	9.43	12.41	11.84
170	16	0.077	9.47	8.51	8.09
171	17	0.082	9.50	10.79	10.23

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
172	18	0.087	9.53	9.08	8.58
173	19	0.092	9.56	11.18	10.53
174	20	0.097	9.59	11.47	10.76
175	21	0.102	9.62	12.41	11.61
176	22	0.107	9.65	12.59	11.73
177	23	0.112	9.69	12.43	11.55
178	24	0.117	9.72	10.38	9.61
179	25	0.122	9.75	10.65	9.83
180	26	0.128	9.78	14.47	13.31
181	27	0.133	9.81	15.70	14.40
182	28	0.138	9.85	14.25	13.03
183	29	0.143	9.88	15.83	14.42
184	30	0.148	9.91	10.86	9.86
185	31	0.153	9.94	8.41	7.62
186	32	0.158	9.97	9.71	8.76
187	33	0.163	10.01	9.42	8.48
188	34	0.168	10.04	6.90	6.19
189	35	0.173	10.07	6.88	6.15
190	36	0.179	10.10	8.69	7.74
191	37	0.184	10.14	9.99	8.87
192	38	0.189	10.17	12.96	11.47
193	39	0.194	10.20	10.53	9.29
194	40	0.199	10.23	6.44	5.66
195	1	0.000	9.00	3.61	3.61
196	2	0.005	9.03	3.02	3.01
197	3	0.010	9.06	3.70	3.68
198	4	0.015	9.09	4.75	4.70
199	5	0.020	9.12	5.93	5.85
200	6	0.026	9.15	6.49	6.38
201	7	0.031	9.18	6.47	6.34
202	8	0.036	9.22	6.67	6.52
203	9	0.041	9.25	7.78	7.57
204	10	0.046	9.28	6.03	5.85
205	11	0.051	9.31	4.80	4.64
206	12	0.056	9.34	2.86	2.75
207	13	0.061	9.37	10.65	10.22
208	14	0.066	9.40	8.44	8.07
209	15	0.071	9.43	9.64	9.20
210	16	0.077	9.47	9.45	8.98
211	17	0.082	9.50	9.47	8.98
212	18	0.087	9.53	4.70	4.44

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
213	19	0.092	9.56	8.61	8.11
214	20	0.097	9.59	8.44	7.92
215	21	0.102	9.62	8.07	7.55
216	22	0.107	9.65	6.52	6.08
217	23	0.112	9.69	6.46	6.01
218	24	0.117	9.72	7.09	6.57
219	25	0.122	9.75	7.99	7.37
220	26	0.128	9.78	7.81	7.18
221	27	0.133	9.81	5.50	5.04
222	28	0.138	9.85	7.25	6.63
223	29	0.143	9.88	8.84	8.05
224	30	0.148	9.91	7.75	7.04
225	31	0.153	9.94	9.67	8.75
226	32	0.158	9.97	10.11	9.12
227	33	0.163	10.01	5.76	5.18
228	34	0.168	10.04	7.29	6.53
229	35	0.173	10.07	6.98	6.24
230	36	0.179	10.10	8.38	7.47
231	37	0.184	10.14	7.79	6.92
232	38	0.189	10.17	9.48	8.40
233	39	0.194	10.20	11.00	9.71
234	40	0.199	10.23	10.53	9.26
235	41	0.204	10.27	5.17	4.53
236	1	0.000	9.00	2.22	2.22
237	2	0.005	9.03	2.62	2.61
238	3	0.010	9.06	3.02	3.00
239	4	0.015	9.09	3.98	3.94
240	5	0.020	9.12	5.89	5.81
241	6	0.026	9.15	5.84	5.74
242	7	0.031	9.18	7.43	7.28
243	8	0.036	9.22	7.31	7.14
244	9	0.041	9.25	6.83	6.65
245	10	0.046	9.28	7.47	7.25
246	11	0.051	9.31	7.25	7.01
247	12	0.056	9.34	7.06	6.80
248	13	0.061	9.37	9.55	9.17
249	14	0.066	9.40	10.17	9.73
250	15	0.071	9.43	8.12	7.75
251	16	0.077	9.47	6.50	6.18
252	17	0.082	9.50	8.73	8.28
253	18	0.087	9.53	7.79	7.36

DOY	Days after cuttings	alfalfa extended out (m)	Adjusted area (m^2)	ETc (mm/day)	adjusted ETc (mm/day)
254	19	0.092	9.56	8.18	7.70
255	20	0.097	9.59	6.98	6.55
256	21	0.102	9.62	6.98	6.53
257	22	0.107	9.65	7.47	6.97
258	23	0.112	9.69	8.29	7.70
259	24	0.117	9.72	7.47	6.92
260	25	0.122	9.75	7.61	7.03
261	26	0.128	9.78	7.53	6.93
262	27	0.133	9.81	8.20	7.52
263	28	0.138	9.85	11.15	10.20
264	29	0.143	9.88	8.56	7.80
265	30	0.148	9.91	6.80	6.18
266	31	0.153	9.94	7.65	6.92
267	32	0.158	9.97	8.13	7.34
268	33	0.163	10.01	8.38	7.53
269	34	0.168	10.04	6.39	5.73
270	35	0.173	10.07	9.81	8.77
271	36	0.179	10.10	6.48	5.77
272	37	0.184	10.14	9.67	8.59
273	38	0.189	10.17	7.27	6.43
274	39	0.194	10.20	6.44	5.69
275	40	0.199	10.23	5.00	4.40
276	41	0.204	10.27	5.46	4.79
277	42	0.209	10.30	6.09	5.32
278	43	0.214	10.33	7.05	6.14
279	44	0.219	10.36	6.03	5.24
280	45	0.224	10.40	6.63	5.74
281	46	0.230	10.43	10.28	8.87
282	47	0.235	10.46	5.30	4.56
283	48	0.240	10.50	4.89	4.19
284	49	0.245	10.53	6.73	5.76
285	50	0.250	10.56	4.41	3.76
286	51	0.255	10.60	4.17	3.54
287	52	0.260	10.63	2.21	1.87

D. Wind speed adjustment

$$u_{z,v} = u_{z,w} \, \frac{\ln\left(\frac{Z_{IBL,w} - d_w}{Z_{om,w}}\right) \ln\left(\frac{Z_{IBL,v} - d_R}{Z_{om,R}}\right) \ln\left(\frac{Z_v - d_v}{Z_{om,v}}\right)}{\ln\left(\frac{Z_w - d_w}{Z_{om,w}}\right) \ln\left(\frac{Z_{IBL,w} - d_R}{Z_{om,R}}\right) \ln\left(\frac{Z_{IBL,v} - d_v}{Z_{om,w}}\right)}$$

$$Z_{IBL} = d + 0.33 \, z_{om}{}^{0.125} \times X_f{}^{0.875}$$

DOY	H (m)	$U_{z,w}$ (m/s)	Z_v (m)	Z_w (m)	h_v (m)	d_w (m)	d_v (m)	d_R (m)	$Z_{om,W}$ (m)	$Z_{om,v}$ (m)	$Z_{om,R}$ (m)	$Z_{IBL,W}$ (m)	$Z_{IBL,V}$ (m)	$U_{z,v}$ (m/s)
90	0.039	2.52	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	2.351
90	0.039	2.50	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	2.334
90	0.039	2.07	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	1.937
90	0.039	1.60	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	1.496
90	0.039	0.44	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	0.409
90	0.039	0.66	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	0.619
90	0.039	1.30	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	1.213
90	0.039	0.70	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	0.654
90	0.039	1.11	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	1.038
90	0.039	1.15	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	1.073
90	0.039	5.23	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	4.887
90	0.039	4.93	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	4.607
90	0.039	5.34	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	4.988
90	0.039	5.52	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	5.159
90	0.039	5.54	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	5.181
90	0.039	5.63	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	5.258
90	0.039	5.46	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	5.101
90	0.039	3.43	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	3.203
90	0.039	1.83	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	1.713
90	0.039	1.28	2	2	0.12	0.026	0.081	0.026	0.005	0.015	0.005	17.475	20.175	1.201