Development of a nomograph for scheduling irrigation for flood irrigated pecan orchards

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Abstract

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. In New Mexico, pecan (Carya illinoinensis) farmers in the Mesilla Valley have been reluctant to adopt soil-based or climate-based irrigation scheduling technologies. In response to low adoption rates, we have developed a conceptually simplified, low tech, practical irrigation scheduling tool specifically for flood-irrigated pecan production. The information presented in the tool which is presented as slide rule nomograph was derived using 14 years of archived climate data and model-simulated consumptive water use. Using this slide rule, 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 employing 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% coefficient of variation, 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.

Introduction

Compared to other crops grown in the Lower Rio Grande Basin, pecan trees have the highest consumptive water use (Blaney and Hansen, 1965; Sammis et al., 1979). 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 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

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This work was supported by the New Mexico Agriculture Experiment Station, and the Rio Grande Basin Initiative: Efficient Irrigation for Water Conservation agreement with the USDA Cooperative State Research Service under contract Nos. 2005-34461-15661 and 2005-4509-03209.

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 bi-weekly 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 (USDA 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; Thompson et al., 2002; Sanden et al., 2003).

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. 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.

ET calendars are primarily used in planning irrigation by employing 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.

Historical 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. Scheduling irrigation with historic ET has been advocated for some areas of California’s semiarid Central Valley (Hansen et al., 1999). Weekly ET calendars have been made available for California almond growers through the University of California Cooperative Extension (Sanden, 2006).

The objectives of this document are to describe the scheduling tool development and validation process for pecan irrigation scheduling, and 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 McGucken et al. (1987). In general terms, the volume balance model simulates daily available soil water in the rootzone by the relation:

$$SM_j = SM_i + USI_j + MSI_i + R_j - sf\left(ET_c\right)_i \qquad (1)$$

where the soil moisture content in the rootzone 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_i) 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 x ET_c falls below the relative moisture content determined by the user-specified management allowable depletion (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:

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

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 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 (OPEC) 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 (Rieger and Daniell, 1988; Garrot et al, 1993). 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:

$$\begin{aligned} &If\ sf = m\left(\frac{SM_{i\ j}}{whc_j}\right) + b > 1 \\ &then \quad sf = 1 \\ &else \quad sf = m\left(\frac{SM_{i\ j}}{whc_j}\right) + b \end{aligned} \qquad (3)$$

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 New Mexico, 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.

DATA QUALITY. Archived climate data from the PSRC weather station for the years1988 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 and only good data was used in the analysis. All rainfall data came from the NCDC weather station because it is a hand read station with a high reliability factor.

INTERVAL DERIVATION. Each year's daily meteorological data including ET_o and pecan-specific GDD data was 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 was set to 45%.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 4 soil water holding capacities and root depths corresponding to the 4 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.

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

Soil texture	Water holding capacity (inches/ft)	Beginning and maximum root depth (inches)	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

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 rainfall using a linear function. This process was conducted with each of the four water holding capacities corresponding to soil type.

Results and Discussion

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 Montieth 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.

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 Figure 1A, annual rainfall for the data set years is approximately 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 to 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 (Figure 1B).

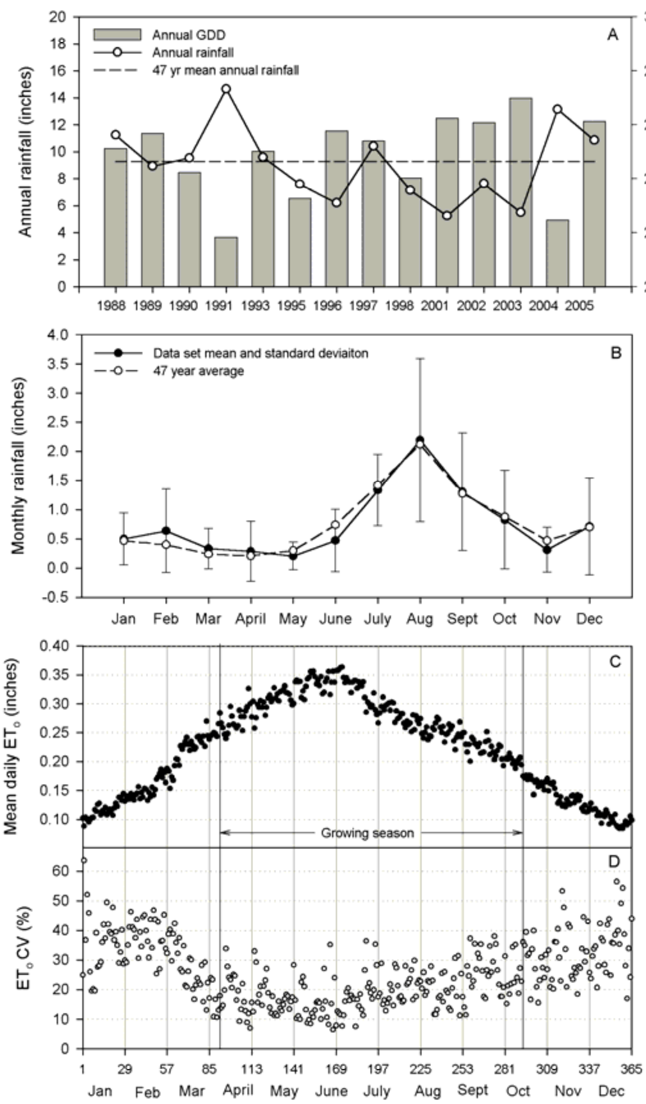

Figure 1. Synopsis of the meteorological data used in the development of the irrigation scheduling calendar. (A) Cumulative annual growing degree day (GDD) and rainfall data for years included in the data set, and 47-year average (1959 -2005) for annual rainfall. (B) Monthly rainfall averages for years included in the dataset, and 47-year monthly average. (C) Potential evapotranspiration (ET_o) averaged for each day from all years

included in the dataset. (D) Averaged coefficient of variation in daily ET_o, expressed as a percentage, for all years included in the dataset.

Daily ET_o averaged over the 14 years of the dataset for each date was fairly consistent (Figure 1C), with a year-to-year coefficient of variation (CV) for each day at approximately 20% in the beginning of the growing season, dropping to 15% mid-season, then rising to 20-25% at the end of season (Figure 1D). 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. In 2005 we found the soil moisture depletion computed by volume balance model in agreement with field measurements at 3 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 days throughout the growing season. Other than general field observations about pecan root systems (Woodroof and Woodroof, 1934), there is a scarcity of literature specifically 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 (Figure 2). 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 days in mid season. 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.

Post-harvest farm operations were considered when choosing an appropriate start date to begin model-scheduled irrigations. 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. We therefore forced the model to begin the irrigation sequence on March 15th. In a separate analysis, there was no difference in regressed intervals using different start dates.

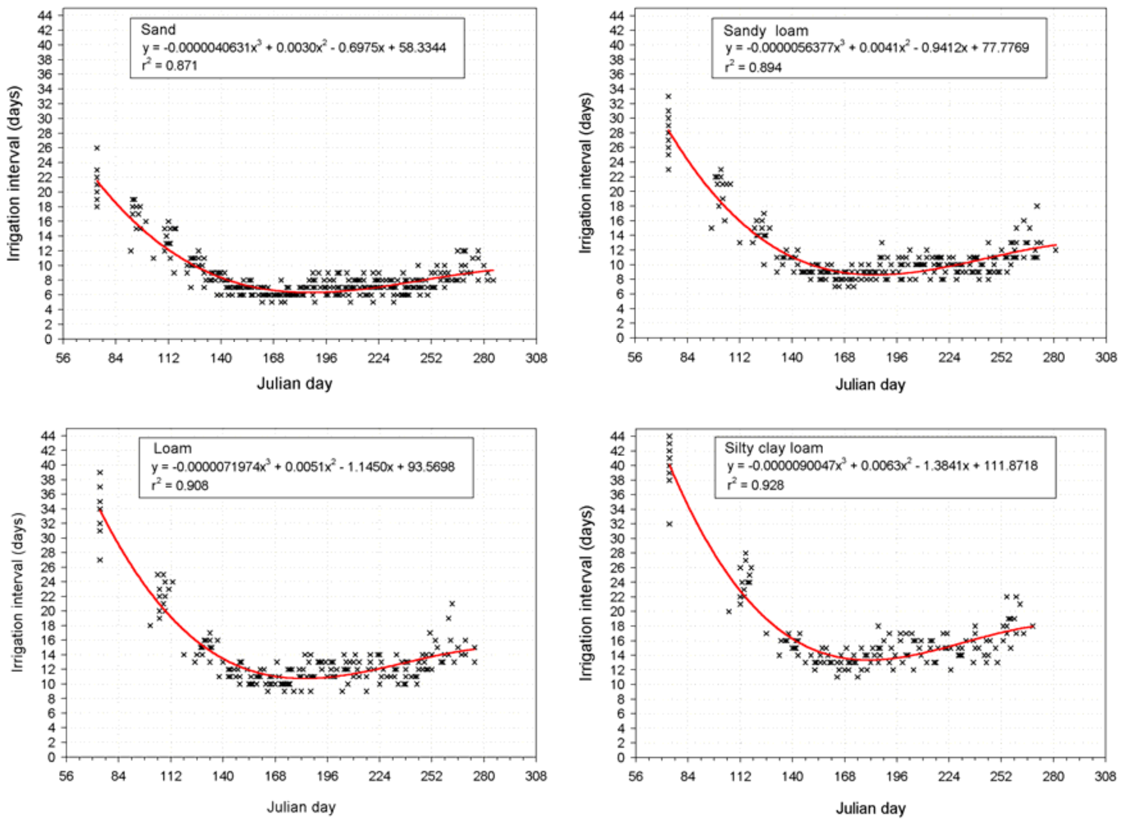

Figure 2. Model-derived irrigation intervals were plotted as a function of Julian date in four soil types. Each point represents the period of time to the next model-scheduled irrigation corresponding to the Julian date of the previous irrigation. Regression functions were used to derive intervals listed on the irrigation scheduling tool.

User-defined MAD is another source of uncertainty in the model. While 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 days in mid season, and longer at the beginning and end of the season.

RAINFALL RULE. The assumption built into the water balance model is that all of the station-reported rainfall contributes to soil moisture. Another assumption of the model is that water infiltration and drainage of soil moisture in excess of whc occurs within a single 24 hour time step. 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 hours, contributing to sustained field capacity moisture content in the root zone for several days.

The overall linear regression (Figure 3), which is approximately 3 days delay for every inch of rain, represents delay as a function of total rainfall. Erring on the side of caution, we devised the "one day increase for every half inch of rain" rule. Using this rule, users would measure rainfall accumulated at their location with a rain gauge. If accumulations exceed one half inch for the duration of the tool-defined interval then the irrigation could be delayed, but if accumulations for the interval were less than one half inch, the user would ignore the rule. Fractional values would always be rounded to the next highest interger. Users that choose not to delay intervals with rainfall will obviously over-irrigate.

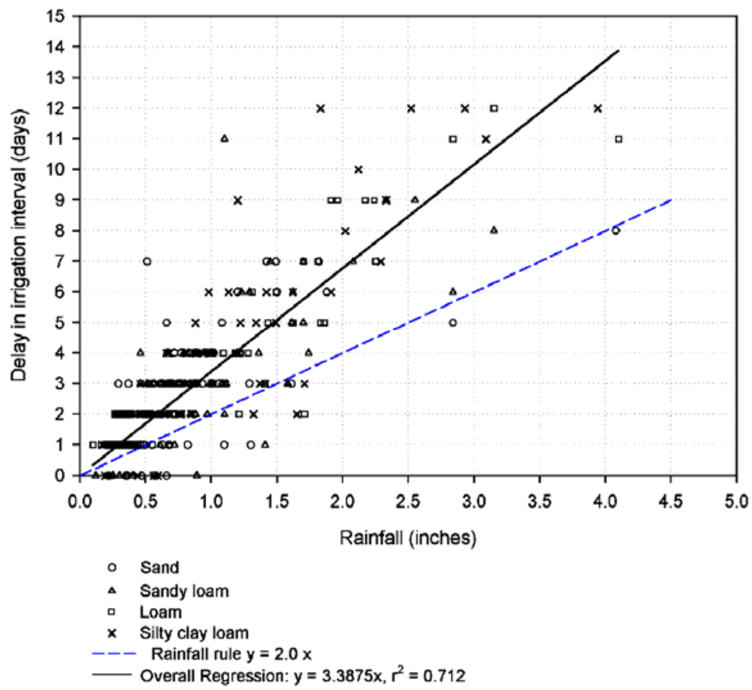

Figure 3. Model-derived irrigation intervals were plotted as a function of Day of the year for four soil types. Each point represents the period of time to the next model-scheduled irrigation corresponding to the Day of the year of the previous irrigation. Regression functions were used to derive intervals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

TOOL DECRIPTION. 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 (Figure 4).

Figure 4. The printed version of the 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 last irrigation, and reads the irrigation interval from the line corresponding to his soil type.

We evaluated 4 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 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 days of water balance model-scheduled irrigations across all soil types, with the greatest inaccuracies occurring at the beginning and end of the growing season (Figure 5). 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, then early in fall. Delaying irrigations with the rainfall rule resulted in greater scheduling accuracy, lower variability, and the elimination of 1 to 2 irrigations in the coarser textured soils.

The averaged annual soil moisture depletion (across all years and soil types) was 45.14 ± 8.2% when using the rainfall rule, and 43.5 ± 10.11% when the rainfall rule is ignored. The coefficient of variation 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.

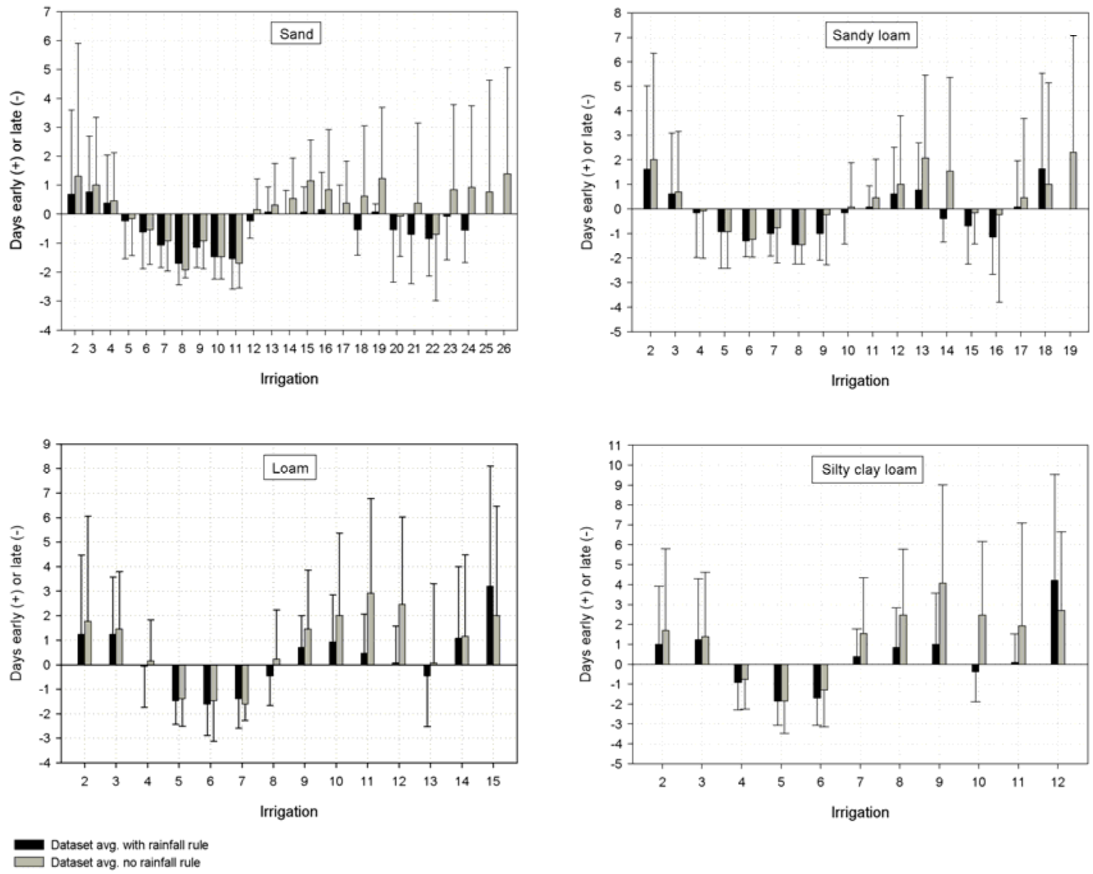

Figure 5. Averaged differences (days early or late) in irrigations scheduled with the irrigation scheduling tool and irrigations scheduled by the volume balance model. Differences were recorded using water holding capacities for the four representative soil types, and climate data for each year included in the dataset, with the rainfall rule (solid bars) and without the rainfall rule (shaded bars). Error bars represent one standard deviation.

Overall, the model-estimated annual loss in ET (the cumulative annual difference between stressed and non-stressed ET) resulting from irrigations scheduled late using the tool was less than 1% of the average non-stressed ET of 52.8 inches. As expected, ET losses were greater in the coarse texture soil, with lower water holding capacity, than in the fine textured soil. High estimated ET losses using the 1995 climate data occurred because summer monsoons were delayed approximately 4 weeks. High losses in 1996 resulted from higher spring temperatures and lower overall rainfall.

Conclusions

Producing a simplified irrigation scheduling calendar to circumvent labor-intensive soil moisture 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 either 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 24hr timestep model. For sprinkler or drip irrigation methods, more complex transport functions may 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.

References

Al-Jamal, M.S., T.W. Sammis, J.G. Mexal, G.A. Picchioni, 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(2005) 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.

Hill. R.W.,and R.G. Allen. 1996. Simple irrigation scheduling calendars. J. Irrig. Drain. Engrg., ASCE 122(2):107-111.

Kallestad, J.C., T.W. Sammis, J.G. Mexal, 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. Rep. 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.

Raes, D., A. Sahli, J. Van Looli, N. Ben Mechlia, and E. Persoons. 2000. Charts for guiding irrigation in real time. Irrig. Drainage Syst. 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. New Mexico State University, Las Cruces. WRRI Report No. 115.

Sammis, T.W., Mapel, C.L., Lugg, D.G. Lansford, R.R. McGuckin, J.T. 1985. Evapotranspiration crop coefficients predicted using growing degree days. Trans. ASAE 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, April 2006, University of California Cooperative Extension. 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.

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. International Water Irrigation 22(3):24-30.

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(2007):253-262.

Woodroof, J.G., and N.C. Woodroof. 1934. Pecan root growth and development. J. Agr. Res. 49 (6):511-530.