Monitoring and Management of Pecan Orchard Irrigation: A Case Study

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ADDITIONAL INDEX WORDS. ***Carya illinoiensis*, granular matrix sensor, tensiometer, pedotransfer function, irrigation scheduling, farm computer use**

SUMMARY. **Optimal pecan (*Carya illinoiensis*) production in the southwestern United States requires 1.9 to 2.5 m of irrigation per year depending on soil type. For many growers, scheduling flood irrigation is an inexact science. However, with more growers using computers in their businesses, and with soil moisture sensors and computerized data-collection devices becoming more inexpensive and accessible, there is potential to improve irrigation and water use efficiencies. In this project two low-cost soil monitoring instruments were introduced to a group of pecan producers. They were also given instruction on the use of Internet-based irrigation scheduling resources, and assistance in utilizing all of these tools to improve their irrigation scheduling and possibly yield. The objectives were to determine whether the technology would be adopted by the growers and to assess the performance of the sensors at the end of the season. Three out of the five growers in the project indicated they used either the granular matrix (GM) sensors or tensiometer to schedule irrigations, but compared to the climate-based irrigation scheduling model, all growers tended to irrigate later than the model's recommendation. Graphical analysis of time-series soil moisture content measured with the GM sensors showed a decrease in the rate of soil moisture extraction coincident with the model's recommended irrigation dates. These inflection points indicated the depletion of readily available soil moisture in the root zone. The findings support the accuracy of the climate-based model, and suggest that the model may be used to calibrate the sensors. Four of the five growers expressed interest in continued use of the tensiometer, but only one expressed a desire to use the GM sensor in the future. None of the participants expressed interest in using the climate-based irrigation scheduling model.**

New Mexico is one of the top three producers of improved-variety pecans in the United States, and production has increased five-fold in the last 30 years. In 2005, New Mexico produced 62 million pounds of high-quality improved-variety pecans that garnered the highest price per pound in the nation [U.S. Department of Agriculture (USDA), 2006]. According to the 2002 New Mexico agricultural census, more than 70% of the state's pecan production came from Doña Ana County, which had over 23,745 acres on 1056 farms (New Mexico Department of Agriculture, 2004).

Pecans naturally require large quantities of soil moisture to thrive (Sparks, 2002; Wolstenholme, 1979). In commercial pecan production, irrigation is one of the most important inputs affecting yield, especially in mature orchards (Garrot et al., 1993; Rieger and Daniell, 1988; Sparks, 1986; Stein et al., 1989). With all nutrients in sufficient supply it is ultimately non-water-stressed evapotranspiration (ET) that contributes most to carbohydrate production (Andales et al., 2006). Compared to other crops grown in the Lower Rio Grande Basin, where water is a scarce commodity, pecan trees have the highest consumptive water use (Blaney and Hansen, 1965). The amount of irrigation water required to produce a crop of pecans ranges from 1.9 to 2.5 m per year depending on soil type, with yearly ET measured at 1.31 m (Miyamoto, 1983) to 1.42 m (Sammis et al., 2004). In the interests of water conservation, the goals of growers and the research community have been to maximize irrigation application efficiency through proper design and operation of the irrigation system, and at the same time maximize water use efficiency and profitability through careful irrigation scheduling.

For pecan producers to increase irrigation application efficiency, it is critical to quantify the water applied, used in evapotranspiration, and lost to drainage. Estimating water applied during border irrigation is inexact at best. Border irrigation is a type of flood 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. In practice, farmers let water advance down the bordered plot a given distance from the end before closing the gate, or they will completely fill the bordered plot before switching the irrigation to the next bordered plot. This method typically over-irrigates the trees nearest the gate and may under-irrigate at the end of the run, although application efficiencies in flood-irrigated orchards in the Mesilla Valley of New Mexico have been reported as high as 89% (Al-Jamal et al., 2001). By using soil moisture sensors in their irrigation program, growers can better estimate when to schedule sufficient water to the end of the bordered plot and thereby increase water use efficiency. Quantifying the amount of water delivered over the entire plot, however, remains problematic for this type of irrigation.

For growers using computers for their business, there is potential to improve water use efficiency. The Internet has facilitated the collection and distribution of real-time, relatively local scale climate information. Grow-

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
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
0.4536	lb	kg	2.2046
1.1209	lb/acre	$kg \cdot ha^{-1}$	0.8922
(°F – 32) ÷ 1.8	°F	°C	(1.8 × °C) + 32

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ers connected to the Internet have access to this information and can apply it with relative ease to estimate crop ET and soil moisture depletion using a climate-based irrigation scheduling model found on the New Mexico Climate Center website (Sammis, 2006). In 2005, only 16% of New Mexico farms used computers for farm business, but 57% of farms in New Mexico had Internet access (USDA, 2005).

In recent years some soil moisture sensors and automated data-collection devices have become inexpensive and accessible. The quality of data generated from these new devices rivals that produced from expensive instruments formerly available only to the research community (Leib et al., 2003; Shock et al., 2001). Use of GM sensors has become a popular method for measuring soil water potential. Numerous manufacturers of automated irrigation control and soil moisture monitoring equipment have designed their systems to incorporate the GM sensor output (Shock, 2003). However, easy-to-use devices that automatically collect data, compute soil water content, display graphical output, and track the historical dynamics of soil water movement with each irrigation cycle can be prohibitively expensive, especially for small-scale farmers. For the computer-savvy growers there are significant cost-saving opportunities by using cheaper and simpler data loggers, and doing the data conversions and graphical analysis on their own computers. The trade-off is the time consumed in learning the technique and doing these manipulations. Using both of these climate-based and soil-based tools, growers can schedule irrigations according to crop consumptive use and site-specific soil water status.

In this project, two low-cost (<$250 for both) soil moisture monitoring instruments were provided to five intermediate- to small-scale pecan growers, along with instruction on the use of Internet-based irrigation scheduling resources. The objectives of the study were to determine if the farmers would adopt the technology, and to assess the performance of the GM sensors.

Materials and methods

PARTICIPANT SELECTION AND STUDY LOCATION. The Doña Ana County extension agent selected five small- to intermediate-scale pecan farmers based on their expressed interest in improving soil moisture monitoring, and whether they operated a computer as part of their farming operation. Each of the growers was initially contacted in person in Feb. 2005 to discuss the project. Later that month the instruments were installed in each grower's orchard. All of the participants of this study have farms located in the Mesilla Valley from Vado, N.M., to 8 miles north of Doña Ana, N.M.

INSTALLATION OF SOIL-BASED INSTRUMENTS. Each grower received two GM sensors (Watermark; Irrometer Inc., Riverside Calif.), four data loggers (HOBO H08-002-02; Onset Computer, Bourne, Mass.), and datalogger software (Boxcar 3.7; Onset Computer). Since these data loggers record a voltage signal, the input cable lead connected to the GM sensor (2.5 Stereo Cable; Onset Computer) was modified by adding a large resistor to reduce the voltage drop across the sensor and minimize data logger battery drainage. A 10-kiloohm, ¼-W, 0.1% tolerance metal film resistor (Mouser Electronics, Mansfield, Texas) was soldered to the cable leads as described by Allen (1999).

The GM sensors were buried according to the manufacturer's recommendations at approximately the middle of the root zone, 40- to 45-cm depth, at two locations in each orchard. To assess the unevenness of the irrigations in a single bordered plot, one GM sensor was installed between the first and second tree in a row closest to the irrigation turnout, and the other at the end of the plot between the last and second last tree in the same row. A row is defined here as the line of trees that run parallel to the direction of water flow and to the longitudinal soil borders. Interior rows were chosen to avoid edge effects. Since feeder root distribution has been shown to be evenly distributed between trees in a row, the sensors were placed equal distance between trees, approximately 4.6 m from the trunk.

Each grower received a pair of data loggers for each GM sensor; one to actively record data, the other to remain dormant until launched and swapped with the field loggers as they were collected for downloading. Data loggers were housed in gilled shelters to protect them from rain and direct sunlight. The shelters were fabricated from four 19-cm-diameter plastic salad plates, bolts, and polyvinyl chloride (PVC) tubing spacers.

Each grower also received one 18-inch tensiometer (model R or LT; Irrometer Inc., Riverside Calif.), which was placed approximately 1 m from the GM sensor at the end of the plot furthest from the turnout. Growers were given an estimated target soil moisture tension approximating 50% to 60% of field capacity (FC) based on the manufacturer's recommendations for soil texture, and on literature references (Curtis and Tyson, 1998; Paramasivam et al., 2000; Sammis, 1996a).

SENSOR DATA CONVERSIONS. The derivation of volumetric soil moisture from the GM sensor output required three mathematical conversions: converting logged voltage to resistance, converting resistance to soil matric potential, and converting matric potential to volumetric soil moisture using pedotransfer functions (PTF) specific to soil texture classifications. The resistance of the GM sensor was calculated using Eq. 1:

$$R = 10 \times V/(2.5 - V) \qquad \text{[Eq. 1]}$$

where R is the resistance (kiloohms), and V is the voltage recorded by the data logger (volts).

The resistance of the GM sensor was converted to soil matric potential using Eq. 2, developed by Shock et al. (1998):

$$\Psi_m = (4.093 + 3.213 \times R) \div (1 - 0.009733 \times R - 0.01205 \times T) \qquad \text{[Eq. 2]}$$

where Ψ_m is matric potential (kilopascals), R is the resistance of the sensor (kiloohms), and T is the average soil temperature (°C). We assumed that the soil temperature for this region was approximately 20 °C during the summer.

Farm soil texture classifications, on which water holding capacity and PTF were based, were determined by the growers, and verified using the Doña Ana County Soil Survey (Bulloch and Neher, 1980). However, typical of layered alluvial soils, considerable soil texture spatial variability, both vertically and horizontally, was observed within the plots at all locations. Soil pedotransfer functions, in the form described by van Genuchten (1980), (Table 1), were used to convert soil water potential to volumetric soil moisture. Empirically derived b-values and air entry potential values based on soil physical and hydrologic properties

Table 1. Pedotransfer functions for southwestern U.S. soils used in converting measured water potential Ψ_m (kPa) to volumetric moisture content θ_v ($m^3 \cdot m^{-3}$). Saturated moisture content θ_σ ($m^3 \cdot m^{-3}$), coefficient *a*, and the exponents *n* and *m* are empirically derived soil texture-specific constants.

Texture category	Pedotransfer function $\theta_v = \theta_s[1/(1 + a\Psi_m)^n]^m$
Clay	$0.524[1/(1+0.1393\Psi_m)^{1.0704}]^{0.0658}$
Clay loam	$0.489[1/(1+0.4556\Psi_m)^{1.1006}]^{0.0914}$
Silty clay	$0.517[1/(1+0.1532\Psi_m)^{1.0769}]^{0.0714}$
Silty clay loam	$0.517[1/(1+0.1651\Psi_m)^{1.0966}]^{0.0881}$
Silty loam	$0.518[1/(1+0.3489\Psi_m)^{1.1458}]^{0.1273}$
Silt	$0.564[1/(1+0.1958\Psi_m)^{1.1489}]^{0.1296}$
Loam	$0.474[1/(1+0.7375\Psi_m)^{1.1596}]^{0.1377}$
Loamy sand	$0.402[1/(1+1.9608\Psi_m)^{1.3501}]^{0.2593}$
Sandy clay	$0.455[1/(1+0.8666\Psi_m)^{1.3501}]^{0.0892}$
Sandy clay loam	$0.445[1/(1+1.1148\Psi_m)^{1.1347}]^{0.1187}$
Sandy loam	$0.422[1/(1+1.4225\Psi_m)^{1.2332}]^{0.1891}$
Sand	$0.386[1/(1+2.2523\Psi_m)^{1.4965}]^{0.3318}$

for southwestern U.S. soils were used in the PTFs (Israelsen, 1932; Sammis, 1996b). B-values and air entry potentials were derived according to Campbell (1985).

TECHNOLOGY TRANSFER. The growers were given instruction during demonstration, as well as a manual describing the steps to activate the data loggers, and to retrieve and import data logger text files into a spreadsheet program (Excel; Microsoft Corp., Redmond Wash.). The manual also described the steps to enter Eq. 1, Eq. 2, and Eq. 3 into the spreadsheet for converting the sensor voltage output into soil matric potential and soil moisture content. The manual contained blank worksheets for collecting tensiometer data, and listed contact information for the manufacturers of the equipment. For four of the five growers, the researcher manually installed a cumulative soil moisture spreadsheet file with the conversion equations on their computer. The growers then received instruction, and demonstrations on how this file was to be appended and used as the sole data source for graphing soil moisture depletion through time. The graph would allow the grower to extrapolate a future time when the soil moisture would reach a target of 50% to 60% of field capacity, and schedule the next irrigation. Growers were given the target volumetric soil moisture based on PTF for their soil texture.

The growers also received written instructions, and in some cases, a demonstration on their computer, on how to extract estimated pecan ET from the New Mexico Climate Center web site. Daily ET values listed on this site are computed from a climate-based model using Penman's reference ET, an empirically derived pecan crop coefficient, and regional weather data (Sammis, 1996c; Sammis et al., 2004). Using modeled ET along with a texture-based estimate of soil water holding capacity within a root zone of 3 to 4 ft, growers could estimate the amount of soil moisture lost to ET each day, or since their last irrigation.

POST-SEASON DATA ANALYSIS. Irrigation dates were deduced from time-series GM sensor data sets from three of the five growers for which we had complete season-long information. The actual irrigation dates were entered in the climate-based irrigation scheduling model and compared with the model's predicted irrigation dates. Model inputs and parameters were set to include soil water-holding capacity based on soil texture, root zone depth of 4 ft, an estimated 4.7 inches of water applied at each irrigation, and maximum allowable soil moisture depletion (MAD) of 45%. The model also had a soil moisture stress function that linearly decreased ET when MAD was less than 45% (Andales et al., 2006; Garrot et al.,1993). The cumulative difference between non-stressed ET and stressed ET was determined for each data set for the season and converted to yield loss using a water production function of 56.20 lb/acre per inch of lost ET (Sammis et al., 2004), and revenue loss based on an average in-shell price of $1.35/lb.

To assess the calibration of the GM sensors, the maximum measured soil moisture content immediately after each irrigation was compared to the predicted FC moisture content based on the PTF for that particular soil texture. In addition, the measured soil moisture contents at the model-predicted irrigation dates were checked for consistency across irrigation cycles, and correspondence to the predicted moisture content at the 45% MAD. The GM sensor data used in the analysis were taken from sensors located at the end of the border, furthest from the irrigation gate. Data from sensors nearest the irrigation gate were not included since the gates tended to leak, resulting in perpetually high moisture levels and peaks corresponding to irrigation in adjacent borders.

Results and discussion

TECHNOLOGY TRANSFER. The farmer participants in this study had diverse backgrounds, computer skills, and farming objectives. They owned and operated pecan orchards ranging from 10 to 278 acres, providing up to 100% of their income (Table 2). Their average age was 48.5 years, and all had some college education. Most considered themselves proficient on the computer (Table 3). However, the degree to which they utilized computers to perform and track farm business activities varied and did not correlate with age or farm size. Most did not keep a log of inputs, such as irrigation dates or fertilizer applications with their computer.

Most growers have relied on surface water for the majority of their irrigations when water was available. In recent years, drought conditions in the southwestern United States have forced the local irrigation district to reduce the allotment of surface water for irrigated agriculture. The balance of the water required to produce a pecan crop has come from pumping ground water. All of the participants in this study had their own wells and could irrigate as needed, but when surface water was available there could be a delay of a few days from the time of placing an order with the irrigation district office to the time of delivery. Previously, the growers had used calendar day, soil probe, and "moisture by feel" to schedule irrigations (Table 4). Some had previous experience using tensiometers, but none had

Table 2. Characteristics of the study participants related to the scale of farming operations, farming experience, and personal information gathered in interviews.

Grower no.	Age (yr)	Farming experience (yr)	Farm size (acres in pecan)[z]	Farm revenue (× $1000)	Proportion of personal income from pecan sales (%)	Education level[y]
1	48	27	171	>100	100	Some college
2	22	7	14	10–30	<1	BS
3	54	20	60	>100	10–50	BA
4	55	5	10.5	10–30	25	BS, some graduate school
5	64	35	280	>100	30	BSME

[z] 1 acre = 0.4047 ha.

[y] BS = Bachelor of Science; BA = Bachelor of Arts; BSME = Bachelor of Science in mechanical engineering.

Table 3. The responses of participants to questions regarding their computer use and skill level in personal interviews. Growers were asked if they used computers to conduct farm business: for accounting, to log crop inputs, to order farm supplies, to obtain weather information, or conduct business transactions online. Growers were also asked to rank their own computer skills in word processing, data analysis using spreadsheet and graphical software, and ability to communicate and retrieve information on the Internet.

	Computer use activity[z]					Computer skills[y]			
Grower no.	Track farm expense and revenue	Track farm inputs	Order farm supplies	Collect weather info	Interact with buyers and growers	Word processing	Spreadsheet	Graph data	E-mail and web browsing
1	Y	Y	S	Y	N	E	E	G	E
2	Y	N	N	N	N	E	E	E	E
3	N	N	N	N	N	C	C	C	G
4	Y	N	Y	Y	Y	A	A	C	G
5	Y	N	S	Y	N	E	E	A	E

[z] Y = yes; N = no; S = sometimes.

[y] E = excellent; G = good; A = average; C = challenged.

Table 4. Grower responses to post-season personal interview questions regarding irrigation scheduling, instrument use, and project evaluation.

	Response by grower				
Question	1	2	3	4	5
How have you previously scheduled irrigations?	Calendar, soil probe[y]	Calendar[z]	Calendar, moisture by feel[x]	Calendar, soil probe	Calendar, soil probe
Had you ever used a tensiometer to measure soil moisture before?	No	No	Yes	Yes	No
Had you ever used the climate-based irrigation scheduling model?	No	No	No	No	No
Did you use the GM sensors[w] to monitor soil moisture?	Initially	No	No	Yes	No
Did you use the tensiometer to schedule irrigations?	Yes	Yes	No	Yes	No
Did you keep a record of the tensiometer readings?	Initially	No	No	No	No
Did you use the on-line climate-based irrigation scheduling model?	Once	No	No	No	No
Did the person making the scheduling decisions also collect and analyze the data?	Yes	Yes	No	No	Yes
Which instrument was most useful?	Both	Tensiometer	None	Tensiometer	None
Will you use any of these methods to schedule irrigations in the future?	Yes	Yes	No	Yes	Maybe
Were you satisfied with the training you received?	Yes	Yes	Yes	Yes	Yes
How much could you spend on soil moisture sensing equipment on an annual basis?	$200–800	$275	$0	$600	$500

[z] Calendar scheduling = interval between irrigations is based on predetermined time.

[y] Soil probe = metal rod is pushed into the soil; resistance is proportional to soil dryness.

[x] Moisture by feel = moisture level is determined by touching soil core samples or excavated soil.

[w] GM sensors = Watermark granular matrix sensors.

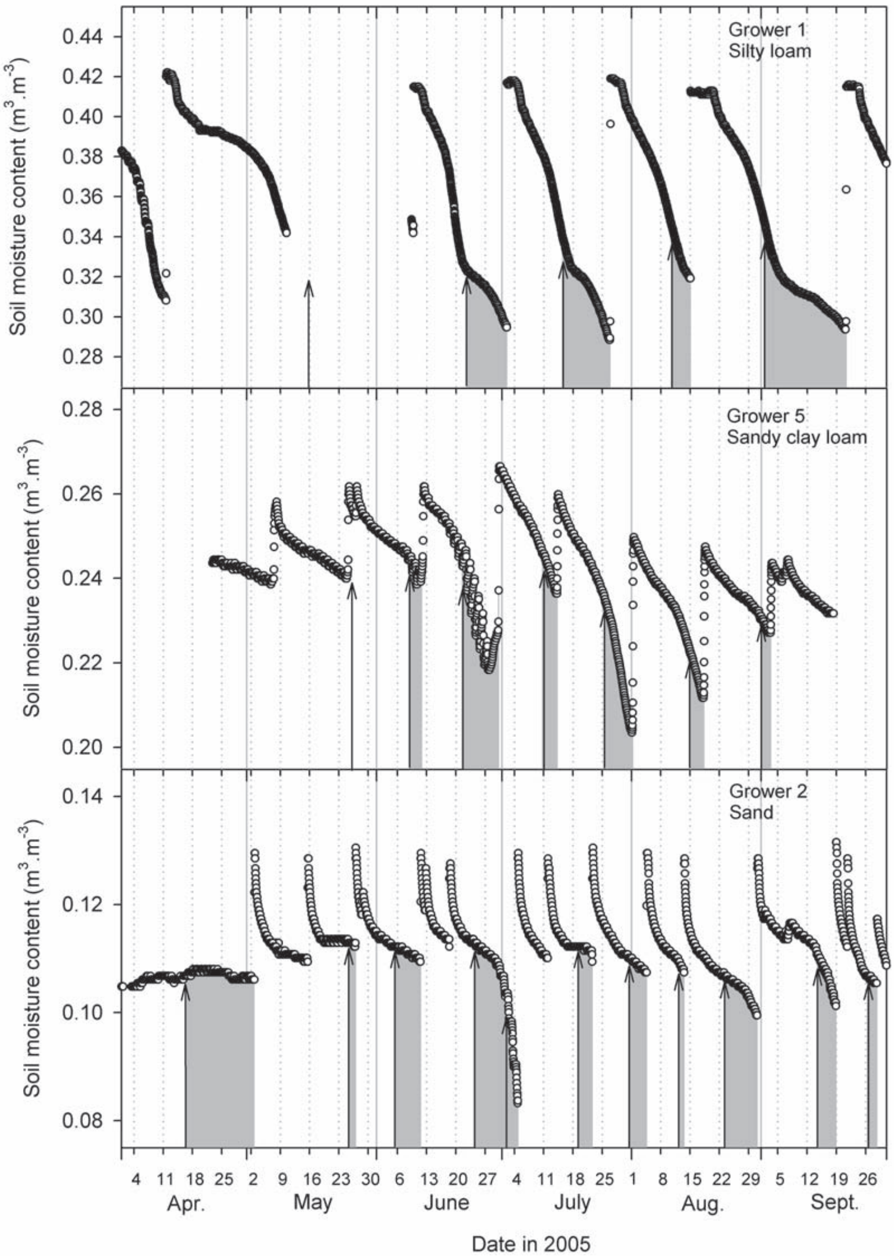

Fig. 1. Time series soil moisture content during the 2005 growing season at three pecan orchards measured with granular matrix sensors and data loggers. Open circles represent hourly soil moisture content readings from sensors located near the end of the bordered plot, furthest from the irrigation gate. Arrows indicate the next irrigation predicted by the climate-based irrigation scheduling model. Shaded areas represent periods of potential water-stress when soil moisture was below 45% maximum allowable soil moisture depletion.

used the climate-based model for estimating ET, even though it has been promoted and demonstrated at the Western Pecan Growers Conference held annually in Las Cruces N.M. and has been available on-line for more than 4 years.

At the conclusion of the season, growers expressed they had little time or patience to collect and manipulate GM sensor data on their computers, or to retrieve the estimated ET from the web site. Only one of five collected logged GM sensor data on a weekly or semi-weekly basis, graphically analyzed it, and used the information; two of five left the activated data loggers in the orchard for several months and never collected the data, even though they read the tensiometer adjacent to the GM sensor every few days. One of the growers was so frustrated and discouraged with his inability to manipulate data in a spreadsheet that he discontinued the project after 2 months. While three of five growers used the tensiometer information to aid in scheduling irrigations, none recorded the tensiometer readings, plotted the data on graph paper, or used the readings to predict a future date when the soil moisture potential would be at the prescribed target.

Even though the cost of the instruments used in this study was a fraction of the cost of more automatic systems, potential savings apparently did not provide incentive for growers to collect their data and do their own computational and graphical analysis. In cases where the tensiometer readings or GM sensor data were used, the timing of irrigations was allowed to go longer than the optimal interval predicted by the climate-based irrigation scheduling model (Fig. 1). Grower 1, who only used the tensiometer as an aid, was still 2 to 11 d late in scheduling irrigations, except in September when an entire irrigation was missed. The cumulative difference between non-stress ET and stressed ET was 11.0 inches, which translates to a theoretical yield loss of 619 lb/acre, and revenue loss of $840/acre. Grower 2, who also used the tensiometer as an aid, irrigated at an interval consistent with the model during the beginning of the growing season. However, after May he was 4 d late, and appeared to have skipped an irrigation in late June. The cumulative difference in non-stress ET and stressed ET was 3.3 inches, equivalent to 186 lb/acre of lost yield, or $250/acre in lost revenue. Grower 5 used neither the tensiometer nor the GM sensors to schedule irrigations, and irrigated 2 to 8 d late for most of the growing season except in the month of May. The cumulative difference in non-stress ET and stressed ET was 5.4 inches, equivalent to a theoretical yield loss of 303 lb/acre, or $410/acre in lost revenue. Overall, the estimated loss in revenue exceeded by a factor of 4 to 14 the cost of the equipment or hiring a consultant to schedule irrigation at a fee of $60/acre.

The reported overall in-shell yields for 2005 were 2315 lb/acre for Grower 1, 1778 lb/acre for Grower 2, and 2680 lb/acre for Grower 5. Local yields in mature, well managed, non-stressed orchards typically exceed 3300 lb/acre in an “on” year. However, many factors affect actual yield including: alternate bearing, tree age, tree spacing, pruning

Table 5. Expected and measured volumetric soil moisture content (MC) at field capacity (FC) and at 45% of maximum allowable depletion (MAD) for three soil types. Expected values were derived from regional pedotransfer functions. Measured values are derived from graphed time-series granular matrix sensor data corresponding to maximal soil moisture (assumed to be field capacity) and MC on dates the irrigation scheduling model predicted 45% moisture depletion.

Grower		Expected MC ($m^3 \cdot m^{-3}$)		Measured MC ($m^3 \cdot m^{-3}$)	
no.	Soil type	FC	45% MAD	FC	45% MAD
1	Silty loam	0.37	0.27	0.42	0.32–0.33
5	Sandy clay loam	0.30	0.23	0.26	0.23–0.24
2	Sand	0.15	0.11	0.13	0.11

regime, prior water or nitrogen stress, and disease. In this study, the yield for the bordered plot at Grower 1's orchard was only 45% of the overall orchard yield. Trees in this block were over 30 years old, in need of pruning at the top of the canopy, and have recently produced low yields in both "on" and "off" years. Trees at Grower 2's orchard were severely water stressed in 2003 and 2004 to the point of early defoliation and severe branch dieback, and have yet to fully recover. In such situations, theoretical yield may not match actual yield even with sufficient irrigation at optimal timing.

While some frustration with learning how to use the equipment and computer programs was expected, some of the shortcomings of this project were due to poor communication that may stem from a lack of incentive. By the end of the season it was apparent that most of the growers had difficulty with the instruments and spreadsheet manipulations, but during the season only two of the growers communicated any problems to the researcher or the county agent by phone or email. To minimize lost time and resources in future studies we recommend the following criteria for selecting grower participants: 1) Motivation to collect data needs to come from the grower's desire to increase profits, and the proportion of personal income dependent on pecan sales should exceed 50%. 2) The person making the irrigation scheduling decisions needs to have demonstrated computer skills in spreadsheet programs. 3) Most importantly, future outreach programs should be less neutral with regards to rewards and expectations. If growers were actually paid a monthly stipend for gathering the data like a technician they would be obliged to record the data and solve the technical problems when they arose. The research community needs to include such stipends in grant proposals.

TECHNOLOGY ASSESSMENT. Regardless of which soil moisture potential sensor is used, calibration is a constant concern. Soil temperature, clay content and mineralogy, excessive sand content, salinity, and hysteresis can affect the transportability of calibration functions across soil types. In this study, we assumed the electrical resistance to matric potential equation (Eq. 2) was universal across soil textures. This is reasonable since, in theory, the GM sensor has its own matric potential and should operate independent of soil texture. However, it has been shown that in coarse textured soils, where there is potentially poor contact at the soil-sensor interface, the calibration equations may need to be modified (Irmak and Haman, 2001). Equation 2 was actually derived using data produced by the GM sensor situated in a silt loam soil (Shock et al., 1998).

Since we recommended a target volumetric moisture content for 45% MAD based on a soil texture-specific PTF at each site, it was important for the sensor output to reasonably concur. However, this method resulted in some substantial discrepancies between expected and measured values, but in two of the three cases for which we collected complete data, there was modestly close agreement (Table 5). One source of potential error was in the assignment of a single texture-specific PTF, when in fact, the soil profile in the root zone at each site was layered and non-uniform. Other potential sources of error include the use of a fixed soil temperature in Eq. 2, and possible poor soil contact with the sensor in the sandy soils. However, the greatest discrepancies were found in the silty loam soil.

Clearly, calibration of each GM sensor at each location to absolute moisture content values by thermogravimetric methods and multi-step regression would be far too time-consuming to be practical. We propose that the grower or irrigation manager set a target moisture content for each sensor based on the climate-based irrigation scheduling model's recommended irrigation dates. The measured moisture content on those dates would represent the target maximum allowable soil moisture depletion based on consumptive water use for the whole orchard.

Post-season analysis of the time-series GM sensor data (Fig. 1) indicated that, in many cases, the rate of soil moisture depletion slowed on or near the model-recommended irrigation dates. If the actual irrigation was missed or delayed, the rate of moisture depletion became more rapid as the moisture content decreased, suggesting that readily available soil moisture in the middle root zone (where the sensor was located) was depleted and the moisture gradient between the middle and lower root zone had increased. This correlation also implied that the model's parameters and assumptions were fairly accurate, which was further supported by the relatively consistent moisture content observed on all modeled irrigation dates throughout the season. These results support our proposal that the model may be used to calibrate the sensors if the sensors are placed in the middle of the root zone and in a location where the moisture status is representative of the whole plot. However, given the sensitivity of the GM sensor to soil temperature (Shock et al., 1998), this type of calibration may need to be reset in the summer months.

Given the outcome of this project and the comments from participants, any improvement for future implementation of these tools needs to focus on simplicity. We suggest the following: 1) some data manipulation steps should be eliminated by developing template spreadsheets and macro programs that automatically convert logger voltage to volumetric moisture content, and graph the time series data. The growers should only need to import, copy, and paste the data logger file into the template. 2) Information on the irrigation scheduling model web page needs to be simplified and more specialized to local pecan production. It was not clear whether the web site was too difficult to navigate, or growers had an inherent distrust of modeled values. An alternative way this information could be accessed by the growers is for a regular column to appear in the daily newspaper, written by the county extension office, with crop irrigation information based on the irrigation scheduling model. Daily and cumulative ET for a variety of crops along with a recommended interval between irrigations for each crop in a few soil types could be reported as a guide.

Conclusions

We had negligible success at transferring these cost-saving soil moisture monitoring technologies to growers because: 1) many participants did not have the skills in spreadsheet programs as they had claimed; 2) many participants did not have a substantial financial incentive to improve yield; 3) most participants needed continued help through the learning phase but did not communicate this with the research and extension community; 4) there were too many steps involved in data procurement and analysis; 5) the recommended target moisture content for scheduling irrigation based on PTFs did not agree fully with the GM sensor output, creating added confusion about data interpretation. All of the growers in this study understood conceptually that better management of water inputs could translate into higher yields. While three out of five growers indicated they had used either a GM sensor or tensiometer to schedule irrigations, they all irrigated 2 to 11 d late throughout the season based on modeled ET dates. The estimated revenue lost based on theoretical yield exceeded the cost of the equipment or irrigation consultant fees.

By utilizing a functional calibration based on a threshold soil moisture depletion computed using the climate-based ET model, growers or irrigation consultants may avoid scheduling errors that would arise if GM sensors were calibrated to an inaccurate absolute moisture content using a PTF.

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