YIELD RESPONSE TO WATER IN IRRIGATED NEW MEXICO PECAN PRODUCTION: MEASUREMENTS & POLICY IMPLICATIONS

R. Skaggs[1]
Z. Samani[2]
A.S. Bawazir[3]
M. Bleiweiss[4]

ABSTRACT

Pecans are a major agricultural crop in New Mexico. Currently there are approximately 11,000 hectares of pecans in the Elephant Butte Irrigation District, consuming more than one third of the annual diversion. The research presented here provides previously unavailable broad-scale estimates of pecan ET and pecan yield response to water. The data at the foundation of this paper were generated using the Regional ET Estimation Model (REEM) developed at New Mexico State University for agricultural and riparian vegetation (Samani et al. 2005, 2006, 2007). REEM uses remotely sensed satellite data to calculate ET as a residual of the energy balance. This research extends the results of REEM to an analysis of yield response to water in irrigated pecan production in the EBID. The study region is rapidly urbanizing and experiencing growing competition for scarce surface and groundwater supplies. The results of this research provide new insight into pecan water use and yields. This research illustrates the linkages that can be made between remote sensing technology, farm-level water management, and yield outcomes. This research sheds new light on the long-standing practice of deficit irrigation in pecans, the yield and conservation impacts of this practice, as well as water conservation policy implications.

ACKNOWLEDGEMENTS

This research is part of the "Efficient Irrigation for Water Conservation in the Rio Grande Basin" project (a joint project of the Texas A&M University System Agriculture Program & New Mexico State University). This research was also supported by the New Mexico Governor's Water Innovation Fund, the New Mexico Agricultural Experiment Station, Western Pecan Growers' Association, the U.S. Environmental Protection Agency, the U.S. Geological Survey, and the New Mexico Water Resources Research Institute.

[1] Professor, Agricultural Economics & Agricultural Business, New Mexico State University, Las Cruces, NM 88003 USA. rskaggs@nmsu.edu
[2] Professor, Civil Engineering, New Mexico State University, Las Cruces, NM 88003 USA. zsamani@nmsu.edu.
[3]Assistant Professor, Civil Engineering, New Mexico State University, Las Cruces, NM 88003 USA. abawazir@nmsu.edu.
[4] Science Specialist, Entomology, Plant Pathology, and Weed Science, New Mexico State University, Las Cruces, NM 88003 USA. mbleiwei@nmsu.edu.

INTRODUCTION

The need for accountability by water resource users is increasing worldwide and is especially acute in the western United States, where more than 90% of the region's water is consumed by irrigated agriculture. The West's population and economy are growing and diversifying, and there is pressure to transfer water to non-agricultural uses, including municipal, industrial, recreational, and environmental. It is commonly assumed that agricultural irrigation wastes large quantities of water due to inefficient tools and technologies. It is often further assumed that reducing inefficiencies in agricultural water use will result in supplies of freshwater that can be reallocated to other sectors, or used in expanding agricultural output. Adjudication of water rights is also underway in many basins throughout the West, where state-level water managers are seeking to define, verify, and formalize water resource property rights.

Adjudications often involve quantification of water consumed through evapotranspiration (ET) in the process of crop production. Basin-wide ET accounting is now feasible as a result of recent advances in remote sensing technology. Remote sensing has made it possible to combine ground measurement of ET with large scale remotely sensed satellite data and ground level climatological data to arrive at regional values of ET. This combination of ground-level and remotely sensed data provides the most advanced and cost-effective approach to estimating ET over large areas with non-uniform, field-level crop production conditions. Remote sensing also provides a means to assess the degree to which crops are produced under water deficit conditions, provides insight into consumptive use thresholds, and allows for predictions of the potential outcomes of conservation efforts or investments designed to improve an irrigation system.

The research presented here provides previously unavailable broad-scale estimates of pecan ET and the pecan water production function in southern New Mexico. The data which form the foundation of this paper were generated using the Regional ET Estimation Model (REEM) developed at New Mexico State University for agricultural and riparian vegetation (Samani et al. 2005, 2006, 2007). REEM uses remotely sensed data to calculate ET as a residual of the energy balance. This paper extends the results of REEM to an analysis of the yield response to water in irrigated pecan production in southern New Mexico, specifically within the Elephant Butte Irrigation District. The results of this research provide new insight into pecan water use and yields. This research illustrates the linkages which can be made between remote sensing technology and farm-level water productivity analysis. This research also sheds new light on the long-standing practice of deficit irrigation, as well as the yield and conservation impacts of this practice. The research results lend new insight into the true "thirst" of southwestern pecan production, and the hydrological and policy impacts of pecan water use in the region.

IRRIGATED PECAN PRODUCTION IN SOUTHERN NEW MEXICO AND PREVIOUS RESEARCH

The pecan tree (*Carya illinoinensis*) is native to the southern United States, and is the only native tree nut grown for commercial use in the United States. The pecan is an alternate bearing tree, with a deep and phreatophytic rooting habit (Sparks 2005). Commercial pecan production is dispersed throughout 14 states, with the major production occurring in Georgia, Texas, and New Mexico. The United States is the world's largest pecan producer, although pecans rank number three in total U.S. tree nut production behind almonds and walnuts. Pecans are traded internationally, with the United States and Mexico accounting for almost all world exports.

The pecan industry is important to the Southwest, and especially in New Mexico. Pecans ranked fourth in New Mexico's cash receipts for agricultural commodities in 2003, behind milk, cattle and hay (USDA-NASS 2003). Pecans are a high value crop, and unlike the other leading U.S. pecan-producing states, all New Mexico nut production is from improved rather than native varieties. More than 70% of New Mexico's pecan production occurs in the south-central region of the state, along the Rio Grande, in the Elephant Butte Irrigation District (EBID), also home to the Las Cruces, NM metropolitan area and several smaller towns and settlements. Pecans are also grown in the Rio Grande Valley in the nearby El Paso, TX metropolitan area.

Pecan trees in the EBID account for a large proportion of the region's consumptive use of limited ground and surface water supplies. Pecan trees also have significant aesthetic value in the rapidly urbanizing river corridor, and are grown across the spectrum of farmers (e.g., lifestyle or rural residential as well as commercial growers of all sizes). The 2002 U.S. Census of Agriculture identified 10,514 hectares of pecans in the study region; this is approximately one third of the region's irrigated farmland. Surface water in the District is supplemented by ground water on some, but not all, farms. Most of the EBID is irrigated via traditional basin or basin-furrow methods (with no runoff from the end of the field), and on-farm efficiency (crop consumptive use relative to farm delivery) can be very high as a result of deficit irrigation practices. Efficiencies are also high as a result of level basins and short advance times on heavy soils. For example, Samani and Al-Katheeri (2001) used on-site flow measurement and chloride tracing and found basin and basin-furrow irrigation efficiency to be as high as 95% for pecans. Al-Jamal et al. (1997) also used chloride tracing and found efficiencies ranging from 70-76% for chile pepper fields, 77-80% for onions, and 97% for alfalfa. Deras (1999) applied the same methods and found on-farm efficiencies ranging from 79-98% for pecans, 87-98% for alfalfa, 88-87% for cotton, 89-97% for corn, and 83-94% for chile peppers.

The conventional wisdom is that pecans are a particularly thirsty tree, and require more irrigation water to maximize yield than any other crop grown in the Southwest U.S. (Sammis et al. 2004), that pecan water use is greater than that of most row crops (Andales et al. 2006), and that pecans naturally require large quantities of soil moisture to thrive (Kallestad et al. 2006). Given the steady and growing competition for water resources in the Southwest, the question of how much water is needed or consumed by pecan trees in the region has been studied extensively throughout the years. Miyamoto (1983) provides a brief summary of earlier researchers which found that mature trees in Brownwood, TX and the El Paso, TX – Las Cruces, NM region require 18 cm per month during the summer, and may consume as much as 130 cm per season, and usually between 68 and 100 cm per season depending on tree size. Miyamoto (1983) extended this research in the El Paso – Las Cruces region using the soil water depletion method, and determined that the seasonal (1 April through 15 October) consumptive use of full-grown trees ranged from 100-130 cm for close-spaced, full-grown trees.

Worthington et al. (1987) found seasonal (April through October) consumptive water use in one mature pecan orchard in El Paso, TX was 109 cm, while seasonal consumptive water use in a younger orchard was 27 cm. These researchers used lysimeters and Class A evaporation pan techniques. Steinberg et al. (1990) used weighing lysimeters to measure water use of young pecan trees in Stephenville, TX. Daily ET for these immature trees measured during the month of August was 8.8 mm. Frias-Ramirez (2002) estimated ET using the water balance method in a Las Cruces, NM commercial pecan orchard in 1996-1997. The seasonal ET estimated was 112 cm in 1996 and 102 cm in 1997.

Sorensen (1997) used the water balance method and a computer model to estimate ET in a Las Cruces area commercial pecan orchard in 1994 and 1995. From the water balance method, the yearly estimates for two sites were 269 cm and 216 cm in 1994 and 206 cm and 399 cm in 1995. Sorensen (1997) reported that his calculated ET was overestimated due to underestimation of drainage. His estimates of ET on two sites using the Arizona Scheduling System (AZSCHED) were 109 cm and 118 cm in 1994, and 108 cm and 134 cm in 1995.

More recently, ET in a mature, commercial pecan orchard south of Las Cruces was studied intensively by Sammis et al. (2004) in 2001 and 2002. Using the one-propeller eddy covariance and energy budget methods, these authors found that the seasonal (April through November) ET measured in 2001 was 126 cm and 117 cm in 2002. Annual ET measured in 2001 was 146 cm and 137 cm in 2002. The yields measured by the farmer/owner of the research orchard were 2349 kg/ha in 2001 and 3681 kg/ha in 2002.

Reveles (2005) used one-propeller eddy covariance and energy budget techniques to measure pecan ET in 2004 in a large commercial orchard located south of Las Cruces. An annual pecan ET of 139 cm was estimated for 2004, after adjustments for missing data.

Although extensive pecan ET research has been conducted over the last 25 years, all previous research is site-specific, and clearly dependent upon production conditions at each farm or orchard studied. The feasibility of extending these research results spatially or temporally over an entire production region is problematic, given the extreme variability in pecan orchards at the farm level. Excluding Sorensen’s (1997) self-described over-estimates, previous research has found a fairly narrow range of pecan ET. The most recent Sammis et al. (2004) and Reveles (2005) annual results ranged from 137 cm to 146 cm. However, the two orchards from which these results were obtained are intensively managed orchards, both part of the region's largest commercial pecan farming operations. The management characteristics of these farms are distinctly different from the majority of pecan farms in New Mexico's Elephant Butte Irrigation District.

Furthermore, although researchers have investigated pecan tree water consumption, there has been very little research on pecan water production functions, i.e., the relationship between yield and water applied to or consumed by the pecan tree. Thus, there is a large gap in our knowledge of the economic outcomes of water consumed in pecan production. Sammis (Undated) attempted to address this knowledge gap using ET results reported by Miyamoto (1983) to derive a pecan water production function. Sammis (Undated) assumed that the dry yield of pecans was similar to that of alfalfa, and arrived at the following water production function (WPF) for pecans (in his original units): $Y = -27 + 50.5\ ET$, where Y = yield in pounds/acre and ET is in inches. Even assuming that this derived water production function relationship for pecans is correct (i.e., the dry yield assumptions hold), this WPF is subject to the spatial and temporal limitations of Miyamoto's (1983) original experimental data.

Pecan tree water consumptive use is currently a subject of intense debate in the state of New Mexico. As shown in Figure 1 below, EBID pecan acreage has grown significantly since 1960, as the acreage shares of other historically important crops such as cotton have shrunk. The current water rights adjudication process has yet to determine each crop's duty of water; however, pecans are believed to be the most water-needy crop, and are also relative newcomers to the region's irrigated agricultural economy. Numerous water resource stakeholders and managers in the region currently are demanding to know the nature of agriculture's water use, the outcomes achieved as a result of each crop's water use, and the degree to which water can be conserved by agricultural irrigators.

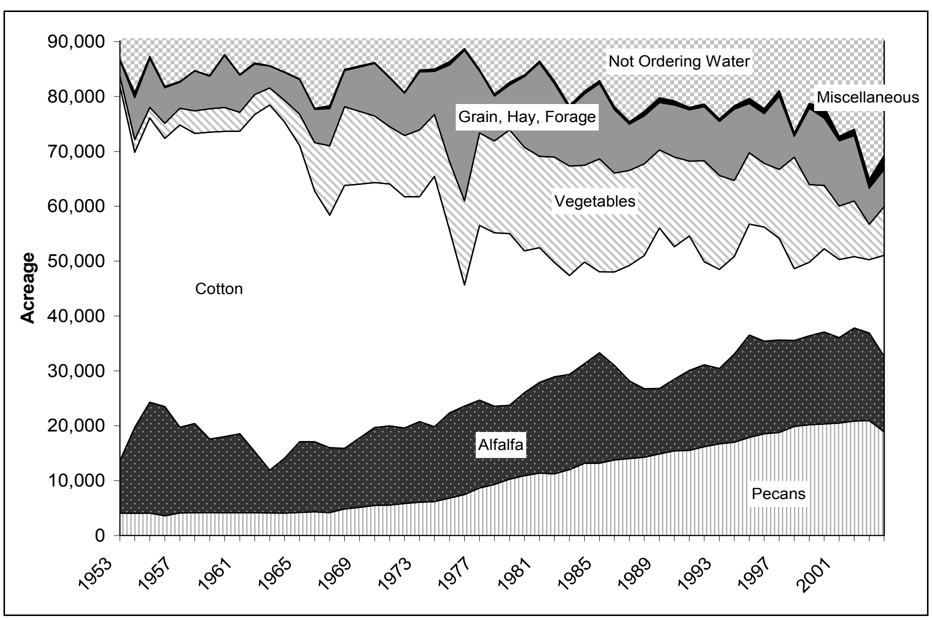

Figure 1. Changes in irrigated acreage in New Mexico's Elephant Butte Irrigation District, 1960-2004. Source: EBID.

METHODS AND PROCEDURES FOR BROAD SCALE ESTIMATES OF PECAN CONSUMPTIVE USE

Over the last two years, the boundaries of 228 mature pecan orchards (≥10 acres) in the Elephant Butte Irrigation District were delineated using the 2005 Digital Orthophoto Quarter Quadrangle (DOQQ) maps. REEM estimates of monthly ET in these orchards were generated for 2002.[5] Figure 2 shows the distribution of total annual REEM-calculated ET for these orchards. As shown in Figure 2, there is a high degree of variability in ET across the 228 orchards. The maximum annual ET found was 131 cm (4.27 feet) while the minimum was 66.7 cm (2.19 feet). The average ET weighted by land area was 105.2 cm (3.45 feet). Eighty-five percent (n = 213) of the orchards had total annual ET ranging between 80.1 and 120.0 cm. It was noted above that the Sammis et al. (2004) and Reveles (2006) research was conducted on orchards which belong to intensively managed, large, commercial pecan farms. The ET results of these previous studies place these farms into the far right-hand tail of the distribution of broad-scale pecan ET estimated through REEM. Clearly, these previously researched farms are not representative of typical pecan consumptive use in the EBID. As will be shown below, the yield outcomes of these model farms are also atypical.

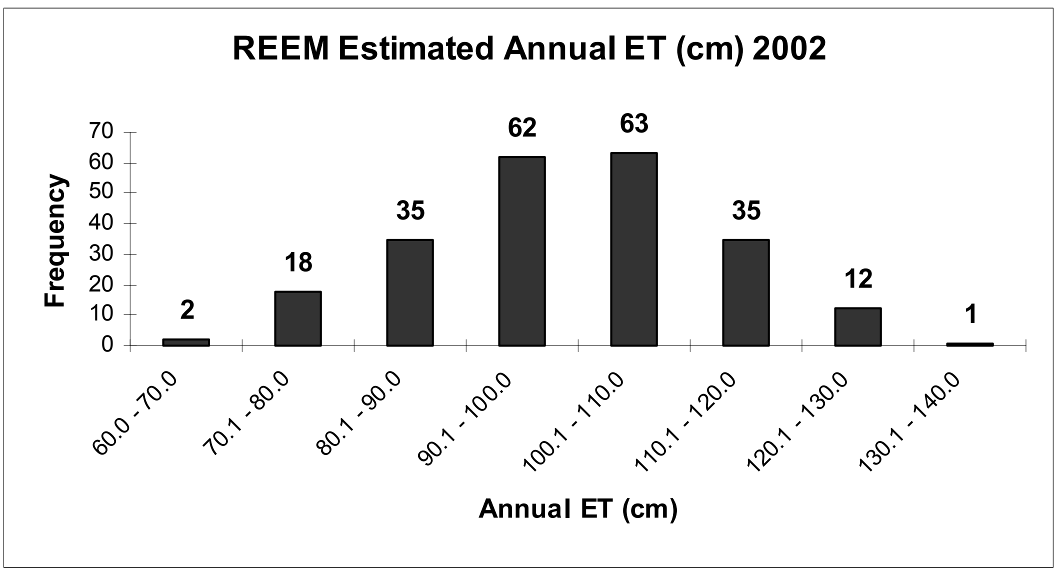

Figure 2. Annual pecan ET by farm (n = 228), Elephant Butte Irrigation District, New Mexico, 2002, estimated using REEM (Samani et al. 2005, 2006, 2007).

THE RELATIONSHIP BETWEEN WATER AND CROP YIELDS

Much research effort has been expended and much literature has been published on crop-water relations. Extensive experimental work has resulted in numerous water production functions which represent yield response as a function of water applied (e.g., Hexem and Heady 1978). These production functions have been used to predict yields under a range of soil, climate, and management conditions and are often used in irrigation project

[5] Technical information about REEM can be found in Samani et al. 2005, 2006, 2007.

planning to aid in optimal water use decision making and to derive estimates of irrigation water demand. Water production functions can be simple two-variable functions where all other inputs are assumed to be held constant, or they can incorporate different levels of another key input, such as fertilizer. Complex water production functions which include several inputs other than water (e.g., fertilizer, soil characteristics, varieties, stand density, etc.) as well as interaction effects, are relatively rare, given the high cost of generating the necessary experimental data. Complex water production functions derived using experimental data from long-lived perennial tree crops are extremely rare.

As noted above, remote sensing technology now provides the means to assess ET across large areas, on potentially hundreds of farms or parcels. ET results for 228 pecan farms presented in Figure 2 above illustrate that the results of such an analysis. Unfortunately, data to characterize the relationship between ET and yields over large areas are not as readily available. Farmers typically are reluctant to disclose their on-farm yields and often consider requests for such information to be invasions of their privacy. Even when yields are reported, there are numerous reasons why farmers may either under- or over-report their actual crop yields.

Doorenbos and Kassam (1979) have suggested that the relationship between yield and ET is generally linear. They note differences in the linear relationship between crops and recommend that the relationship be defined in terms of maximum potential ET and yield in order to account for differences in climate, crop variety, etcetera. Their formula,

$$(1 - Ya/Ym) = ky(1 - ETa/ETm) \tag{1}$$

where:
- Ya = actual harvested yield
- Ym = maximum harvested yield
- ky = yield response factor
- ETa = actual evapotranspiration
- ETm = maximum evapotranspiration,

relates relative yield decrease to relative ET deficit through an empirically-derived yield response factor (ky) estimated from analysis of experimental field data. A ky of 1.0 means that for the total growing period, yield deficits are directly proportional to ET deficits, a ky of less than 1.0 indicates that the decrease in yield is proportionally less than the increase in the ET deficit, and a ky of greater than 1.0 means that yield decreases are proportionally greater than increases in ET deficit. Doorenbos and Kassam (1979) indicate that in most cases 80-85% of yield variation due to different water treatments can be explained using the relationship shown in equation (1).

Knowledge of ky provides insight into the yield cost of limited water supply to the growing crop. In order to estimate ky, yield data must be obtained experimentally, or accurate yield information must be forthcoming from producers. In this research, remotely sensed parcel-level estimates of crop ET were combined with yield information obtained from a small group of producers. Simple regression techniques were applied to the available yield and ET data to reveal ky for pecans in the broader study region.

EMPIRICAL DERIVATION OF AN ET-YIELD FUNCTION FOR SOUTHERN NEW MEXICO PECANS

Operators of ten geographically dispersed pecan parcels for which ET estimates were calculated using REEM provided reliable yield information to this research project. Both the yields and the estimated ETs for the ten orchards were normalized, and subjected to simple regression analysis, such that (1 – Ya/Ym) = f(1-ETa/ETm), where Ya and ETa are actual yield and ET and Ym and ETm are maximum yield and ET. The parcel with the highest REEM-calculated ET was established as the maximum ET value, this parcel also had the highest reported yield. The data points for the "maximum ET" farm are plotted at the origin, because for this observation Ya = Ym and ETa = ETm.

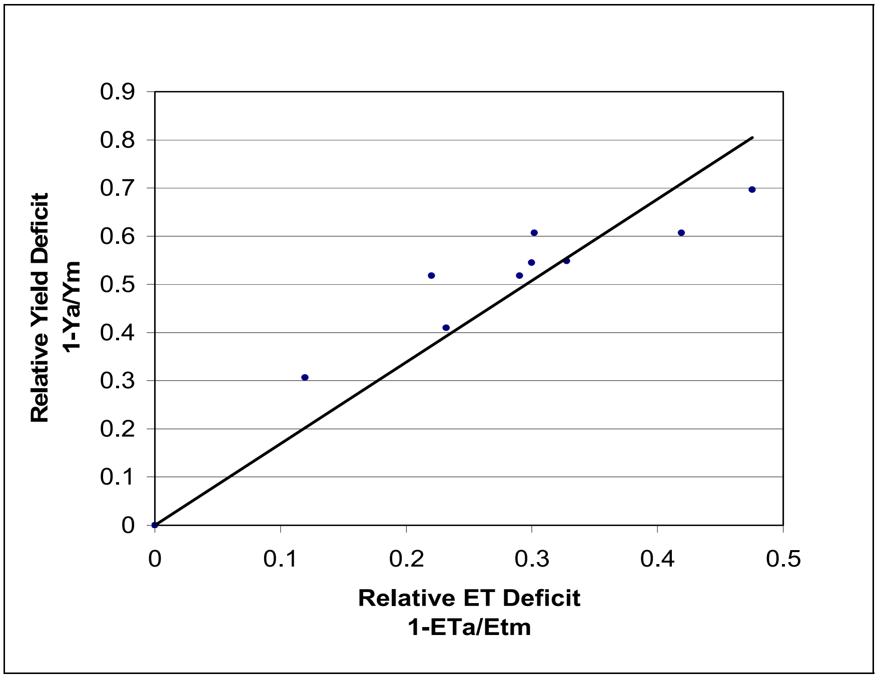

Figure 3. Linear function of relative yield deficit vs. relative ET deficit, 10 pecan orchards, Elephant Butte Irrigation District, New Mexico, 2002.

When the normalized relative yield deficit is regressed on the normalized relative ET deficit in a linear function, the result is shown in equation (2). The R^2 value for this equation was 0.82, thus these results are consistent with Doorenbos and Kassam (1979) findings of the simple equation's ability to explain water-related yield variation.

$$(1 - Ya/Ym) = \underset{(SE = 0.09)}{1.692}*(1-ETa/ETm), \quad n = 10, \; R^2 = 0.82 \qquad (2)$$

The constant slope coefficient (1.692) of equation (2) is ky. This coefficient is the yield penalty which results from pecan consumptive water use at less than the regional maximum obtained under field, not experimental, production conditions. If a pecan orchard is experiencing a 20% ET deficit (i.e., it is being irrigated such that the trees are consuming 80% of the water they are able to consume), then there is a 34% yield penalty (i.e., actual yield is 66% of potential yield). This high ky value indicates a high sensitivity to water deficit, and places pecans in the same category as bananas, maize, and sugarcane with respect to yield response to water deficit (Doorenbos and Kassam 1979). While the simple function with constant ky provides previously unavailable insight in pecan yield response to water, it does not capture yield responses to water deficits in different growth phases, and thus represents the ET-yield deficit relationship over the total growing period.

There are clearly both large yield costs and decreased water use efficiency from deficit irrigation of pecans. REEM results indicate that of the 228 orchards (covering 5,842.7 hectares) analyzed, 90% (or 205) had ET deficits greater than 10% in the year of analysis (relative to the most well-watered orchard found among the 228). Assuming that all 228 orchards actually *could be* irrigated at the level found on the most well-watered and highest yielding commercial production orchard, what is the total yield "cost" of deficit irrigation? It is estimated that the yield cost on these orchards as a result of deficit irrigation is 5,931 metric tons. Relative to actual 2002 pecan production, the state's pecan crop would have been more than 36% larger if the yield potential had been reached in 2002 (USDA-NASS 2003). At the 2002 season average price of $2.76/kg, the value of lost production would be almost $16.4 million. There is currently no information available to indicate that such an increase in production would result in a significant decrease in nut price paid to pecan producers, thus we have used the season average price to value the yield cost. Given the total size of the New Mexico pecan crop (16,329 metric tons in the 2002, and 24,948 metric tons in 2003), this yield cost is large from an industry perspective.

If all 228 orchards studied in this project were technologically and financially able and willing to decrease their ET deficits as a result of timely and accurate application of irrigation water in accordance their tree's water needs, pecan yields in the region would likely increase. However, total consumptive use of water by pecans in the region would also increase. Using the results and analysis presented above, we estimate that total consumptive use by the 228 orchards studied would increase by approximately 14.5 million m^3 (or 11,755 ac-ft) if the orchards were well-watered. Thus, current low levels of water productivity and deficit irrigation practices are actually resulting in a relatively large water savings.

SUMMARY, CONCLUSIONS AND IMPLICATIONS

The native range of pecan trees follows the river bottoms of the Mississippi River and its tributaries and the rivers of central and eastern Texas and their tributaries (Sparks 2005). As a result, pecans are a thirsty tree. Nut size and kernel development in pecan trees is also especially sensitive to soil moisture availability (Sparks undated). In this research, ET for 228 pecan orchards was estimated using a model which incorporates remotely sensed data. Reliable nut yields for a small number of orchards were used to develop a function relating ET and yield deficits in the study region. Using the methods of Doorenbos and Kassam (1979), a strong relationship between ET deficit and yield deficit was found and the total yield cost and total ET deficit for 228 orchards was estimated.

This research illustrates value of remote sensing procedures and models in deriving broad-scale consumptive use estimates. Estimates derived from a single farm or from a small sample of farms cannot comparably represent basin-wide consumptive use. This is due to field-level variability in production, management, and irrigation system characteristics. Previous research by Skaggs and Samani (2005a, 2005b) found extremely long irrigation durations, inefficient irrigation practices, inadequate irrigation infrastructure, and lack of interest in making improvements to the current irrigation system or methods on smaller, non-commercial pecan farms in the Elephant Butte Irrigation District. These findings were attributed to the nature of residential/lifestyle or retirement agriculture in the study region. In addition, Kallestad et al. (2006) reported on a project that introduced a small group of the region's pecan producers to soil monitoring instruments and internet-based irrigation scheduling resources, with the objective of improving irrigation and water use efficiencies in the interest of water conservation. Kallestad et al. (2006) indicated that they had negligible success in transferring the soil moisture monitoring technologies to growers for several reasons, including because the growers lack a substantial financial incentive to improve yields.

On-farm application efficiencies on commercial farms in the study region have been found to be relatively high, and basin-wide water balance analysis shows that little irrigation water escapes consumptive use somewhere in the basin. This phenomenon occurs because any upstream water users' "sloppy" water management results in downstream water users' supplies, including legally-required deliveries of water from New Mexico to Texas. Although pecans have the *potential* to be a very thirsty crop, this research has found that few producers are actually achieving potential ET levels (and yields) in their orchards. The current operating and structural limitations of the EBID make it difficult for pecan producers to change their irrigation practices (i.e., through scheduling) if they rely heavily on surface water. Furthermore, most farmers with wells depend on shallow, partially saline groundwater. These farmers are reluctant to apply low quality water to their crops unless it is absolutely necessary. Many producers are not dependent upon pecan production (or farming) for their livelihoods, thus they do not appear to be interested in making significant changes in their on-farm irrigation systems (e.g., intensive scheduling, drip irrigation, ditch lining). The common property nature of those segments of the water delivery system not owned by the irrigation district creates an additional disincentive for investments and improvements by individual water users (Skaggs and Samani 2005a, 2005b). All these limitations mean that many pecan producers are not motivated to strive for or reach potential consumptive use and yields. Indeed, the majority of pecan producers studied in this research are well below ET and yield levels achieved by the region's leading commercial producers. Thus, we question the conventional wisdom that significant water conservation (and release of water for other sectors or users) will result if pecan producers "improve" their irrigation practices or technology.

Efforts to increase water "conservation" by EBID pecan producers through public and private investments designed to increase the ability of those producers to more accurately and effectively irrigate their trees will likely increase total consumptive use of water in the region. Examples of popular technical remedies conventionally believed to conserve water include drip irrigation, irrigation scheduling, and canal lining. From a pecan producer standpoint, these remedies would indeed "conserve" water, because yields and water productivity would increase. For other, downstream and/or future users, the increased "conservation" by pecan producers would likely increase net depletions and result in a severe reduction of their surface and ground water supplies.

REFERENCES

Al-Jamal, M. Salameh, T.W. Sammis and T. Jones. 1997. Nitrogen and Chloride Concentration in Deep Soil Cores Related to Fertilization. *Agricultural Water Management* 34:1-16.

Andales, A., J. Wang, T.W. Sammis, J.G. Mexal, L.J. Simmons, D.R. Miller and V.P Gutschick. 2006. A Model of Pecan Tree Growth for the Management of Pruning and Irrigation. *Agricultural Water Management* 84:77-88.

Deras, J.R.D. 1999. *Evaluation of Irrigation Efficiency and Nitrogen Leaching in Southern New Mexico*. Unpublished master's thesis, New Mexico State Department of Civil, Agricultural, and Geological Engineering.

Doorenbos, J. and A.H. Kassam. 1979. *Yield Response to Water*. Irrigation and Drainage Paper 33. Food and Agriculture Organization of the United Nations, Rome. Available online: http://www.fao.org/AG/AGL/aglw/cropwater/parta.stm.

Frias-Ramirez, J.E. 2002. *Physiological Model of Light Interception and Water Use in Pecan Trees*. Unpublished Ph.D. dissertation, New Mexico State University, Las Cruces, NM

Hexem, R.W. and E.O Heady. 1978. *Water Production Functions for Irrigated Agriculture*. Iowa State University Press, Ames, Iowa.

Kallestad, J.C., T.W. Sammis, J.G. Mexal and J. White. October-December 2006. Monitoring and Management of Pecan Orchard Irrigation: A Case Study. *HortTechnology* 15(4):667-673.

Miyamoto, S. 1983. Consumptive Water Use of Irrigated Pecans. *Journal of the American Society of Horticultural Science* 108(5):676-681.

Reveles, A. 2005. *Evapotranspiration of Mature Pecan Trees*. Unpublished Master's thesis. Department of Civil Engineering, New Mexico State University, Las Cruces, New Mexico.

Samani, Z. and N. Al-Katheeri. 2001. Evaluating Irrigation Efficiency in the Mesilla Valley. Paper presented to the American Society of Agricultural Engineers State Conference, Las Cruces, New Mexico.

Samani, Z., M. Bleiweiss, S. Nolin, and R. Skaggs. Regional ET Estimation from Satellites. In: Water District Management and Governance, Proceedings of the Third

International Conference on Irrigation and Drainage, United States Committee on Irrigation and Drainage, 2005, pp. 613-619. ISBN 1-887903-18-6.

Samani, Z., M. Bleiweiss, T. Schmugge, and R. Skaggs. Monitoring Water Use In the Rio Grande Valley Using Remotely Sensed Data. In: *Earth Observation for Vegetation Monitoring and Water Management,* Eds. G.D. Urso, M.A. Osann Jochum, and J. Moreno. Published by the American Institute of Physics, 2006. ISBN: 0735403465.

Samani, Z., A.S. Bawazir, R.K. Skaggs, M. Bleiweiss, V. Tran, and A. Piñon. Water Use by Agricultural Crops and Riparian Vegetation: An Application of Remote Sensing Technology. *Journal of Contemporary Water Research and Education* 137:8-13, September 2007. ISSN 1936-704X.

Sammis, T. Undated. Spreadsheet for Estimating the Amount of Nitrate-Nitrogen Loading to Groundwater and Irrigation Efficiency. Available online at the New Mexico Climate Center website: http://weather.nmsu.edu/nitrogenchloride/crops/Pecan-b3.xls.

Skaggs, R.K. and Z. Samani. 2005a. *Irrigation Practices vs. Farm Size: Data from the Elephant Butte Irrigation District.* Agricultural Experiment Station and Cooperative Extension Service Water Task Force Report #4, New Mexico State University.

Skaggs, R.K. and Z. Samani. 2005b. Farm Size, Irrigation Practices, and On-Farm Irrigation Efficiency. *Irrigation and Drainage* 54:43-57.

Sammis, T.W., J.G. Mexal and D. Miller. 2004. Evapotranspiration of Flood-Irrigated Pecans. *Agricultural Water Management* 69:179-190.

Sorenson, R.B. 1997. *Pecan Response to Irrigation Scheduled at 50% Available Water.* Unpublished Ph.D. dissertation. New Mexico State University, Las Cruces, New Mexico

Sparks, D. Undated. *Kernel Development in Pecan – A Function of Soil Water*. Department of Horticulture, University of Georgia, Athens, GA. Available online: http://www.geocities.com/CollegePark/Campus/3370/h20.htm?20078.

Sparks, D. August 2005. Adaptability of Pecan as a Species. *HortScience* 40(5):1175-1189.

Steinberg, S.L., J.M. Marshall, and J.W. Worthington. 1990. Comparison of Trunk and Branch Sap Flow with Canopy Transpiration in Pecan. *Journal of Experimental Botany* 41(227):653-659.

U.S. Department of Agriculture National Agriculture Statistics Service. 2003. *New Mexico Agricultural Statistics*. Issued cooperatively with the New Mexico Department of Agriculture.

Worthington, J.W., J. Lasswell and M.J. McFarland. 1987. Irrigation-The Tree's Perspective. *Pecan South* 21(1):4-8, 22-23.