Extension Education Methods

Development of a Simple Irrigation Scheduling Calendar for Mesilla Valley Pecan Growers

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SUMMARY. For farmers to accurately schedule future water delivery for irrigations, a prediction method based on time-series measurements of soil moisture depletion and climate-based indicators of evaporative demand is needed. Yet, numerous reports indicate that field instruments requiring high in-season labor input are not likely to be used by farmers. In New Mexico, pecan (*Carya illinoensis*) farmers in the Mesilla Valley have been reluctant to adopt new soil-based or climate-based irrigation scheduling technologies. In response to low adoption rates, we have developed a simple, practical irrigation scheduling tool specifically for flood-irrigated pecan production. The information presented in the tool was derived using 14 years of archived climate data and model-simulated consumptive water use. Using this device, farmers can estimate the time interval between their previous and the next irrigation for any date in the growing season, in a range of representative soil types. An accompanying metric for extending irrigation intervals based on field-scale rainfall accumulation was also developed. In modeled simulations, irrigations scheduled with the tool while using the rainfall rule were within 3 days of the model-predicted irrigation dates in silty clay loam and loam soil, and less than 2 days in sandy loam and sand soil. The simulations also indicated that irrigations scheduled with the tool resulted in less than 1% reduction in maximum annual consumptive water use, and the overall averaged soil moisture depletion was 45.14% with an 18.1% cv, relative to a target management allowable depletion of 45%. Our long-term objective is that farmers using this tool will better understand the relationships between seasonal climate variation and irrigation scheduling, and will seek real-time evapotranspiration information currently available from local internet resources.

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Irrigation scheduling is a process by which the timing and amount of water applied are determined

to meet the evapotranspiration demands of the crop. Both the water delivery system and the availability of water to the plant need to be considered in the scheduling process. Flood irrigation, which is the most common irrigation method for pecan production in the Mesilla Valley of New Mexico, is a type of irrigation practice in which a leveled orchard is divided by parallel soil ridges and water is successively delivered to each bordered plot from a well head or field ditch at its upper end. Depending on where the grower is located in the network of canals and ditches administered by the irrigation district, delivery of surface water may take several days to a week from the time water is ordered. Therefore, growers must be able to predict several days in advance when their soil moisture will be at a management allowable depletion (MAD) level.

New Mexico is one of the top three producers of improved variety pecans in the United States, and production has increased 5-fold in the last 30 years. More than 70% of New Mexico's pecans come from Doña Ana County (New Mexico Department of Agriculture, 2004). Compared with other crops grown in the Lower Rio Grande Basin, pecan trees have the highest consumptive water use (Blaney and Hanson, 1965; Sammis et al., 1979). While pecan production has grown in past decades, an increasing number of small to mid-sized orchards have been sold to larger farms or subdivided to accommodate rapidly expanding suburban development. As parcel sizes become smaller, existing surface water delivery systems become less efficient and more difficult to manage. This has led to great disparity in application efficiency among residential/lifestyle pecan farms with less than 10 acres, as documented in a recent study of irrigation duration stratified by pecan farm size (Skaggs and Samani, 2005).

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
25.4	inch(es)	mm	0.0394
0.0833	inch/ft	m·m ⁻¹	12.0000
1.6093	mile(s)	km	0.6214
(°F - 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

In the interests of water conservation, the goals of the research community have been to help pecan growers maximize irrigation application efficiency through proper design and operation of irrigation systems, and at the same time, maximize water use efficiency and farm profitability through careful irrigation scheduling. The reduction of water stress with correct timing of irrigations can have a significant impact on yield, nut quality, and precocity (Stein et al., 1989). An incentive for pecan producers to monitor water inputs should come from the perception that the adoption of new soil moisture monitoring technologies will provide a means to increased profitability, which will in turn pay for the costs of those technologies many times over. However, in a limited study at five Mesilla Valley pecan orchards, growers were reluctant to adopt irrigation scheduling approaches that required measuring soil moisture with granular matrix sensors and data loggers, collecting biweekly tensiometer measurements, or tracking soil water balance with an internet-based consumptive water use model (Kallestad et al., 2006). According to the Farm and Ranch Irrigation Survey (U.S. Department of Agriculture, 2002) only 2% of farms in New Mexico use soil moisture-sensing devices, and less than 1% refer to daily crop evaporation reports or computer simulation models as methods in deciding when to irrigate; whereas 26% used a calendar, 23% use soil moisture “by feel,” and 62% of respondents said they use “crop condition” to schedule irrigation. Numerous recent articles and extension reports have concluded that instruments requiring high in-season labor input for field measurements are not likely to be used by farmers (Hill and Allen, 1996; Sanden et al., 2003; Thompson et al., 2002). Common criticisms include: excessive time required in learning equipment operation; too much time spent collecting and managing the data; difficulties accessing consultants for help with data interpretation; and technical problems associated with equipment malfunction or calibration. Up-front equipment costs can also be prohibitive, especially with small farming operations. Farmers are more likely to adopt technologies where the presentation of necessary information is

easy to understand and can be accessed quickly, reliably, and cheaply.

Simplified irrigation calendars based on historic reference evapotranspiration (ET_o), crop coefficients (k_c), plant phenology, and average seasonal rainfall, with intervals derived from modeled soil water balance, have been developed for a variety of annual crops. The simplest calendars provide fixed irrigation intervals with respect to a planting date, and have been used in developing countries where access to soil- and climate-based scheduling technologies are limited (Hill and Allen, 1996). More flexible irrigation calendars account for the unreliability of rainfall and variability in seasonal temperature. Raes et al. (2000, 2002) devised calendars with irrigation intervals for specific crops using 15 to 25 years of historic climate data in a soil water balance model. Interval guidelines were recommended for 10-d increments over the growing season for four different weather conditions, which are based on probability levels for ET_o and rainfall. Guidelines were also devised for delaying the irrigation intervals to account for rainfall. A delay factor is computed by the farmer by dividing the amount of accumulated rainfall by the typical irrigation depth. This factor is then multiplied by the recommended irrigation interval to determine the delay time in days.

Tabulated crop ET or reference ET for a specific region, typically presented in weekly intervals and based on averaged historic climate data, is a common tool for estimating soil water balance. ET calendars are primarily used in planning irrigation by using the “checkbook method.” Similar to balancing a checkbook, the previous day’s adjusted soil water depletion level (*current balance*) is adjusted by adding irrigation and rainfall inputs (*deposits*) and subtracting crop water use from ET tables for that period (*withdrawals*). Using this information, a farmer can track daily soil water balance to a management allowable depletion based on crop root depth and soil water holding capacity. Many state and county extension offices have produced checkbook worksheets and guides to help farmers with this technique, but most also advocate the collection of real-time soil moisture and ET data to confirm the computed balance.

ET calendars are most appropriate for regions where climate is relatively consistent from year to year, and variability in seasonal rainfall and ET_o are small. The advantage of this approach is that farmers can conveniently plan irrigations throughout the growing season without spending time collecting and processing climate and soil moisture data. In areas where weather conditions deviate considerably from an historical average, farmers scheduling with calendars run the risk of overirrigation or deficit irrigation, which could have economic consequences. Scheduling irrigation with historic ET has been advocated for some areas of California’s semiarid Central Valley (Hanson et al., 1999). Weekly ET calendars have been made available for California almond (*Prunus dulcis*) growers through the University of California Cooperative Extension (Sanden, 2006).

Since rainfall contributes the greatest amount of variability to the soil water balance, our approach has been to produce a flexible irrigation scheduling calendar using irrigation intervals derived with a soil water volume balance model and historic climate data inputs, but without rainfall. Using this device, farmers that flood-irrigate mature orchards can determine the time interval between their previous and the next irrigation, for any time in the growing season, in a range of representative soil types. This calendar is also flexible in that it provides the user with a simple metric by which recommended irrigation intervals can be delayed, based on field-scale rainfall accumulations. Our hope is that farmers will use this tool as a scheduling guideline, be able to predict irrigations with moderately low risk, and better understand the relationship between seasonal climate variation and irrigation timing. Additionally, as some growers become more aware of the benefits of proper irrigation timing, they will become open to more sophisticated technologies such as real-time ET information currently available from local internet resources and electronic soil-based monitoring systems.

The objectives of this article are to describe the scheduling tool development and validation process and to elaborate on the potential for applying this process to other pecan-growing

regions, as well as for a broader scope of crops and irrigation methods.

Model description

The volume balance model used in this study is one component of an existing object-based growth and irrigation scheduling model (GISM) in spreadsheet format, modified for simulating irrigation management of a variety of crops, including mature pecan orchards (Al-Jamal et al., 2002). The elements of this model were previously described in McGuckin et al. (1987). In general terms, the volume balance model simulates daily available soil water in the root zone by the relation:

$$SM_j = SM_i + USI_j + MSI_j + R_j - sf(ET_c)_i \quad [1]$$

where the soil moisture content in the root zone at a particular timestep SM_j is the sum of the soil moisture in the previous timestep (SM_i) plus any user-scheduled irrigation (USI_j), plus any model-scheduled irrigation (MSI_j) in the previous timestep, plus rainfall (R_j) inputs, minus moisture lost to crop evapotranspiration (ET_c), which may be modified by a water stress function scalar (sf). After an irrigation or heavy rainfall, when the soil moisture is in excess of the texture-specific water holding capacity (WHC) in the user-defined rooting depth, the model sets volumetric soil moisture to the product of the whc times the rooting depth at that timestep, minus the ET_c for that period. The model assumes excess water is lost to drainage within the following timestep. Irrigations are scheduled by the model when SM_i , diminished by $sf \times ET_c$, falls below the relative moisture content determined by the user-specified MAD.

The model requires daily meteorological input data collected from a user-selected weather station. Maximum and minimum humidity, temperature, solar radiation, wind speed, and soil temperature data from a network of local automated Campbell weather stations are gathered every night and made available on the New Mexico Climate Center's web site. The climate center also computes ET_o using a modified Penman-Monteith FAO-24 equation (Sammis et al., 1985) and accumulated growing degree days (GDD) for a variety of crops (Sammis et al., 1985). The daily GDD specific for pecan is calculated using an averaging method with no

maximum or minimum cutoff temperatures, and a base air temperature of 60 °F as follows:

$$\begin{aligned} GDD &= T_{ave} - T_b \quad \text{if } T_{ave} > T_b \\ &\text{else} \\ GDD &= 0 \end{aligned} \quad [2]$$

where $T_{ave} = (T_{max} + T_{min})/2$, and T_b = crop specific base temperature. Station rainfall data can also be used in the computation of soil water balance.

The model requires user-defined physical parameters such as texture-specific soil water holding capacity and irrigation amount, and phenological parameters such as the starting and maximum rooting depth and root growth rate. For mature pecan trees, it was assumed that the starting and maximum root depths were the same.

The pecan crop coefficient (k_c) was computed from ET measurements collected in 2001 and 2002 at a mature pecan orchard 5.1 km south of Las Cruces using a one propeller eddy covariance system (Sammis et al., 2004). The model uses a fourth-order polynomial regression function of daily crop coefficient on an explanatory variable of GDD. The pecan crop coefficient polynomial is used to calculate daily ET_c by scaling ET_o input.

When soil moisture content falls below 45% of field capacity, the rate of ET in pecan trees can drop (Garrot et al., 1993; Rieger and Daniell, 1988). Below this stress threshold, the trees close their stomata to use less water. At each time-step, the model computes a variable scalar to modify ET_c according to the conditional function:

$$\begin{aligned} \text{If } sf &= m \left(\frac{SM_{ij}}{whc_j} \right) + b > 1 \\ \text{then } sf &= 1 \\ \text{else } sf &= m \left(\frac{SM_{ij}}{whc_j} \right) + b \end{aligned} \quad [3]$$

where the stress function scalar sf (dimensionless) is the product of a user-defined slope m multiplied by the relative soil moisture content at that timestep, plus a user-defined intercept. The function sets all sf values greater than 1 to 1. For pecans, the slope value is set to 1.82 and the intercept to 0, which corresponds to a MAD of 45%.

Materials and methods

STUDY AREA. The weather station located at the New Mexico State

University Leyendecker Plant Science Research Center (PSRC) 9 miles south of Las Cruces, NM, was selected from among a network of local weather stations for its central location in the Mesilla Valley, and for the large and fairly reliable dataset archived from this site. Rainfall data from a second weather station located on the campus of New Mexico State University, which reports to the Western Regional Cooperative Network of the National Climate Data Center (NCDC), were used to derive the rainfall rule and for tool validation studies (Fig. 1).

DATA QUALITY. Archived climate data from the PSRC weather station for the years 1988 through 2005 were collected and input in the irrigation scheduling model. To assess the quality of the meteorological data, time series plots of daily temperature minima and maxima, daily solar radiation, and daily relative humidity maxima and minima were examined to determine any sensor discontinuities or abnormalities. Data for 1992 were not generated at the station. All climate data for 1994 were eliminated from the dataset due to record-breaking high temperatures. The use of an incorrect scaling factor led to excessive values for measured solar radiation for the periods of 15 Sept. to 31 Dec. 1993. Thus, radiation data for dates up to 15 Sept. for that year were used for the irrigation interval regression, but were not included in the tool simulation analysis.

Measured relative humidity data were errant for all of 1988 and 1989, and from 12 July to 18 Nov. in 2003, with excessive values for maxima and zero for minima (1988) or zero for maxima and minima (1989 and 2003). Since high average daily relative humidity values would only lead to a slight underestimation of ET_o , and values of zero would lead to a slight overestimation of ET_o using the Penman-Monteith equations, all of the data were included.

All data for 1999 and 2000 were eliminated from the dataset because of temperature sensor anomalies for a period of 7 to 14 d consecutively in both years. Because the pecan crop coefficient is a function of accumulative heat units, the resulting ET_c can be over- or underestimated for the duration of the growing season after the temperature sensor anomalies. In contrast, data from 2003 had missing

Fig. 1. Location of the Mesilla Valley in Doña Ana County, NM, and weather stations where meteorological data used in the calendar development of the pecan irrigation scheduling tool were collected. NCDC = National Climate Data Center, PSRC = New Mexico State University Leyendecker Plant Science Research Center, 1 km = 0.6214 mile.

daily values for temperature, relative humidity, and solar radiation for 2 nonconsecutive days. These data points were replaced with interpolated values and were included in the dataset.

The tipping bucket rain gauge at the PSRC station was apparently malfunctioning for most of the years in the dataset, recording accumulations

well below those logged by daily visual inspection at the NCDC station. Given the unreliability of this sensor, all rainfall data came from the NCDC weather station.

INTERVAL DERIVATION. Each year's daily meteorological data, including ET_o and pecan-specific GDD data, were retrieved from the

PSRC archive and input into the model, except for rainfall. For each model run, the soil water holding capacity, root depth, and irrigation amounts listed in Table 1 were included as input parameters with the user-defined MAD set to 45%. In separate analyses, the model was forced to begin irrigation scheduling at one of three chosen start dates: 20 Feb., 1 Mar., and 15 Mar., by manually entering an applied irrigation on that date. Subsequent irrigations were automatically scheduled by the model. The period (in days) between each model-scheduled irrigation was recorded and correlated to the date the irrigation was applied. This was done for each year in the dataset, for four soil water holding capacities and root depths corresponding to the four representative soil types. The dates were converted to day of the year, and the mean irrigation interval for any application date (day of the year) was determined by regression on a cubic polynomial function using SigmaPlot (Systat, Point Richmond, CA). The minimum order polynomial was determined by maximizing the coefficient of determination for each regression.

RAINFALL RULE. Meteorological data collected at the PSRC weather station for all the dataset years, except rainfall, were input into the model. For each tool-defined interval, daily rainfall data retrieved from the NCDC station was sequentially input into the volume balance model. The difference (in days) between model-scheduled irrigation date with or without rainfall was regressed against the quantity of rainfall using a linear function. This process was conducted with each of the four water holding capacities corresponding to soil type.

IRRIGATION SCHEDULING TOOL VALIDATION. The accuracy of the tool was evaluated by simulating tool-scheduled irrigations using the volume balance model (with and without the rainfall rule) and comparing the scheduling accuracy, average annual soil moisture depletion, and annual cumulative ET loss to model-scheduled irrigations. To evaluate the scheduling accuracy of the tool, PSRC climate data were entered into the model for all years of the dataset (except for rainfall data). MAD was set to 99% to prevent a model-scheduled irrigation and force user-scheduled irrigations.

Table 1. User-defined input parameters used in the irrigation scheduling model for each soil type.

Soil texture	Water holding capacity (inches/ft) ^z	Beginning and maximum root depth (inches) ^y	Irrigation amount (inches)
Sand	1.02	48	4
Sandy loam	1.42	48	5
Loam	2.02	42	6
Silty clay loam	2.53	42	6

^z1 inch/ft = 0.0833 m·m⁻¹.^y1 inch = 25.4 mm.

Rainfall data collected at the NCDC station were entered in the model for dates before the first irrigation (15 Mar.), and then sequentially for the dates falling within each tool-defined interval. The time difference between the irrigation date scheduled by the tool (while using the rainfall rule), and the date the water balance model would have scheduled an irrigation (indicated by $sf < 1$) was recorded. This procedure was repeated for each dataset year and for water holding capacities corresponding to each of the four soil types. To determine the effect of ignoring the rainfall rule (underestimating the effect of rainfall on soil water balance), the NCDC station rain data were input into the model for tool defined-intervals as before, but irrigations were scheduled using the tool without the rainfall rule.

In addition to scheduling accuracy, each simulation also was used to derive average annual soil moisture depletion. Soil moisture depletion was determined by dividing the volume of soil moisture remaining in the root zone in the timestep before the tool-scheduled irrigation date minus half of the ET in the following timestep by the maximum volume of water soil water for that soil type and rooting depth. Depletions were averaged from 15 Apr. to 15 Oct.

Results and discussion

Our primary concerns in developing an irrigation scheduling calendar using a multiyear climate database were whether the variation in the data were normally distributed for each day across all years, and were free of long-term trends, and whether systematic errors resulting from suboptimal instrument function significantly effected the accuracy of the output. Random and systematic errors in solar radiation and relative humidity

have been shown to have the greatest effect on the estimated mean daily ET_o using the FAO-Penman Montith equations, followed by temperature, and least of all, wind run (Meyer et al., 1989). However, as far as the output of the volume balance model and values used for the scheduling calendar are concerned, these errors are likely to be smaller than errors resulting from false assumptions about tree root depth or the contribution of rainfall to soil moisture. Another source of error can result from the product of estimated daily ET_o and a fourth order polynomial regression function for k_c tied to GDD. As will be discussed below, the k_c regression function has a narrow descriptive range. When the explanatory variable (GDD) exceeds this range, erroneous ET_c values can result.

DATASET SYNOPSIS. Variation in the 14 years of meteorological data collected from the PSRC station is representative of larger time frames for this region. As shown in Fig. 2A, annual rainfall for the data set years is about centered about the 47-year average (1959–2005). The dataset mean annual rainfall was 9.12 inches, with 2 years above, 3 years below, and 9 years within one standard deviation of the mean. The 47-year mean annual rainfall, measured at the NCDC station, was 9.28 inches. The 108-year average (1892–2000) at the same site is 8.74 inches (Malm, 2003). Similarly, the variability in annual accumulative heat units with a 60 °F base temperature was distributed about a mean of 2487 °F, with 1 year above, 3 years below, and 10 years within one standard deviation of 151.7 °F. The 108-year average cumulative growing degree days was 2391 °F, with a maximum of 2994 °F and minimum of 1819 °F. Generally, the years 1991 and 2004 were

particularly cool and wet, and the years 1996, 2001, and 2003 were hot and dry. Averaged monthly rainfall in the dataset years was also typical of the 47-year average (Fig. 2B).

Daily ET_o averaged over the 14 years of the dataset for each date was fairly consistent (Fig. 2C), with a year-to-year cv for each day at $\approx 20\%$ in the beginning of the growing season, dropping to 15% midseason, then rising to 20% to 25% at the end of season (Fig. 2D). ET_o variation averaged over each month has a similar but lower year-to-year cv (Table 2). Daily ET_o variation exceeding 40% in the fall and winter months were likely due to temperature and cloud cover anomalies. Similar monthly variability in atmospheric demand for water was measured over a 9-year period for the Lower Rio Grande Valley by Enciso and Wiedenfeld (2005) who noted an averaged monthly cv of 14% from March to May, followed by an increase to as much as 30% after September.

INTERVAL DERIVATION. The validity of using a volume balance model to predict irrigation intervals rests on whether the input information about climate, water holding capacity, rooting depth, MAD, crop coefficient, and irrigation quantity are accurate and broadly applicable to local conditions. In 2005, we found the soil moisture depletion computed by volume balance model in agreement with field measurements at three orchards with different soil types (Kallestad et al., 2006). However, information about the depth and distribution of mature pecan roots in different soils is mostly anecdotal and in all likelihood variable. The model's rooting depth input parameter is the greatest source of potential error in the predicted moisture depletion. Decreasing the rooting depth from 48 to 42 inches for trees grown in the finer textured soils (Table 1) resulted in a decrease in the averaged irrigation interval of more than 2 d throughout the growing season. The rationale behind this shallower root depth was that it was thought that lack of adequate soil aeration may inhibit lateral and feeder root growth below 3 ft in clay soils, especially in flood irrigated soils. Other than general field observations about pecan root systems (Woodroof and Woodroof, 1934), there is a scarcity of literature specifically

Fig. 2. Synopsis of the meteorological data used in the development of the pecan irrigation scheduling calendar. (A) Cumulative annual growing degree day (GDD) and rainfall data for years included in the data set, and 47-year average (1959–2005) for annual rainfall. (B) Monthly rainfall averages for years included in the dataset, and 47-year monthly average. (C) Potential evapotranspiration (ET_0) averaged for each day from all years included in the dataset. (D) Averaged cv in daily ET_0 , expressed as a percentage, for all years included in the dataset [$1 \text{ inch} = 25.4 \text{ mm}$, $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$].

addressing the frequency and viability of deeper roots in different soils and moisture regimes.

The approach of deriving irrigation intervals using only atmospheric demand in the volume balance model

was done for three reasons. The first was to increase the accuracy of the soil-specific regression function. Using this method, 87% to 93% of the interval variability is explained by the regression model (Fig. 3). When

rainfall is included, the coefficients of determination falls to between 0.77 and 0.87 for sand and silty clay loam, respectively, and the function predicts an irrigation interval that is increased by 1 to 2 d in midseason. Second, by excluding rainfall and providing the user with a method for delaying irrigations in proportion to rainfall, the accuracy of the soil-specific regression models remain high as well as flexible. Finally, averaging model-derived irrigation intervals across all years for each soil type, instead of entering averaged climate data, provides a means to assess the year-to-year variability in the model-predicted intervals.

Because fine-textured soils are irrigated less frequently, the number of interval data points at the beginning of the season is small, therefore the expected accuracy of the tool regression model during this period is lower than the accuracy for coarser-textured soils. While slight increases in regression model accuracy can be achieved by using a fifth order polynomial function, the errors associated with model assumptions, input information estimates, and the rainfall rule far outweigh the small benefit from the additional complexity.

Postharvest farm operations were considered when choosing an appropriate start date to begin model-scheduled irrigations. The pecan harvest is typically completed before mid-January, after which farmers are involved in pruning and soil preparations up until mid-March, depending on the extent of winter rainfall. Many pecan farmers begin their first irrigation before the third week of March. Therefore, we forced the model to begin the irrigation sequence on 15 March. In a separate analysis, there was no difference in regressed intervals using different start dates.

User-defined MAD is another source of uncertainty in the model. Although there is some literature support correlating 45% MAD to water stress, there is little pecan-specific information correlating 45% MAD to yield. Changing the MAD levels from 45% to 55% delays the volume balance model-scheduled irrigations by 1 to 2 d in midseason, and longer at the beginning and end of the season.

Water holding capacity for layered alluvial soils is another variable

Table 2. Daily evapotranspiration (ET_o) averaged for each month, and monthly precipitation for the Mesilla Valley for 14 years from 1988 to 2005. Coefficient of variation (cv) represents the year-to-year variability between averaged monthly values. Precipitation data were collected at the National Climate Data Center (NCDC) weather station at New Mexico State University. ET_o data were derived from meteorological data collected at the Plant Science Research Center (PSRC) weather station using modified Penman-Montieth equations.

Month	ET_o		Precipitation	
	Mean (inches) ^a	cv (%)	Mean (inches)	cv (%)
January	0.12	30.03	0.44	89.33
February	0.16	31.50	0.72	112.03
March	0.23	22.64	0.35	104.27
April	0.28	18.20	0.52	180.98
May	0.32	14.68	0.24	114.78
June	0.34	13.70	0.53	112.82
July	0.30	18.91	0.61	45.77
August	0.26	19.35	1.40	63.76
September	0.23	20.98	1.00	76.89
October	0.19	23.61	0.84	101.60
November	0.14	27.59	0.38	122.28
December	0.10	30.77	0.83	116.42

^a1 inch = 25.4 mm.

for which there is difficulty in accounting. Whether the user will be able to interpolate between intervals derived for uniform soil profiles to a mixed profile is a concern. To keep the tool simple, we rely on the ability of the user to interpolate values from a small number of data points for each soil type and calendar date to suit their particular situation. We chose to derive interval values for two extreme soil types (sand and silty clay loam) and two intermediate soil types (sandy loam and loam), and provided interval information for only 1 d of each week from late March to mid-October.

RAINFALL RULE. Because the volume balance model is necessarily simplified, there are no means by which total reported rainfall can be partitioned into “effective” rainfall and rainfall that is lost to evaporation or leaf interception. The extent that

Fig. 3. Model-derived irrigation intervals for pecan were plotted as a function of the day of the year in four soil types. Each point represents the period of time to the next model-scheduled irrigation corresponding to the day of the year of the previous irrigation. Regression functions were used to derive intervals listed on the irrigation scheduling tool.

rainfall contributes to changes in soil moisture depends on when in the growing season and irrigation cycle it occurs. Pecan trees in this region do not attain full leaf expansion until mid to late May. Rain occurring before then has a greater opportunity to contribute to soil moisture due to reduced ET and reduced leaf interception. After full leaf expansion, some portion of rain is intercepted by leaves and is transported by deflection to the soil below the margins of the canopy, or evaporates from the leaf surface, especially in the case of light showers in the summer months. However, days with rainfall tend to be cooler, resulting in lower ET, which in itself may compensate for the effect of leaf interception and surface evaporation. The assumption built into the water balance model is that all of the station-reported rainfall contributes to soil moisture, which may lead to an overestimation, especially in the summer months.

Another assumption of the model is that water infiltration and drainage of soil moisture in excess of water holding capacity occurs within a single 24-h timestep. Any quantity of rainfall occurring immediately after a scheduled irrigation is allocated largely to drainage. In reality, for some fine-textured soils, excess rain or irrigation water may stand on the surface for up to 72 h, contributing to sustained field capacity moisture content in the root zone for several days. These simplifications can lead to an underestimation of root zone soil moisture, especially for fine-textured soils. In contrast, even the smallest quantities of rain occurring near the end of the dry-down cycle cause the model to delay the irrigation by a day or more. In reality, the majority of light rain at the end of the dry-down cycle may never penetrate more than a few inches below the surface, and is probability lost to surface evaporation in less than 24 h. These simplifications may lead to an overestimation of root zone soil moisture.

There was no simple method to quantify and account for these soil moisture overestimations and underestimations in deriving the rainfall versus irrigation delay relationship. Because the model is tailored to mature pecans with >70% canopy closure, a reasonable estimation of effective rainfall would be in the range

of 75% to 80% of the total. The overall linear regression (Fig. 4), which is ≈ 3 d delay for every inch of rain, represents delay as a function of total rainfall. Ultimately, an irrigation delay metric needs to be simple and easy to remember and use in arithmetic computations. Erring on the side of caution, we devised the “1 d increase for every 1/2 inch of rain” rule. Using this rule, users would measure rainfall accumulated at their location with a rain gauge. If accumulations exceed 1/2 inch for the duration of the tool-defined interval, the irrigation could then be delayed, but if accumulations for the interval were less than 1/2 inch, the user would ignore the rule. Fractional values would always be rounded to the next highest integer. Users that choose not to delay intervals with rainfall will obviously overirrigate.

TOOL DESCRIPTION. The tool is comprised of a printed card with the irrigation interval data for the four representative soil types arranged

horizontally and listed below their corresponding calendar dates. The card slides through a printed jacket with cut-out windows, instructions, and arrows to guide the user to the correct information. Also included on the tool is a description of the rainfall rule, and a table for calculating acre-inches of water to apply per irrigation based on acreage, soil type, and irrigation water salinity. The tool user slides the card through the jacket to the position where the calendar date corresponds to his last irrigation, and reads the irrigation interval from the line corresponding to his soil type (Fig. 5).

We evaluated four prototypes of the tool to determine a format that would be easiest for the growers to use and understand: 1) a wheel, with interval data for each soil type arranged radially, which spun inside a jacket with cut-out windows aligning date with the interval; 2) a line graph of the intervals for each soil type as a function of calendar date printed on a card that slid through a

Fig. 4. The difference, or delay (in days), between model-scheduled irrigation intervals for pecan without rainfall and the modeled intervals that resulted by sequentially adding reported rainfall from the National Climate Data Center (NCDC) weather station to the model. Delays were recorded using water holding capacities for the four representative soil types and climate data for each year included in the dataset. The linear regression for all soil types and all rainfall for the years in the data set is shown with the solid line. The rainfall rule, where the tool user adds 1 d to the recommended interval for every 1/2 inch of rainfall accumulated during the interval, is represented by the dashed line and accounts for rainfall lost to leaf interception and leaf surface evaporation (1 inch = 25.4 mm).

Fig. 5. The printed version of the pecan irrigation scheduling estimator tool, with the irrigation interval data for the four representative soil types arranged horizontally and listed below their corresponding calendar dates on a sliding card, and information about delaying irrigations with rainfall accumulations. The user slides the card through a printed jacket with cut-out windows that align the calendar date corresponding to his/her last irrigation, and reads the irrigation interval from the line corresponding to his/her soil type (1 inch = 25.4 mm).

jacket, which had a narrow cut-out window aligning date with line position and the y-axis scale printed on the jacket; 3) a vertical list of the interval data printed on a card that slid through a jacket; 4) and a horizontal list of the interval data as described above. The prototypes were presented to the general public at the Southern New Mexico State Fair, to local pecan growers attending a New Mexico State University (NMSU) sponsored field day, and to various individuals attending or employed at NMSU. Study participants were guided through the operations necessary to obtain the information using each prototype and then completed a short written survey to evaluate performance and rank preferences. The

horizontal and vertical prototypes were favored over the wheel and graph.

TOOL VALIDATION. With regard to scheduling accuracy, tool-scheduled irrigations were, on average, within 1 to 2 d of model-scheduled irrigations across all soil types, with the greatest inaccuracies occurring at the beginning and end of the growing season (Fig. 6). Generally, the tool-scheduled irrigations were early before full leaf expansion, late during the spring when temperatures are highest and relative humidity is lowest, slightly early during the summer monsoon season, late again in late summer, and then early in the fall. Delaying irrigations with the rainfall rule resulted in greater scheduling

accuracy, lower variability, and the elimination of one to two irrigations in the coarser-textured soils.

The averaged annual soil moisture depletion (across all years and soil types) was $45.14\% \pm 8.2\%$ when using the rainfall rule, and $43.5\% \pm 10.11\%$ when the rainfall rule was ignored. The cv was 18.2% with the rainfall rule delay and 23.3% without the rainfall rule delay. There were no significant differences when soil type and rainfall rule delay were considered separately.

Overall, the model-estimated annual loss in ET (the cumulative annual difference between stressed and nonstressed ET) resulting from irrigations scheduled late using the tool was less than 1% of the

Fig. 6. Averaged differences (days early or late) in pecan irrigations scheduled with the irrigation scheduling tool and irrigations scheduled by the volume balance model. Differences were recorded using water holding capacities for the four representative soil types, and climate data for each year included in the dataset, with the rainfall rule (solid bars) and without the rainfall rule (shaded bars). Error bars represent 1 SD.

average nonstressed ET of 52.8 inches (data not shown). As expected, ET losses were greater in the coarse-textured soil, with lower water holding capacity, than in the fine-textured soil. Differences ranged from less than 0.1 inch to 0.4 inch on fine-textured soils, from less than 0.3 inch to over 1.1 inch on coarse-textured soils.

LIMITATIONS OF THE CROP COEFFICIENT FUNCTION. Mathematically, k_c is derived by dividing measured daily ET by the estimated ET_o , and is usually expressed in terms of a relationship to an environmental parameter (cumulative GDD) or a time parameter (day of year) via a regression function. The function may be further stratified by tree age, trunk diameter, or percentage of canopy closure. The danger in using a fourth order polynomial to describe this relationship is that when the explanatory variable is cumulative, the year-to-year range can be large and exceed regression function's ability to describe the relationship properly for any year. An example of this is shown in Fig. 7.

The daily ET_o values for 1994 were higher than in 1991 for most of the year (Fig. 7A). The climate data for 1994 were not included in the calendar development dataset because of record-breaking high temperatures. The cumulative GDD for that year was 2817 °F. In contrast, 1991 was a cool, wet year with a cumulative GDD of 2182 °F (Fig. 7B). With this cumulative difference of 635 °F (25% of the data set mean cumulative GDD of 2487 °F) there is a counterintuitive effect on the value of the model-computed k_c (Fig. 7C). A higher cumulative GDD for 1994 resulted in a k_c that falls precipitously after day 260, whereas a low cumulative GDD results in a perpetually high k_c after day 260. Consequentially, the model computed late-season ET values abnormally high for 1991 and low for 1994.

Some of the high variability in the late season irrigation interval data points shown in Fig. 3 can be attributed to this effect. Although there is a balanced mix of hot and cool years in the dataset, and the derived irrigation interval function may have compensated for some of this error, our analysis has shown that this error has a stronger bias in

hot years, contributing to increased irrigation interval periods, than decreased interval periods in cool years.

Conclusions

Producing a simplified irrigation scheduling calendar to circumvent labor-intensive soil moisture

Fig. 7. Systematic error resulting from the polynomial pecan crop coefficient. (A) daily potential evapotranspiration (ET_o) for a high temperature record breaking year (1994) and a cool and wet year (1991). (B) Cumulative daily growing degree days for 1991, 1994, and average for all years included in the dataset. The average did not include 1994. (C) Daily crop coefficient (k_c) derived with a fourth order polynomial as a function of growing degree days for 1991, 1994, and the average for all the years included in the dataset where ET_c is pecan evapotranspiration [1 inch = 25.4 mm, $(°F - 32) \div 1.8 = °C$].

monitoring involves balancing a number of trade-offs. The tool needs to be conservative enough to minimize potential crop damage in hot dry years, yet accurate enough to minimize unnecessary irrigations. The information must be simple, straightforward, and readily understood; and versatile so that missing information can be easily interpolated. Ultimately, it must provide a low-risk compromise between managing crop water in response to environmental variability with sensors or simply guessing when to irrigate. The basic problem addressed in this calendar development process was determining the extent to which a 15% to 20% year-to-year variability in daily atmospheric demand for water translates into variability in model-scheduled irrigations, and how that variability in model-scheduled irrigations affects the accuracy of the calendar. Clearly, the availability of high-quality local meteorological data has made development of this tool possible.

The tool developed was tailored for managing flood-irrigation in mature pecan orchards. The rapid application rate of flood irrigation is conducive, albeit simplistically, to a 24-h timestep model. For sprinkler or drip irrigation methods, more complex transport functions may be required to model infiltration and lateral water movement in that time framework. Alternatively, water infiltration and extraction could be considered over longer timesteps, but such a model would require more generalizations to account for climate variability and would therefore increase risk.

Tailoring the tool to account for different orchard maturity is also possible. Crop coefficient scaling factors have been developed for younger orchards with smaller canopy cover (Wang et al., 2007). However, we chose to avoid including additional scaling factors to reduce complexity.

Literature cited

- Al-Jamal, M.S., T.W. Sammis, J.G. Mexal, G.A. Piccioni, and W.H. Zachritz. 2002. A growth-irrigation scheduling model for wastewater use in forest production. *Agr. Water Mgt.* 56(1):57–79.
- Blaney, H.F. and E.G. Hanson. 1965. Consumptive use and water requirements in New Mexico. Tech. Rpt. 32. New Mexico State Engineer Office, Santa Fe.
- Enciso, J. and B. Wiedenfeld. 2005. Irrigation guidelines based on historical weather data in the lower Rio Grande Valley of Texas. *Agr. Water Mgt.* 76:1–7.
- Garrot, D.J., M.W. Kilby, D.D. Fangmeier, S.H. Husman, and A.E. Ralowicz. 1993. Production, growth, and nut quality in pecans under water stress based on the crop water stress index. *J. Amer. Soc. Hort. Sci.* 118(6):694–698.
- Hanson, B., L. Schwankl, and A. Fulton. 1999. Scheduling irrigations: When and how much water to apply. University of California Irrigation Program, Water Management Ser. Publ. No. 3396, University of California, Davis.
- Hill, R.W. and R.G. Allen. 1996. Simple irrigation scheduling calendars. *J. Irr. Drainage Eng. Amer. Soc. Civil Eng.* 122(2):107–111.
- Kallestad, J.C., T.W. Sammis, J.G. Mexal, and J. White. 2006. Monitoring and management of pecan orchard irrigation: A case study. *HortTechnology* 16(4): 667–673.
- Malm, N.R. 2003. Climate guide, Las Cruces, 1892 to 2000. New Mexico State University Agr. Expt. Sta. Res. Rpt. 749.
- McGuckin, J.T., C. Mapel, R. Lansford, and T.W. Sammis. 1987. Optimal control of irrigation scheduling using a random time frame. *Amer. J. Agr. Econ.* 69(1):123–133.
- Meyer, S.J., K.G. Hubbard, and D.A. Wilhite. 1989. Estimating potential evapotranspiration: The effect of random and systematic errors. *Agr. For. Meteorol.* 46:285–296.
- New Mexico Department of Agriculture. 2004. Pecans: Orchards, acreage, and production by county. 15 June 2006. <http://www.nass.usda.gov/nm/nmbulletin/62_04.pdf>.
- Raes, D., A. Sahli, J. Van Looli, N. Ben Mechlia, and E. Persoons. 2000. Charts for guiding irrigation in real time. *Irr. Drainage System* 14(4):343–352.
- Raes, D., M. Smith, E. De Nys, K. Holvoet, and A. Makarau. 2002. Charts with indicative irrigation intervals for various weather conditions. 25 Sept. 2006. <<http://www.fao.org/ag/Agl/aglw/ias/docs/paper3.pdf>>.
- Rieger, M. and J.W. Daniell. 1988. Leaf water relations, soil-to-leaf resistance, and drought stress in pecan seedlings. *J. Amer. Soc. Hort. Sci.* 113(5):789–793.
- Sammis, T.W., E.G. Hanson, C.E. Barnes, H.D. Fuehring, E.J. Gregory, R.F. Hooks, T.A. Howell, and M.D. Finkner. 1979. Consumptive use and yield of crops in New Mexico. *Water Resources Res. Inst. Rpt. No. 115*. New Mexico State University, Las Cruces.
- Sammis, T.W., C.L. Mapel, D.G. Lugg, R.R. Lansford, and J.T. McGuckin. 1985. Evapotranspiration crop coefficients predicted using growing degree days. *Trans. Amer. Soc. Agr. Eng.* 28(3):773–780.
- Sammis, T.W., J.G. Mexal, and D. Miller. 2004. Evapotranspiration of flood-irrigated pecans. *Agr. Water Mgt.* 69: 179–190.
- Sanden, B. 2006. Management and monitoring of almond irrigation in Kern County. *Kern Soil and Water*, Apr. 2006. 20 Sept. 2006. <http://cekern.ucdavis.edu/newsletterfiles/Kern_Soil_and_Water8849.doc>.
- Sanden, B., G. Poole, and B. Hanson. 2003. Soil moisture monitoring in alfalfa: Does it pay? 6 Oct. 2006. <http://ucanr.org/alf_symp/2003/03-53.pdf>.
- Skaggs, R. and Z. Samani. 2005. Irrigation practices versus farm size: Data from the Elephant Butte Irrigation District. *Water Task Force Rpt. 4*. New Mexico State University Coop. Ext. Serv. Las Cruces.
- Stein, L.A., G.R. McEachern, and J.B. Storey. 1989. Summer and fall moisture stress and irrigation scheduling influence pecan growth and production. *HortScience* 24(4):607–611.
- Thompson, A.L., J.C. Henggeler, D.L. Bockhold, and K.A. Sudduth. 2002. Comparison of eight irrigation scheduling tools on soybean and cotton. *Intl. Water Irr.* 22(3):24–30.
- U.S. Department of Agriculture. 2002. Census of agriculture, Geographic Area Series, Farm and Ranch Irrigation Survey for 2002 and 1997. 10 Sept. 2006. <http://www.nass.usda.gov/8080/Census/Create_Census_FRIS.jsp>.
- Wang, J., T.W. Sammis, A.A. Andales, L.J. Simmons, V.P. Gutschick, and D.R. Miller. 2007. Crop coefficients of open canopy pecan orchards. *Agr. Water Mgt.* 88:253–262.
- Woodroof, J.G. and N.C. Woodroof. 1934. Pecan root growth and development. *J. Agr. Res.* 49(6):511–530.