Annual Project Report - 2001
Estimating Pima and Upland Cotton Evapotranspiration
Using the Surface Renewal Technique

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February 12, 2002

Introduction

This is a report on the second season of evapotranspiration and soil water depletion measurements from over an irrigated cotton field in the Westland Water District region of the San Joaquin Valley in California. Sensible heat flux density (*H*) was measured using the surface renewal (SR) method, which was first proposed by Paw U and Brunet (1991) and later refined for field applications by Snyder et al. (1996) and Spano et al. (1997). When combined with measurements of net radiation (R_n) and soil heat flux density (*G*), the latent heat flux density (*LE*) is estimated as the residual of the energy balance equation using Eq. 1.

$$LE = R_n - G - H \qquad (1)$$

The SR method uses fine-wire thermocouples to measure high frequency temperature fluctuations. Then the sensible heat flux density is determined using a structure function to identify ramp-like characteristics in the temperature traces. The method is explained in Paw U et al. (1995), Snyder et al. (1996), and Spano et al. (1997).

Because of changes in the reference evapotranspiration (*ETo*) equations, better weather station siting, and new cotton varieties, measurements are needed to provide the more accurate crop coefficient (*Kc*) values. To obtain new K_c values, an experiment was designed to simultaneous measure *ETc* of two cotton varieties using the SR method. The crop coefficients were determined as

$$Kc = \frac{ETc}{ETo} \qquad (2)$$

The SR method was compared with a commonly used soil water depletion method that uses standard neutron scatter procedures for measuring field changes in soil moisture. The neutron probe is used by growers to identify irrigation volume requirements and to assist in scheduling proper irrigation timing for cotton. Procedures were developed to estimate *ETc* from neutron probe sampling data and to compare these values with real time SR data in the same fields and proximity.

Methods and Materials

The 2001 experiment was conducted near the University of California West Side Research and Extension Center near Five Points. Upland (Acala) variety cotton (GOSSYPIUM HIRSUTUM) was planted in late March, but because of a poor stand, it was replanted on April 24, 2001 in a field about 1.0 km north of the West Side Center. Pima variety cotton (GOSSYPIUM BARBADENSE) was planted on March 30, 2001 in a field about 10 km east-northeast of the Center. The soil in both fields has characteristics similar to a Panoche Clay Loam. In 2000, the experiment was *conducted* on a cotton ranch about one mile south of California Hwy 198 where it crosses the Fresno-Kings County border. Although the soil survey for this area is not complete, the soil also has similar characteristics to Panoche Clay Loam. One field was planted to Pima cotton on March 29, 2000 and the other nearby field to Upland cotton on April 6, 2000.

Net radiation (R_n) was measured with a Fritzchen net radiometer (Q7.2 from REBS, Inc) mounted at about 2 m height. Soil heat flux density was measured at about 4 cm depth using heat flux plates (HMT3 from REBS, Inc) and averaging soil temperature sensors (TCAV from Campbell Scientific, Inc.) buried at about 2 cm deep to measure changes in store soil heat above the flux plates. High frequency temperature was measured using 0.003-inch diameter type-T fine-wire thermocouples (FW3 from Campbell Scientific, Inc.). Sensible heat flux density (H) was measured with a 1-dimensional sonic anemometer (CA27 from Campbell Scientific, Inc.). Campbell Scientific data loggers were used to monitor measurements (CR10X for SR and 21X for the sonic anemometer).

The SR data were collected at 4 Hz and time lags of 0.25 and 0.50 seconds were used with the structure function (Van Atta, 1977) to determine temperature ramp characteristics. Then, H was calculated as

$$H = \alpha \rho C_p \left(\frac{a}{l+s} \right) z \qquad (3)$$

The factor a is the mean ramp amplitude, $l+s$ is the inverse ramp frequency, z is the measurement height above the ground, ρ is the air density, C_p is the air heat capacity at constant pressure, and α is a coefficient to correct for uneven heating of the air under the measurement height. In this experiment, α was determined as the slope of a linear regression through the origin of H measured with a sonic anemometer versus H calculated using equation 3 and α =1.0. The coefficient α is set equal to the slope to estimate H using the SR method. Latent heat flux density ($LE=ET_c$) was calculated as the residual in the energy balance equation (Eq. 1).

Reference evapotranspiration (ET_o) was calculated using hourly weather data from the West Side Field Station (WSFS) at Five Points using the Penman-Monteith equation, which is recommended by the American Society of Civil Engineers (Walter et al., 2000). This equation is also used by the California Irrigation Management Information System (CIMIS) to calculate hourly ET_o. The PM equation gives similar results as the Pruitt-Doorenbos (PD) equation (Ventura et al., 1999), which has been used by CIMIS since it's inception.

Soil moisture depletion measurements using a standard neutron scatter approach were used to estimate ET near the SR stations. At each of the two SR stations, seven Neutron probe access tubes were installed to a depth of eight feet and were calibrated using a range of soil moisture levels throughout the season to develop a standard calibration relationship between probe count and measured volumetric soil moisture. Readings were taken at one-foot intervals on a weekly basis unless irrigation was in progress. In the case of irrigation events, measurements were taken one to two days prior to the irrigation event and then again two to four days after the irrigation event once field capacity was again reached.

Calculations of crop water use were developed from soil water depletion (SWD) measurements using a volume balance approach. Water loss that occurred between soil moisture measurement dates was summed through out the entire soil profile and the cumulative loss estimate was developed. This estimate was then used with the number of days between readings to establish average-daily water loss values for that period. In order to develop an estimate of seasonal crop water use, crop water loss during irrigation events was assumed to be intermediate between the water loss during the period prior to irrigation and the water loss period immediately following the irrigation. During the first days following planting the soil water losses wee estimated using an average daily bare soil evaporative estimate of ETo * 0.15. The above procedure was then used to compare the ETc estimates developed from the SR with the soil moisture depletion method to estimate ETc.

Results and Discussion

A sample plot of hourly energy balance data measured in the Pima plot during 22-26 August is graphed in Figure 1. Note that positive values for R_n indicate the addition of net radiation to the surface. Positive values for H and LE indicate positive fluxes of sensible and latent heat upward to the air. Positive values for G indicate heat flux downward into the soil.

Clearly, most of the energy for evaporation is supplied by net radiation (Fig. 1). The sensible heat flux density fluctuates between about $H = -100$ and 150 W m^{-2} on most days. In the afternoon, H typically decreases and become negative. When H and G are negative, it means that additional energy (i.e., more than R_n) is being supplied to evaporate water and the LE is higher than R_n. In Fig. 1, the sensible heat flux density values became more negative during the afternoons indicating that conditions changed from non-advective to advective during the period.

Figure 2 shows the daily ET_c calculations for both varieties during the 2001 season. Measurements started on May 19, so the ET_c values before that date were estimated using ET_o and a fixed $K_c = 0.25$. Because measurements started near the end of the initial growth stage (i.e., when the ground cover was less than 10%), the initial K_c = 0.25 was estimated from data in both seasons. After measurements started, the ET_c values were higher for Pima until mid-August. The higher ET_c for Pima during the rapid growth phase was most likely due to the earlier planting date. Note that the ET_o was unseasonably high during May 2001. Then the Pima ET_c dropped to quite low values during September and early August. During September, the Upland ET_c values remained considerably higher than Pima. It is believed that the Pima ET_c dropped due to water stress that hastened the onset of senescence. Visually, the Pima variety was clearly stressed, with wilting and a sparse canopy during the late season. The Upland variety was tall, dense and showed no signs of water stress.

In 2000, Pima developed quicker and had a denser canopy than Upland. In both seasons, Pima had higher ET_c rates during rapid growth and midseason. In the 2000 season, however, the ET_c for Pima did not drop as much during September 2000 (Fig. 3) as it did in 2001 (Fig. 2). It is believed that a high water table in 2000 led to a dense Pima canopy and high ET_c late in the season, whereas no water table and stopping irrigation too early led to lower Pima ET_c during late season in 2001.

Figure 4 shows that the difference in ET_c between the varieties is likely due to differences R_n-G. This was also somewhat true in the 2000 season (Fig. 5), but the canopies were similar in 2000, so the R_n–G values were also similar.

Neutron probe depletion estimates show ETc values peaking shortly after the 20th of June, figure 6, and maintaining high values through August 17th before consistently declining values were observed. In both the SR and SWD methods it was clear that ETc declined at a faster pace in the Pima in comparison to the Upland cotton. This is likely evidence that soil water storage was declining at a faster rate in the Pima site due to an earlier irrigation termination date, a more restricted root zone, or a combination of the two factors. By September 12, both methods showed ETc at levels at 1 to 3 mm per day in the Pima while the Acala site maintained a 4 to 5 mm per day water loss.

Both varieties had lower K_c values than are typically reported in the literature from California. This was especially true for the SR method. For example, DWR Bulletin 113-3 (1975) reports midseason K_c values as high as 1.31 for cotton. In the two years of experimentation, we typically observed midseason K_c<1.00 for both varieties (Figs. 7 and 8). The exception was for Pima during 2001 immediately following irrigation. However, the K_c value again dropped K_c<1.00 within a few days after irrigation. The *Kc* developed using SWD measurements found peak values in the 1.05 to 1.15 range with an average peak value of 1.1, again well below Bulletin 113-3 values but slightly higher than the SR estimates.

Because the Pima variety had a sparse canopy during 2001, the wetted soil surface received considerable solar radiation during midseason. It also had a high net radiation immediately following irrigation. Values around K_c=1.00 have also been observed using ET_o from CIMIS and lysimeter measurements in Davis (T.C. Hsiao, personal communication). There was little difference in the ET_o rates during the two seasons except for the high ET_o during May 2001 (Fig. 10).

The monthly average ET_o values reported in Bulletin 113-3 are considerably lower than monthly average ET_o calculated using the CIMIS West Side Field Station data and either the PD or PM equation (Fig. 11). In addition, ET_o values from the nearby, Firebaugh CIMIS station are also considerably higher than the Bulletin 113-3 average for the San Joaquin Valley. Because the Bulletin 113-3 *ETo* means are an average for the entire valley and the Westland Water District region is known to have higher ET_o than much of the valley, the difference could also be partly due to averaging ET_o estimates for the San Joaquin Valley.

Conclusions

The objective of this experiment was to determine if Pima and Upland cotton varieties have different K_c values and hence ET_c rates using two independent methods. The Upland variety had similar K_c values in both seasons and the K_c values were similar between Upland and Pima in the 2000 season. However, the K_c values were quite different for Pima in 2001. It is believed that the difference resulted from applying the last irrigation too early in the season and the resulting water stress. Because there was a water table under the crops during 2000, no water stress was observed. In both seasons, the Pima variety developed faster and had a higher K_c during rapid growth and midseason. It seems that the midseason K_c value developed by the SR method was slightly below K_c=1.00 regardless of the variety except for the year 2000 Pima. Because of what appears to be anomalous readings for Pima in the 2001 season, it is desirable to repeat the experiment one more year and improve the certainty with which we can make more wide-reaching estimates of crop water use in San Joaquin Valley cotton.

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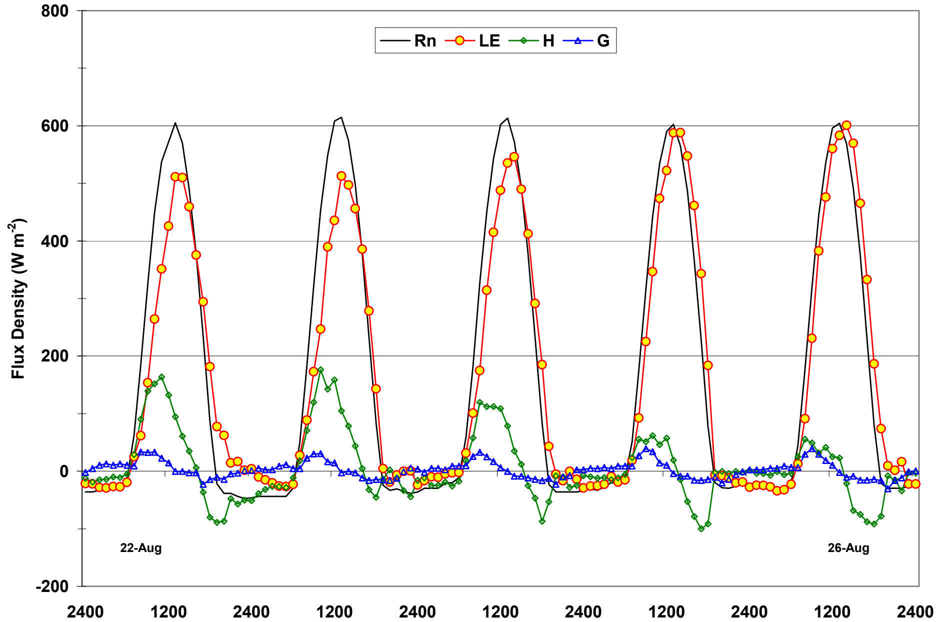

Figure 1. Energy balance components measured over Upland variety cotton during the period 22-26 August 2001. The field was surface irrigated on 13 August.

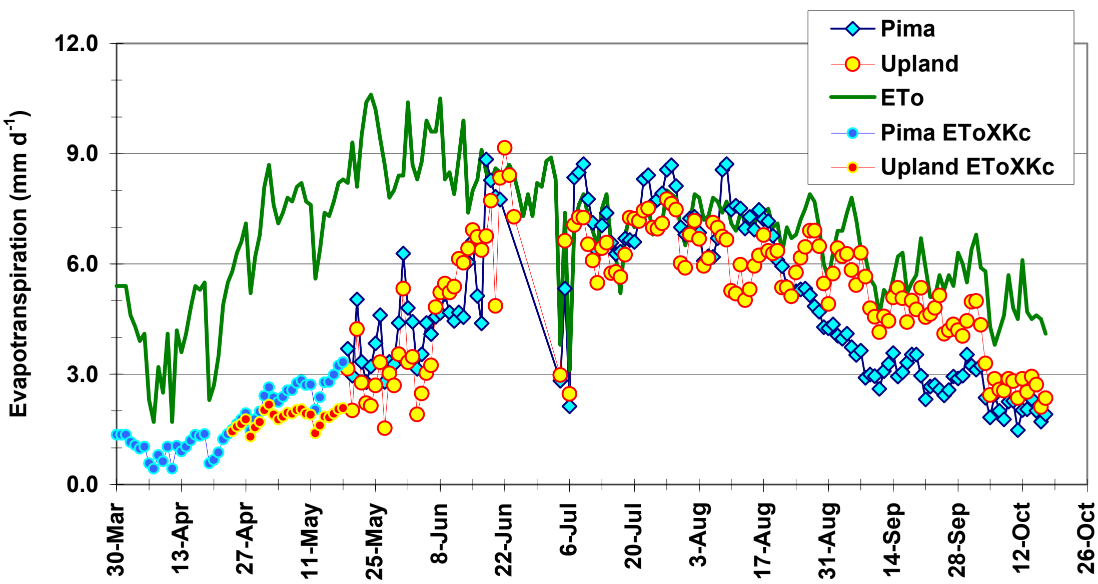

Figure 2. Daily ET_c and ET_o during the 2001 season. ET_c was calculated from ET_o and estimated K_c values before May 19.

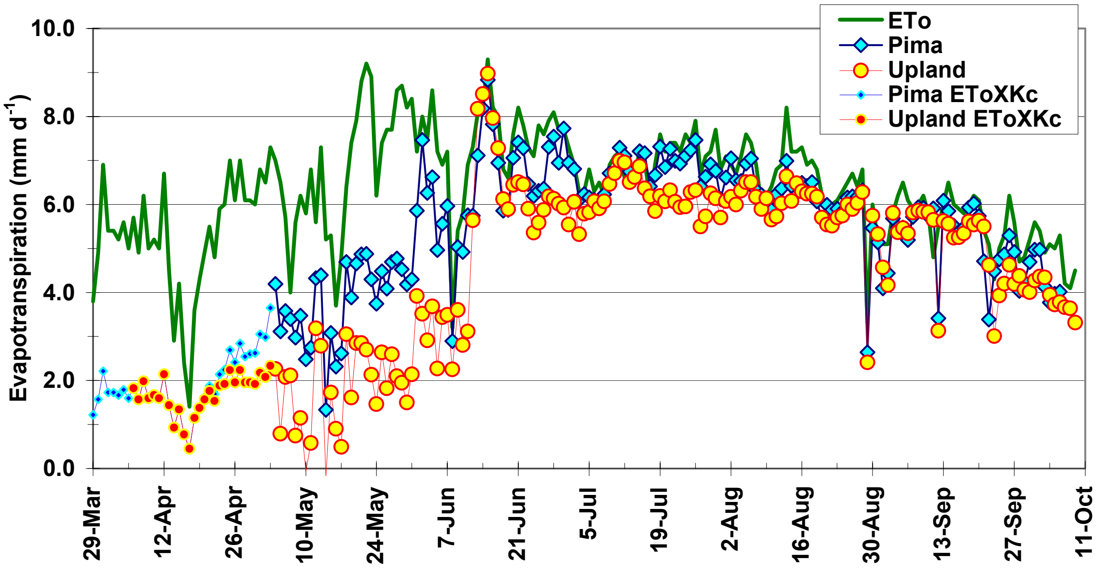

Figure 3. Daily ET_c data for Pima and Upland cotton during the year 2000-growing season. Daily ET_c was calculated from ET_o and K_c values before May 5.

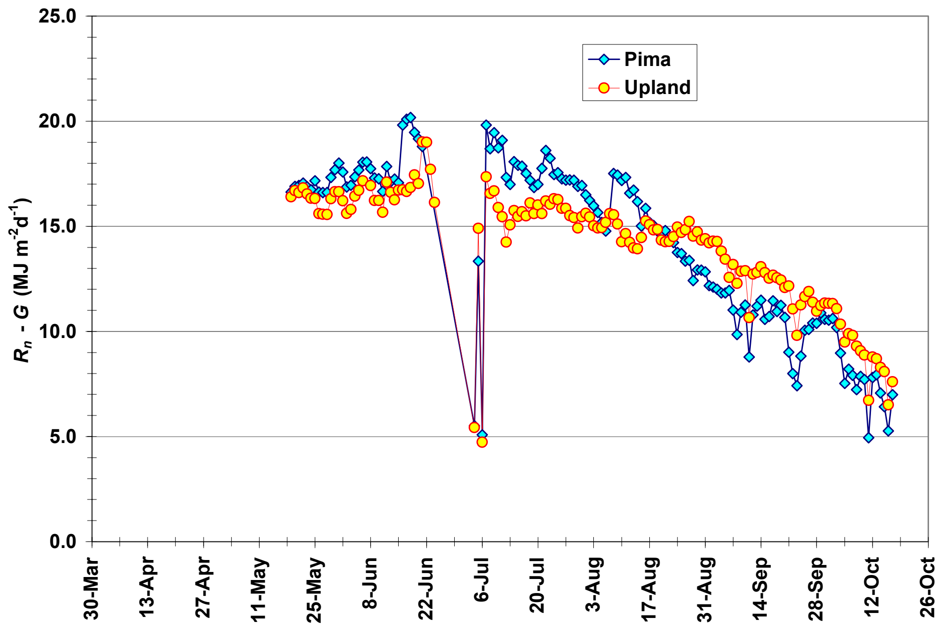

Figure 4. Plot of Daily R_n-G for Pima and Upland cotton varieties during the 2001-growing season.

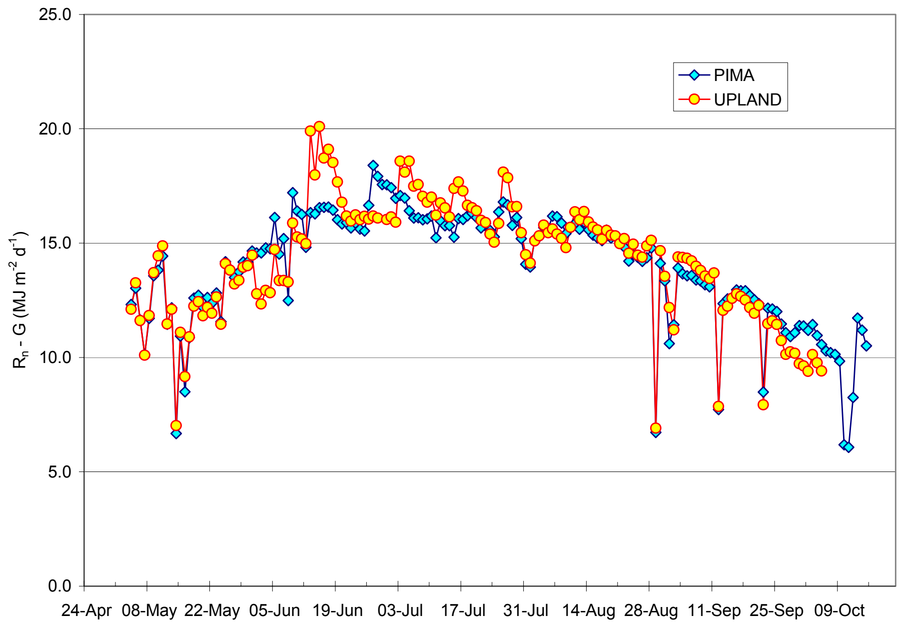

Figure 5. Plot of Daily R_n-G for Pima and Upland cotton varieties during the 2000-growing season.

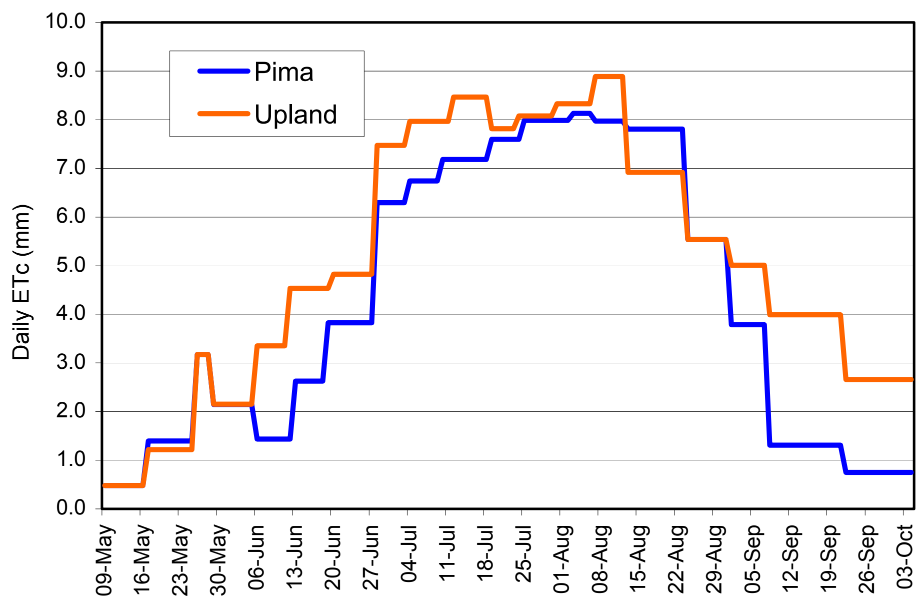

Figure 6. Plot of Daily ETc for Pima and Upland cotton varieties from Neutron Probe data during the 2001-growing season.

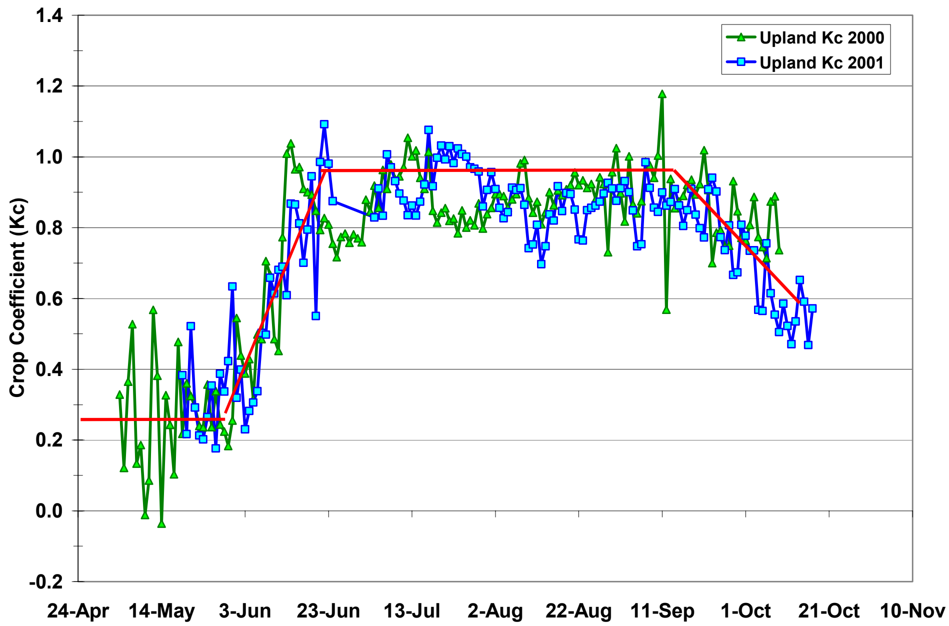

Figure 7. Crop coefficient (K_c) curves for Upland variety in both seasons.

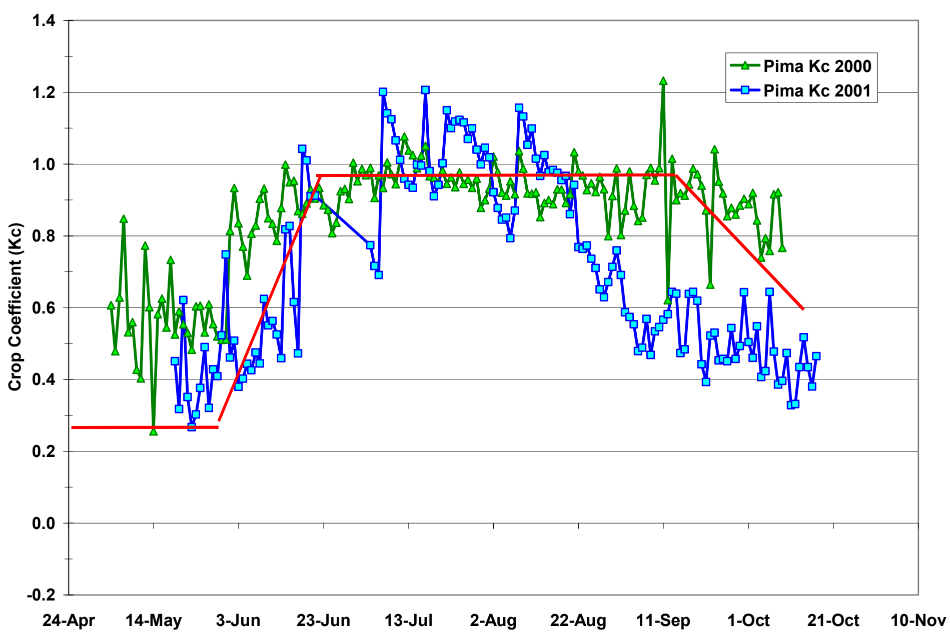

Figure 8. Crop coefficient (K_c) curves for Pima variety in both seasons.

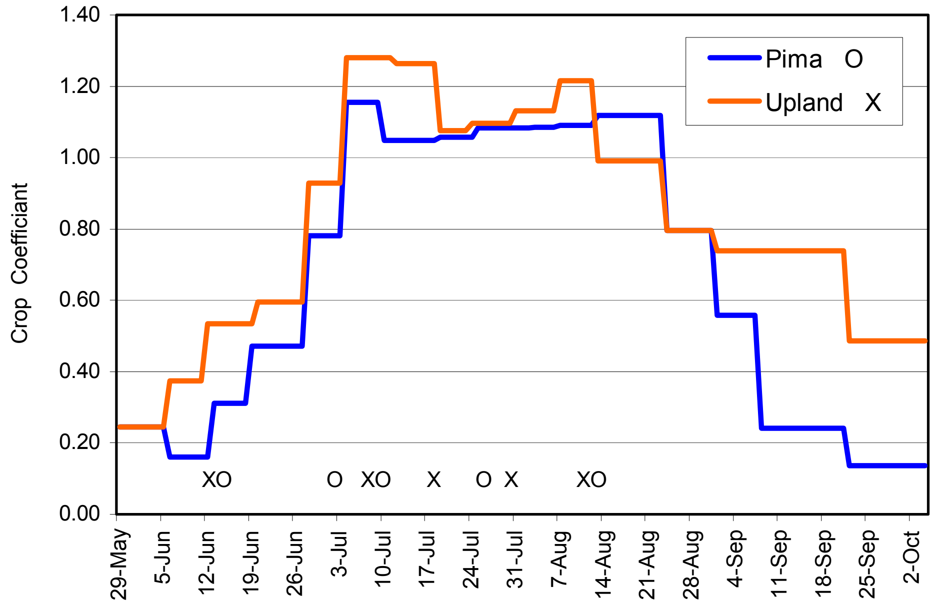

Figure 9. Crop coefficient (K_c) curves for Pima and Upland varieties in the 2001 season. 'O' indicates Pima irrigations, 'X' indicates Upland irrigations.

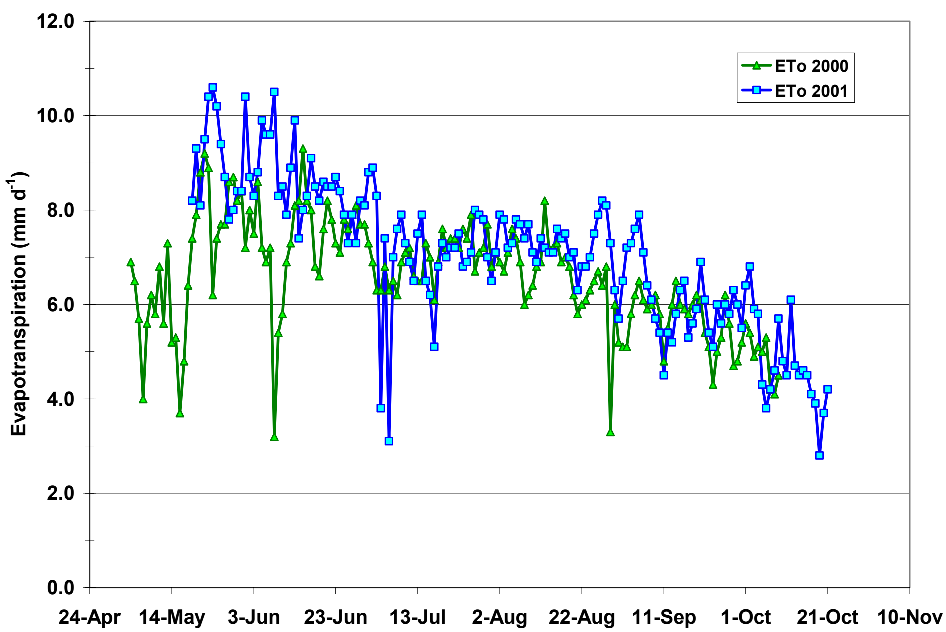

Figure 10. A comparison of ET_o rates during 2000 and 2001 seasons.

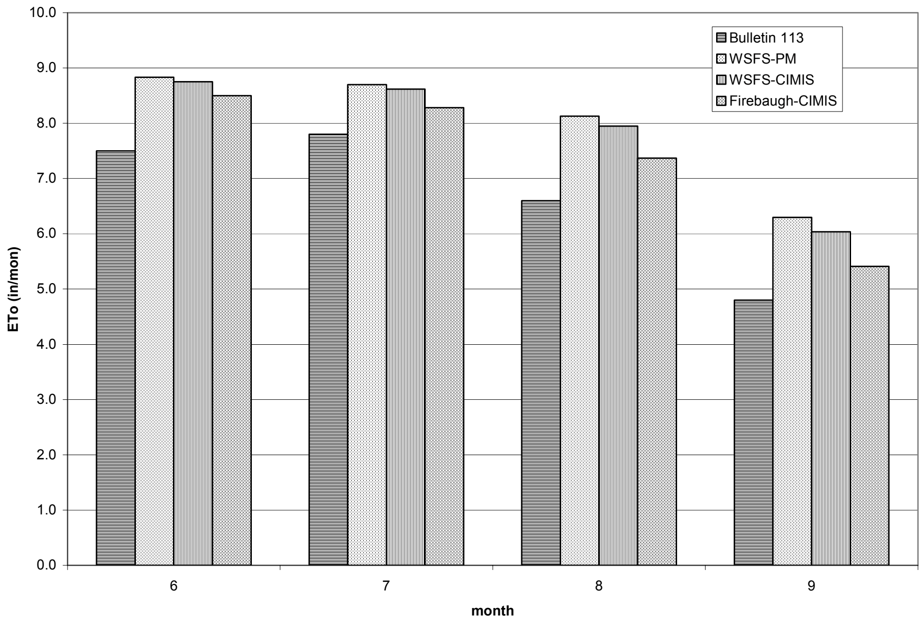

Figure 11. A comparison between monthly ET_o values for the San Joaquin Valley from DWR Bulletin 113-3 and ET_o calculated using the Penman-Monteith equation and hourly data from the West Side Research and Extension Center (WSFS-PM) and using the Pruitt-Doorenbos (1977) hourly equation and data from the West Side Research and Extension Center (WSFS-CIMIS) and from the Firebaugh (Telles Ranch) CIMIS station (Firebaugh-CIMIS).