IRRIGATION SCHEDULING OF ALFALFA USING EVAPOTRANSPIRATION

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ABSTRACT

This paper describes the Irrigation Scheduling Alfalfa (ISA) model, which is used to determine irrigation timing and amounts for scheduling the irrigation of alfalfa for up to nine cutting cycles. The model uses a water balance approach to estimate changes in soil available water content, which users employ to determine when and how much water to apply. Graphics are employed to assist users with the decision making process. Water stress is quantified as a function of the soil water depletion, and reductions in the actual crop evapotranspiration relative to full crop evapotranspiration are used to estimate yield reductions due to stress. The ISA model was developed using Microsoft Excel.

IRRIGATION SCHEDULING ALFALFA MODEL

This paper reviews the methodology used in the Irrigation Scheduling Alfalfa (ISA) model, which uses reference evapotranspiration (ET_o) and crop coefficient (K_c) values to estimate well-watered crop evapotranspiration (ET_c) using the single K_c approach corrected for rainfall and irrigation frequency. Crop coefficient curves are determined for each cutting cycle based on the input cutting dates and recent research. The ISA model includes the calculation of daily stress coefficient (K_s) values, based on the depletion of available soil water content, to estimate the actual crop evapotranspiration (ET_a). Finally, the relative yield of each cutting cycle is calculated using the ratio of ET_a to ET_c.

EVAPOTRANSPIRATION AND CROP COEFFICIENTS

Reference Evapotranspiration. Knowing when and how much to irrigate is extremely important to achieve efficient irrigation and to optimize alfalfa production. The easiest and most common method to use a water balance approach based on estimating crop evapotranspiration as: $ET_c = ET_o \times K_c$. Recently, a standardized method for estimating ET_o was published by the United Nations – Food and Agriculture Organization (Allen et al., 1998) and the "American Society of Civil Engineers – Environmental Water Resources Institute" or "ASCE-EWRI" (Allen et al., 2005). The new equation has standardized the calculation of ET_o, and it has improved the dissemination of ET_o information. Standardized reference evapotranspiration is defined as the evapotranspiration rate from a 0.12 m tall, uniform vegetation of wide extent that is not stressed, and it quantifies the weather effects on evaporation rates. Although ET_o is technically a virtual evapotranspiration, it is an approximation for the evapotranspiration of a large field of well-watered pasture grass.

The standardized ET_o equation is a modification of the Penman-Monteith equation (Monteith, 1965), where the canopy resistance was fixed to 70 s m^{-1} for monthly and daily estimates and to

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50 s m^{-1} and 200 s m^{-1} for daytime and nighttime hourly calculations. The aerodynamic resistance was defined as an inverse function of the wind speed measured at 2 m height (u_2) over a grass surface (r_a=208/u_2). An Excel application program and documentation on how to calculate standardized ET_o using monthly, daily, or hourly data is available from the internet on the webpage http://biomet.ucdavis.edu under the heading "Evapotranspiration". In the California Irrigation Management Information System (CIMIS) network, ET_o is calculated with the Pruitt and Doorenbos (1977) hourly ET_o equation, but the two equations give nearly identical results.

Crop Coefficients. Daily K_c values are determined as the ratio $K_c = ET_c/ET_o$, where ET_o is estimated from weather data and ET_c is measured. It is assumed that the derived K_c and the equation $ET_c = ET_o \times K_c$ will give good estimates of ET_c under similar crop and ET_o conditions in the future. The single K_c approach to determine K_c curves (Doorenbos and Pruitt, 1977) is used in the ISA model. The method requires the input of K_c values for use during (1) the initial growth period, (2) mid-season (or mid-cycle), and (3) at the end of the season. The dates that identify the end point for the (1) initial, (2) rapid, (3) mid-cycle, and (4) end of the season are also needed (Fig. 1); however, these are estimated from the alfalfa green-up and cutting dates as described below.

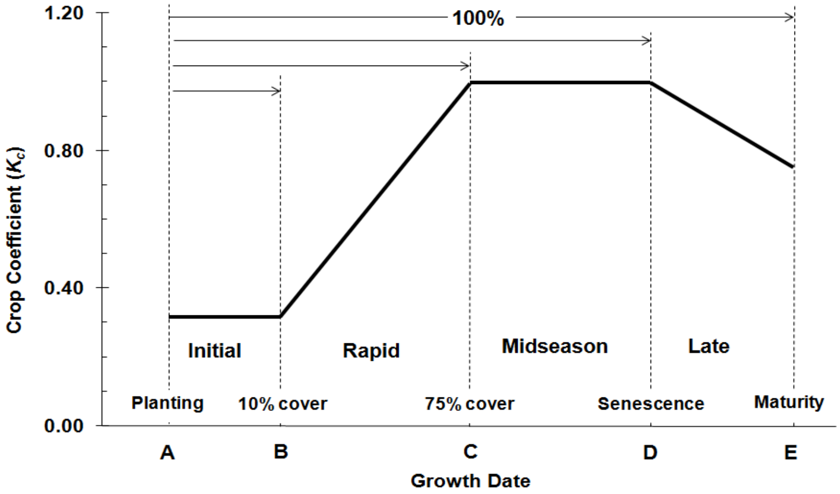


Figure 1. General crop coefficient curve approximation for field crops showing the periods (1) initial, (2) rapid, (3) midseason, and (4) late and the corresponding beginning and end dates.

Using data from Hunsaker et al., (2002), the lengths of each growth period were found to be either constant or linear functions of the mean ET_o rate during each growth period. The length of the initial period (following cutting), was always close to 5 days so that is the default value used in ISA. For rapid growth, the period length is given by $L_R = 15.50-0.66 \times E_R$, where E_R is the mean ET_o rate. For the mid-cycle period, the length is expressed as $L_M = 30.25 – 1.94\ E_M$, where E_M is the mean ET_o. The length of the late-season period is estimated as $L_L = 8.48 -0.53\ E_L$, where E_L is the mean ET_o during the late season period.

The alfalfa ET_c rate varies with the time of the year and with the canopy cover. Thus, cutting dates, crop growth, and weather will all affect the ET_c rate. For example, Hunsaker et al. (2002)

found that the basal crop coefficient (K_{cb}) value, during the initial growth period after each cutting, varied from $K_{cb} = 0.20$ to 0.40. The K_{cb} value is used to estimate only transpiration from vegetation, so it does not include soil evaporation (Allen et al., 2005). Thus, the K_c including soil evaporation, which is used in the ISA model, should be somewhat higher depending on wetting frequency and soil evaporation properties. The default value for the K_c during initial growth was set to $K_c = 0.30$ in the ISA model; however, it can be modified.

Daily peak ET_c estimates are estimated from the input monthly climate data and a modified PM equation. The equation is identical to the standardized tall reference evapotranspiration (ETr) equation (Allen et al., 2005) except that the aerodynamic resistance is changed from $r_a = 118.3/u_2$ to $r_a = 147.0/u_2$ s m^{-1}. The revised r_a value was determined using the Shuttleworth (2006) and Snyder (2007) methods. A linear regression of the Snyder (2007) versus Shuttleworth (2006) ET_c estimates gave a slope = 1.00, intercept = 0.01, and $R^2 = 1.00$. Using the Indio data, the $r_a = 118.3/u_2$ gave a ratio $ET_r/ ET_o = 1.48$, whereas the $r_a = 147.0/u_2$ gave a $K_c = ET_c/ET_o = 1.30$. Hunsaker et al. (2002) conducted an extensive research project in Arizona and found a basal $K_{cb} = 1.22$ for mid-cycle alfalfa; however, the basal K_c value does not include soil evaporation and the research site was considerably less windy than Indio, so the $K_c = 1.30$ seems reasonable. Data from Davis were also input into the model and a mid-cycle $K_c = 1.24$ was found, which is similar to the K_c commonly used in California's Central Valley.

The rapid growth period follows initial growth and the K_c is assumed to increase linearly from the initial K_c (on date B) to the peak K_c at the end of the rapid growth period (on date C). During the late period, the K_c value drops from the peak K_c (on date D) to the K_c just before cutting (on date E). In Hunsaker et al. (2002), the K_{cb} at cutting was consistently near 1.05, and, since the soil evaporation rate should be low at cutting, the $K_c = 1.05$ was used at the end of the late period in the ISA model.

In the ISA model, K_c values are not allowed to fall below the estimated K_c for bare soil evaporation, which is estimated from the ET_o rate and rainfall frequency following Ventura et al., 2005) using a soil hydraulic factor $\beta = 2.65$, which gives K_c values that are similar to those reported for typical soils (Doorenbos and Pruitt, 1977). Since the K_c values for bare soil are higher during low ET_o, higher rainfall periods, the bare soil K_c correction sometimes affects the initial K_c values during the spring. It is rarely a factor during dry, high ET_o periods.

Water stress decreases plant transpiration and reduces yield below its potential. A water stress coefficient (K_s) is included in the ISA model, and it is multiplied by the ET_c to estimate actual evapotranspiration (ET_a). The K_s factor in ISA is patterned after that described in Allen et al. (1998) with corrections from Hunsaker et al. (2002). It is based on the depletion of available water as shown in Fig. 2. Until the soil water depletion (Dr) exceeds the readily available water (R_{AW}), no water stress is assumed and $K_s = 1.00$. When D_r exceeds R_{AW}, the K_s value is calculated as: $K_s = \frac{T_{AW} - D_r}{(1-p)T_{AW}}$, where $p = 0.55 + 0.04(5 - ET_c)$ is the fraction $p = R_{AW}/T_{AW}$ (Fig. 2) and ET_c is the unstressed crop evapotranspiration.

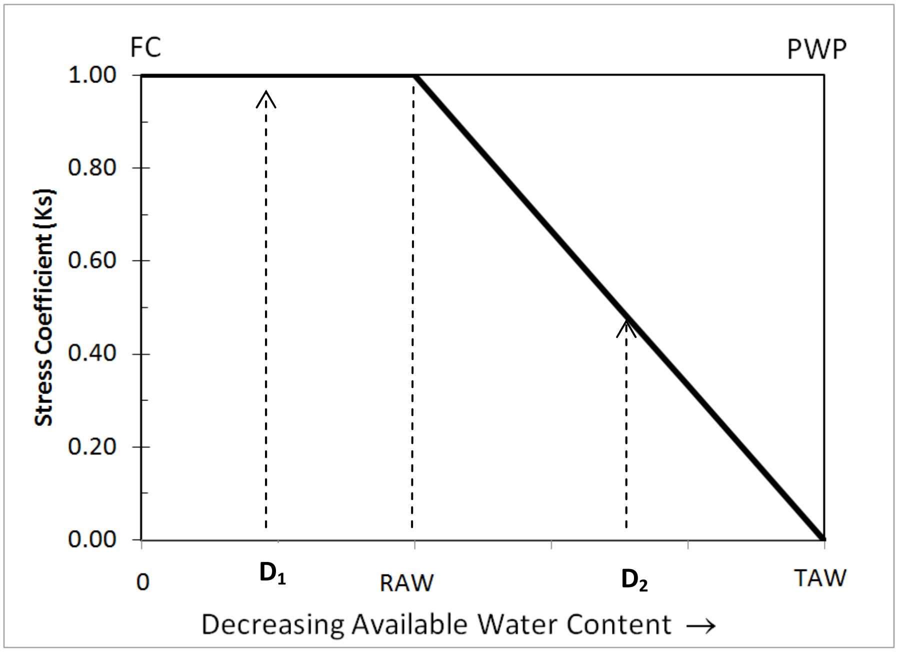
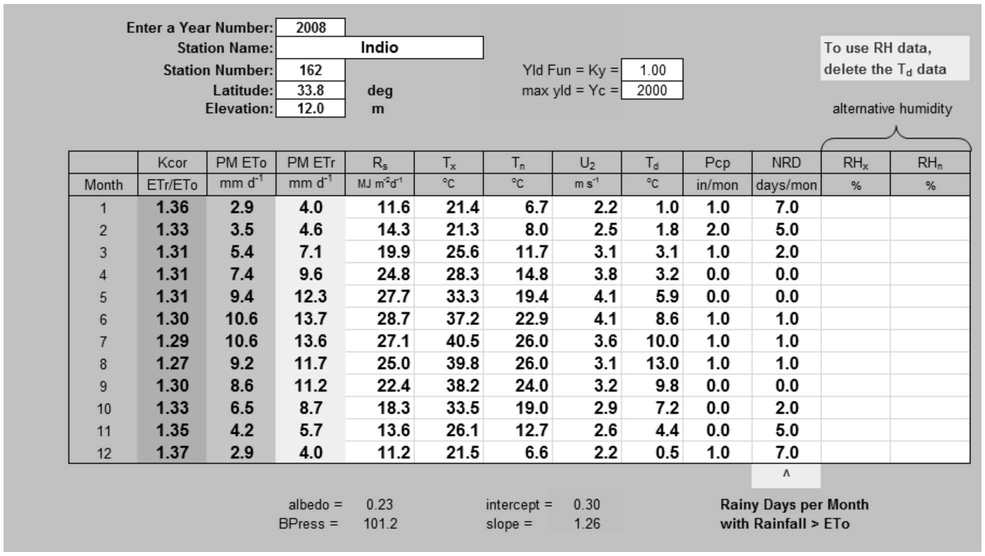


Figure 2. Stress Coefficient plotted versus decreasing available water from field capacity (FC) to the permanent wilting point (PWP). The $K_s = 1.00$ until the available water depletion (D_r) exceeds R_{AW}. Then it drops linearly from $K_s = 1.00$ to $K_s = 0.00$ when $D_r = T_{AW}$. For example, $K_s = 1.00$ at depletion D_1 and $K_s = 0.50$ at depletion D_2.

The effect of water stress on yield is considered by calculating the ratio of the cutting cycle cumulative ET_a / ET_c. The potential yield (Y_c) and yield function (K_y) are input for each cutting cycle, and the equation: $1-\frac{Y_a}{Y_c}=K_y\left(1-\frac{ET_a}{ET_c}\right)$ is rearranged to calculate the stressed yield (Y_a). These calculations are done for each cutting cycle and the results are plotted in the yield chart.

SCHEDULING MODEL

The "Irrigation Scheduling Alfalfa" or "ISA" model was written in Microsoft Excel to help growers determine when and how much to irrigate alfalfa and to estimate the effect of water stress on yield. The model uses monthly inputs of mean daily climate data (Fig. 3) to determine daily ET_o rates using the standardized PM equation (Allen et al., 1998; Allen et al., 2005). The model then computes a smooth fit curve of daily ET_o rates. The number of significant rainy days (NRD), where rainfall is significant when the rainfall depth is greater than the ET_o rate on the same day, are used to calculate an estimate of the number of days between rainfall by month. A smooth curve fit is used to estimate the number of days between rainfall (DBR) events for each day of the year. Then, the daily ET_o rates and DBR are used to compute the bare soil evaporation and the K_c values for bare soil on each day of the year.



Enter a Year Number: 2008
Station Name: Indio
Station Number: 162
Latitude: 33.8 deg
Elevation: 12.0 m

Yld Fun = Ky = 1.00
max yld = Yc = 2000

To use RH data, delete the T_d data

alternative humidity

	Kcor	PM ETo	PM ETr	R_s	T_x	T_n	U_2	T_d	Pcp	NRD	RH_x	RH_n
Month	ETr/ETo	mm d^{-1}	mm d^{-1}	MJ $m^{-2}d^{-1}$	°C	°C	m s^{-1}	°C	in/mon	days/mon	%	%
1	1.36	2.9	4.0	11.6	21.4	6.7	2.2	1.0	1.0	7.0		
2	1.33	3.5	4.6	14.3	21.3	8.0	2.5	1.8	2.0	5.0		
3	1.31	5.4	7.1	19.9	25.6	11.7	3.1	3.1	1.0	2.0		
4	1.31	7.4	9.6	24.8	28.3	14.8	3.8	3.2	0.0	0.0		
5	1.31	9.4	12.3	27.7	33.3	19.4	4.1	5.9	0.0	0.0		
6	1.30	10.6	13.7	28.7	37.2	22.9	4.1	8.6	1.0	1.0		
7	1.29	10.6	13.6	27.1	40.5	26.0	3.6	10.0	1.0	1.0		
8	1.27	9.2	11.7	25.0	39.8	26.0	3.1	13.0	1.0	1.0		
9	1.30	8.6	11.2	22.4	38.2	24.0	3.2	9.8	0.0	0.0		
10	1.33	6.5	8.7	18.3	33.5	19.0	2.9	7.2	0.0	2.0		
11	1.35	4.2	5.7	13.6	26.1	12.7	2.6	4.4	0.0	5.0		
12	1.37	2.9	4.0	11.2	21.5	6.6	2.2	0.5	1.0	7.0		

^

albedo = 0.23
BPress = 101.2

intercept = 0.30
slope = 1.26

Rainy Days per Month with Rainfall > ETo

Figure 3. Sample climate data input for Indio, CA. Note that either the daily mean dew point temperature or the maximum and minimum relative humidity can be input. NRD is the number of significant rainy days per month (i.e., when Pcp > ET_o).

To determine the K_c curves for each cutting cycle, the green up date and up to nine cutting dates are input into the CutDates worksheet. The K_c values are determined for each cutting cycle using the procedures outlined in the above Evapotranspiration and Crop Coefficients sections. The daily K_c values are automatically transferred into the Scheduling worksheet, where the irrigation timing and amounts are determined. The input allowable depletion percentage and the effective crop rooting depth are used to determine the total available water (T_{AW}) content. The irrigation application rate (AR) and application efficiency (AE) are also input into columns in the Scheduling worksheet. All following dates will have the same AR and AE unless they are changed at a later date. This method allows users to change the application rate or efficiency as infiltration and other factors change during the season. The set times for irrigations are computed from the input AR and AE values on dates when a net application (NA) is input into the model. A small table at the top of the Scheduling worksheet is provided to help users determine the application rate in mm h^{-1} from cfs, set time (h), and application efficiency (%). If the current ET_o values are input into the Scheduling worksheet, they override the smoothed curve ET_o values that were computed from the monthly data. All rainfall is assumed effective unless the rainfall depth (mm) is greater than the soil water depletion. Therefore, the effective rainfall (R_e) is easily determined by comparing the depth of rainfall with the soil water depletion and inputting the smaller of the two as the Re.

After all of the other parameters are input, a schedule is developed by inputting NA amounts (mm) into the NA column on days when irrigation is desired. The readily available water (R_{AW}) and the depletion of available water (D_r) are shown in columns to the left of the NA column. When the D_r exceeds R_{AW}, the stress coefficient (K_s) will decrease linearly as a function of the fall in water content from 1.00 at R_{AW} to 0.00 at T_{AW} (Fig. 2). Thus, when D_r exceeds R_{AW}, the ET_a falls below the full crop evapotranspiration ET_c. Assuming that ample water is available and other factors (e.g., high temperature) are not significant stress factors, the highest production generally occurs when water stress is avoided. Therefore, assuming no water-logging problems, one goal is to irrigate so that D_r rarely exceeds R_{AW}. It is also important to have high application efficiency and a convenient set time. Again, the small box at the top of the Scheduling worksheet is used to determine a good set time to minimize water stress and yet optimize efficiency. To achieve optimization, it is best to perform a system evaluation to identify the AE corresponding to different set times.

There is a chart named "ET_Adj" to the right of the Scheduling worksheet that is useful to time irrigation and determine amounts (Fig. 4). The scale at the bottom of the chart can be adjusted to cover different cutting cycles, which are identified by the vertical yellow lines. By entering then NA values on irrigation dates and then looking at the "ET_Adj" chart, it is easy to see if the irrigation is keeping up with the calculated cumulative ET_a. The irrigation dates and amounts are varied until the plot shows that the irrigation applications are keeping up with ET_a. Note that the set times can be varied to force the NAs to keep up with cumulative ET_a and to make sure the irrigation events fall 4-6 days after cuttings. The last irrigation before cutting should be far enough in advance that the soil moisture is low during harvest. It should be timed, with the proper application amount within 4-6 days after cutting.

To the right of the Adjustable chart is the Annual chart which shows the cumulative ET_a and NA for the year (Fig. 5). A sample chart for alfalfa grown near Indio is provided in Fig. 4. Note that the cumulative ET_a leveled off late in the season because the last irrigation was applied on 30 May. Without irrigation to replenish the soil, water stress occurred as the soil water content dropped. Figure 6 shows the Annual chart when irrigation was applied for the entire season.

CONCLUSIONS

This paper reviewed the methodology used in the Irrigation Scheduling Alfalfa (ISA) model using a single K_c method with corrections for rainfall frequency. The approaches used to estimate reference evapotranspiration, crop coefficients, crop evapotranspiration, water stress coefficients, actual evapotranspiration, and actual yield were described. The model is mainly based on concepts presented in Allen et al. (1998) and Hunsaker et al. (2002) and K_c values based on Shuttleworth (2006) and Snyder (2007). ISA includes evapotranspiration corrections for water stress and estimates the effects on yield for each cutting cycle.

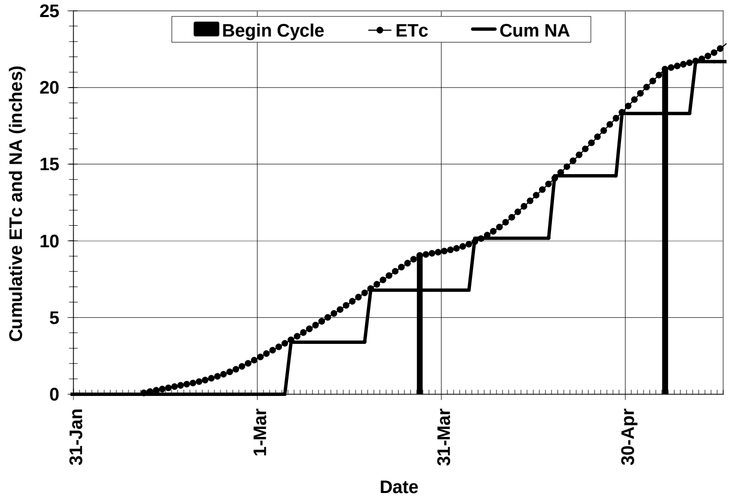


Figure 4. Sample of the ET_Adj chart from ISA.

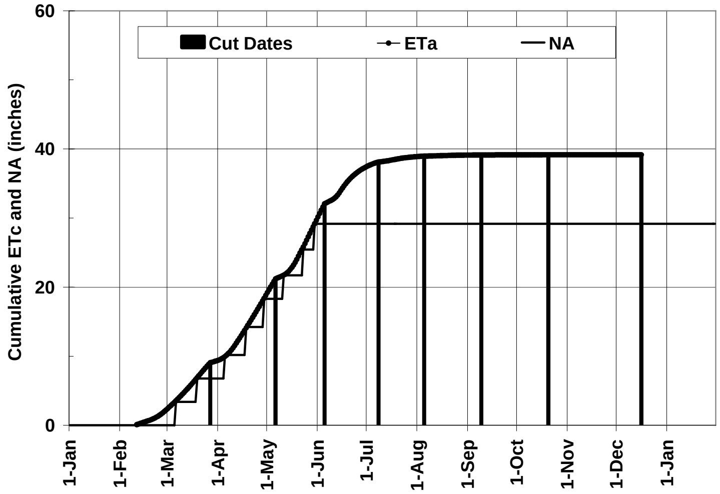


Figure 5. The annual cumulative ET_c cumulative net applications, and cutting dates when the last irrigation was applied on 30 May. Climate data were from Indio, CA.

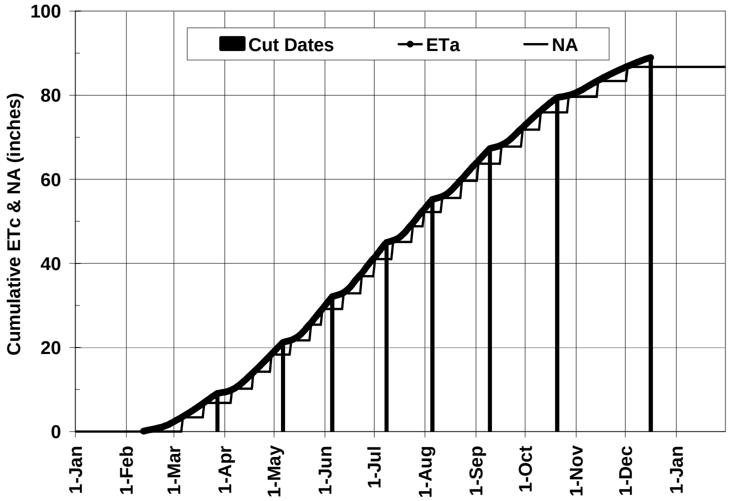


Figure 6. The annual cumulative ET_c, cumulative net applications, and cutting dates when the alfalfa crop was irrigated all season to avoid water stress. Climate data were from Indio, CA.

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