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The Water Balance for Irrigated Pecans in Arid and Semi-Arid Environments: A Review

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Abstract

Despite the importance of irrigated pecan (*Carya illinoinensis*) production in arid and semi-arid regions of the U.S. and Mexico and the reliance of successful production on adequate and optimal management of water, the detailed water balance for irrigated pecan production is poorly understood compared to other important horticultural and agronomic crops. Our goal in this review is to summarize what is known about the water balance of irrigated pecans with an emphasis on flood irrigation (the most common irrigation method) and to identify research needs to improve our understanding of the water balance and how to better manage water for this very profitable and productive crop. We consider the following components of the water balance: 1) evapotranspiration (ET), 2) evaporation from the soil surface (E), 3) water stored in the soil profile (S), and 4) deep percolation (DP). ET represents the largest component of the water balance, comprising 60-90% of the water applied, depending on application methods and management. DP beyond the root zone represents the largest non-plant use component and depending on its original source and fate, can contribute to net groundwater recharge if from surface water, return flow if pumped originally from the groundwater, surface water return flow if moved horizontally and discharged to a stream or drain, or a net loss if moved horizontally and consumed by non-target plants. E represents a consumptive loss that reduces water use efficiency with respect to pecan production, though it can provide some cooling benefits in the orchard. It is generally a small, but not insignificant, quantity of the applied water (5-10%). There is considerable room for improving water use through alternative irrigation methods and/or improved water management.

1. Introduction

Pecan (*Carya illinoinensis*) is an important nut crop produced primarily in the southern region of the United States (US) for both domestic consumption and export, and in northern Mexico (MX), primarily for export. In recent years, production has increased in the southwestern US, especially in Arizona (AZ), New Mexico (NM) and Far West Texas (TX). In such arid areas, irrigation is necessary, with

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amounts for profitable pecan production often in the range of 1.5–2.0 m of water annually applied predominantly by flood irrigation, making pecan production the largest user of agricultural water in the region.

Despite the importance of adequate, good quality water and its management to successful pecan production, the detailed water balance for irrigated pecan production in arid and semi-arid regions of the US and MX is not quantified as precisely as for horticultural and agronomic row crops, due to methodological challenges. Our goal in this review is to summarize what is known about the water balance of flood-irrigated pecans and to identify research needs to improve our understanding of how to better manage water for this very profitable and productive crop.

To provide a framework for this review, we present in Fig. 1 a conceptual model of the water balance for irrigated pecans. The overall water balance is described by the following equation:

$$P + I + S = T_t + T_{nt} + e_s + e_L + \Delta S + LF + DP$$

where the inputs of water are summarized on the left side and the water losses/uses are summarized on the right side. Each individual component is also defined and illustrated in Fig. 1. In the following sections, we summarize what is known about the magnitude of these important components of the water balance and their related processes. We rely on literature plus our own experience, and we identify additional research needs in Section 8.

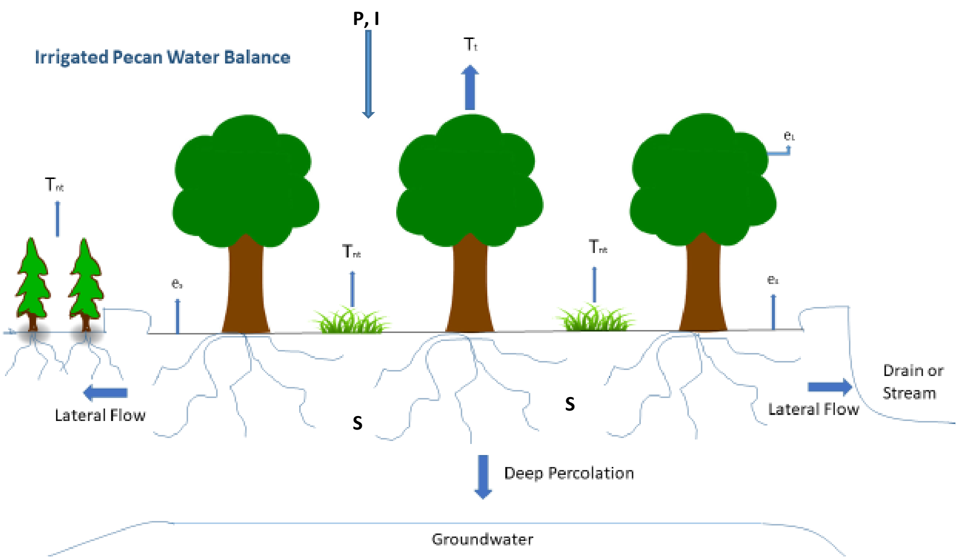

Fig. 1. Conceptual model of an irrigated pecan water balance, where:
P = Precipitation
I = Irrigation
T_t = Transpiration by targeted plants, i.e. the crop
T_{nt} = Transpiration by non-targeted plants. i.e. weeds, cover crops, or other non-crop plants
e_s = evaporation from soil surface
e_L = evaporation from tree leaf surfaces, i.e. water from precipitation or sprinkler irrigation on leaf surfaces
S = Soil water storage; delta S represents the change in storage over a given time period
LF = Lateral flow
DP = Deep percolation

Table 1. Comparison of growing season pecan ET (April-Oct) reported by various investigators.

Reference	Growing season ET, mm
Samani et al (2009), Remote Sensing	413-1095 mm (year 2008)
Miyamoto (1983), soil moisture monitoring	368-1307 mm (years 1972, 1973, and 1981)
Sammis et al. (2004), flux tower	1220-1267 mm (years 2001, 2002)
Bawazir and King (2004), flux tower	1236-1293 mm (years 2002, 2003)

2. Evapotranspiration in Flood-Irrigated Pecans

Evapotranspiration (ET, generally including T_t, T_{nt}, e_s, and e_L) is commonly the largest component of the water balance for irrigated pecans. Transpiration (T) is of course the primary beneficial, but consumptive use for pecan production. There are several common methods of measuring ET, either directly or indirectly, including: 1) measurement of soil moisture depletion over time (Miyamoto 1983; Deb et al. 2013); 2) estimation from remote sensing data (Samani et al. 2009, 2011); 3) calculation from flux tower measurements (Bawazir and King 2004; Samani et el. 2009, 2011); and 4) calculation using available weather plus other measured and/or relatively easy to estimate variables (Samani et al. 2011). Table 1 presents values of pecan ET measured and estimated by various investigators. The maximum pecan ET shown in Table 1 is 1100-1300 mm. The smaller values in Table 1 represent younger orchards with less canopy cover. Lower ET in pecan orchards also can be due to stress factors such as water and/or nutrient deficiency, salinity, diseases, and pests.

Most attempts at constructing water budgets for irrigated pecans depend on measurements or estimates of ET in which it is generally not possible to separate evaporation (E) from T. Thus, most of what is published about E in pecan orchards is tied to ET. Nonetheless, E from the soil surface in pecan orchards can be estimated by a variety of ways, described by Allen et el. (1998), Torres et al. (2019), Samani et al. (2009, 2011), and Sammis et al. (2004). In these studies, E rates were generally in the range of 0.1-2.0 mm/day and total seasonal E was about 80-100 mm or about 5-10% of the total applied water. The remainder of ET in these examples is presumed to be transpiration, which constitutes the majority of ET, commonly about 90% (Samani et al. 2009).

How management and irrigation method impact ET is discussed in greater detail in Section 6. A challenge for irrigated pecan production today and into the future is warming climate, which is impacting annual ET regardless of management. This is illustrated by recent results reported by Mokari et al. (2019) indicating that increasing temperatures have increased pecan water use (represented by total ET). Higher temperatures have both increased the short-term water demand and lengthened the growing season to result in an overall larger seasonal ET for pecans. Continued increases in temperature due to warming climate will put additional pressure on limited water resources in the region, while likely impacting pecan yield.

3. Evaporation from Soil in Flood-Irrigated Pecans: Consumptive Non-Beneficial Use

Exact measurements of E or even estimates of E in irrigated pecans are difficult to make and are thus rare in the literature, but we can summarize a few principles learned from studying evaporation in row crops that inform our understanding of the water balance in pecan orchards (Murtziger et al. 2005; Katul and Parlange 1992; Parlange and Katul 1992; Wallace and Holwill 1997; Evett et al. 1994;

and Ritchie 1972). E from a bare soil surface varies considerably, depending on shading by the crop canopy, with maximum rates when fully exposed to solar radiation and minimum rates under shaded conditions (Klocke et al. 1996; Farrahani and Bausch 1995; and Ritchie 1972). Surface mulch results in much less total E compared to bare soil, with reductions of E rates by 10-80%, depending on rates of mulch and other conditions (Sauer, et al. 1996; Hares and Novak 1992; Brun et al. 1986; Lascano et al. 1994; Staggenborg et al. 1996; and Todd et al. 1991).

Pecan orchards have some unique characteristics compared to row crops that impact the potential E losses from the soil surface. These include:

- Pecans trees are deciduous perennials. Thus, pecan orchards are not replanted every year like row crops, and pecan trees shed their leaves in winter making the orchard floor exposed to sunlight for some period. Trees do not leaf out again until March or April, and it might be mid- to late-May before leaf area is fully developed.
- Pecan trees are commonly planted in a grid on a 9 or 12 m spacing. This leaves considerable open space between trees. Seldom do the trees form a closed canopy in a well-managed orchard, and as much as 25-50% of the orchard floor will be exposed to sunlight at some point during the daylight hours. Younger orchards have even more exposure to sunlight. During daylight hours, there are portions of the orchard floor that are always exposed to sunlight and portions that are always shaded. The relative amounts of shaded area and sunlit area are determined by the maturity of the trees, the time of year, and the time of day, but E is much less in shaded areas (Table 2).
- Flood irrigation is the most common irrigation method in much of the southwestern U.S. production region, and results in wetting up the surface soil to field capacity every two to three weeks, resulting in ideal conditions to support maximum rates of evaporation while the surface soil is wet.
- Pecans have a longer growing/irrigation season (usually 8 months, March – October) compared to row crops and a much larger irrigation requirement (1.5-2.0 m of irrigation water), expanding the timeframe in which significant E losses can occur.
- In pecan orchards, the space between the ground surface and foliage is about 2-3 m, which facilitates better airflow near the surface and potentially more E.

These characteristics point to the possibility of significant E losses in pecan orchards, especially under flood irrigation where E is mainly from the free water surface after flooding, the wet soil surface under the canopy, and the open space between trees. The process of evaporation from a wet soil surface occurs in three stages over a period of about 14 days (Ritchie, 1972; Katul and Parlange, 1992; Parlange and Katul, 1992; Evett et al., 1994; and Wallace and Holwill, 1997). The three stages include: Stage 1) relatively high evaporation rates for 1-4 days, determined primarily by weather conditions while soil moisture is not limiting;

Table 2. Pan evaporation outside and inside mature pecan orchard, July 25 – August 24, 2018 (from Torres et al., 2019)

Pan Position	**Mean Max Air T,** Degrees Celsius	**Mean Max Pan Water T,** Degrees Celsius	**% Sunlight on Surface** (Range)	**Mean Daily Evaporation,** mm
Outside Orchard	34.9	37.4 a	100%	7.6 ± 1.7 a
Inside Orchard, Between Rows	NA	30.5 b	24.2% (20.6 – 28.7)	4.0 ± 1.6 b
Inside Orchard, In Rows	NA	30.8 b	24.2 % 20.6 – 28.7)	4.1 ± 1.4 b

[*] Means followed by the same letter are not significantly different at P=.05.

Stage 2) diminishing evaporation rates for a period of 2-7 days as the soil surface dries out and available moisture to support evaporation is limited at the soil surface by capillary action and vapor diffusion; and Stage 3) stabilized very low evaporation rates limited by lack of moisture to support evaporation. When measurements of evaporation from bare soil are normalized against potential evaporation estimated from pan evaporation, values are near 1.0 during Stage 1, 0.3-0.8 during Stage 2, and generally less than 0.3 during Stage 3 (Burt et al., 2002). In flood-irrigated orchards, the pattern of E between flood irrigation events (usually 10-20 days) is illustrated by the results of Deb et al. (2013), who found that the range of daily E rates for bare soil ranged from a high of 23.4 mm/day immediately after irrigation to a low of 1.1 mm/day after the soil surface dried. It is clear from the results of Deb et al. (2013) that Stage 1 evaporation generally lasted for about 2 days after irrigation, while Stage 2 continued for as long as 20 days.

Since the energy balance at the soil surface is highly variable over space and time in a pecan orchard (due to shading and sun position), the spatial distribution of soil E on the orchard floor is very dynamic on a 24-hr basis (Torres et al., 2019). This makes measuring or estimating E on a fine spatial and temporal scale a difficult task.

A robust study of spatial and diurnal E under a drip-irrigated vineyard canopy in Israel by Kool et al. (2014) quantified E both by direct measurement using "micropans" and by simulation using HYDRUS 2D/3D. In their study, E was highly variable both diurnally and with distance from the vine row, the magnitude being determined mostly by soil water content and the diurnal patterns of canopy shading. A similar study with attention to the dynamic patterns of shading and the spatially explicit process of evaporation is needed for pecan orchards.

4. Water Stored in the Soil Profile

The amount of water stored in the soil profile (S) in pecan orchards in our region is in the range of 50-150 mm and depends on several important soil characteristics, including: a) soil texture, b) soil pore structure, c) characteristics of the rhizosphere, and d) soil sodicity. An important factor that impacts several of these characteristics is soil organic matter (SOM) content. SOM tends to improve soil physical properties and increase water holding capacity (Lepsch et al. 2019; Eden et al. 2017). Addition of carbonaceous materials to soil such as leaf litter and organic mulches that have water adsorbing properties can increase the water holding capacity of the soil profile, while decreasing deep percolation and nutrient leaching (Vanden et al. 2014). Additionally, SOM can increase soil aggregate stability and soil water retention (Obalum et al. 2019; Egrinya et al. 2008; Johnson & Lyon 2019; Leelamanie and Manawardana 2019; Lepsch et al. 2019; Li et al. 2018; Tsegaye et al. 2003).

Specific to pecan orchards, organic waste materials could play an important role in increasing SOM content and improving soil physical characteristics. In NM, large amounts of biomass are produced as a by-product of pecan production, but not utilized (Creegan et al. 2023; Tahboub and Lindemann 2007). Pecan litter can have unique properties compared to other crop residues. For example, shell-based activated carbon from pecans, analyzed by Kaveeshwar et al. (2018) had a high specific surface area (1500 m1 2/g) and pore volume (0.7cm3/g). The long-term integrity of pecan-substrate amendments and associated soil property benefits might be enhanced due to the high lignin content of pecan biomass.

5. Deep Percolation: Non-Consumptive, Non-Beneficial Use

Deep percolation (DP) is the process by which water moves downward from the root zone and then either moves laterally off site or is stored in subsurface strata or the aquifer (Fig. 1). While the amount of water consumed by ET is usually the largest component of the water balance for irrigated pecans, the amount lost by DP is commonly the second largest component (Beyene et al. 2018). Despite DP representing one of the most important components of the water balance for pecans, it has been measured directly much less commonly compared to ET. By difference, we can estimate that DP in flood-irrigated pecans is commonly in the range of 25-35% of the applied water.

There are several methods to estimate DP, including: a) direct measurement of water content and movement in the soil profile using soil moisture sensors (Pereira da Silva and Ferreira 2014), where water that passes 1.5 m in depth is considered DP because the bulk of root systems and thus the majority of plant water use is in the top 1.5 m of soil (Woodroof 1934); b) water table fluctuation, providing a simple approach to quantify the rate of aquifer recharge; c) by difference using the water balance equation in which every component except DP is measured or estimated, leaving the balance equivalent to DP (Shukla 2014; Boyko et al. 2020; Upreti et al. 2015); d) modeling methods, for example the Root Zone Water Quality Model (RZWQM); and e) lysimeter methods combined with theoretical models (Bethune et al. 2008; Selle et al. 2011).

Though considered a non-beneficial use with respect to pecan production,DP can provide several hydrologic benefits. Ochoa et al. (2006) stated that DP, including some lateral flow, can provide: 1) recharge to shallow groundwater or a deeper aquifer, 2) return flow to a stream, and/or 3) dilution of contaminants from outside sources. Several studies have demonstrated that DP from irrigation can be a major component of shallow groundwater recharge (Gutierrez-Jurado et al. 2017; Contor, 2004). In northern NM, Fernald et al. (2010) found an average of 56% (ranging from 37 to 63%) of the total water applied by irrigation was DP.

A practical aspect of DP is intentional leaching to minimize salinity in the soil (Cahn, 2015). The best time to leach salt in a pecan field is during the winter period because trees are not using water. The amount of water that is required to pass through the root zone to control salt at a specific level is called the leaching requirement (LR). Management practices to mitigate high salinity are site-specific, but Miyamoto (2006) mentions three: a) blending or dilution (mixing two sources of water); b) chemical additives (calcium compounds and acidulants to lower sodicity); and c) desalination (removing salt by reverse osmosis). Currently, the latter is not economically feasible in pecan production.

Another important aspect of DP is nitrate leaching, which can be significant since high rates of N fertilization are used in pecan production (Wells 2013; Mokari et al. 2019). Mokari et al. (2019) showed that about 29% of the applied N was lost to leaching of NO_3-N. They concluded that N fertilizer rates were much higher than the plant demand, and improved N and water management are needed to decrease N losses.

It is important to note that in many unsaturated zone studies, DP is equated to recharge, and where river water is the major source of irrigation DP in pecan production, this is not a bad assumption. However, much of the water used for irrigation in pecans is groundwater. DP from this source does not represent recharge but return flow, since the source of the water was pumped originally from the aquifer. Where groundwater pumping exceeds net recharge, aquifers are being depleted. For example, the elevation of deep aquifers in the Rio Grande basin has been dropping over the past 50 years or more (Mayer et al. 2021) and is projected to continue (Hargrove et al. 2023). This is not due entirely to pecan production as other major crops, major cities, and some industrial users in the region also use groundwater, but certainly pecan production is a contributor.

6. Impacts of Alternative Irrigation Methods on the Water Balance

There are three basic irrigation methods used in pecan orchards: flood, sprinkler, and micro-irrigation. Basin flood irrigation currently is the most common method for pecan production in NM and Far West TX in the US, and Chihuahua in MX. Sprinkler systems are not commonly used in the region, but drip irrigation is a method that is of growing interest. Various irrigation methods and their impact on the water balance are described briefly below.

Basin flood irrigation is arguably the least expensive and simplest system to maintain but has drawbacks. In addition to higher E rates, the application of inputs such as nitrogen or pesticides are not as easily made as with other irrigation methods. Applied inputs (as well as salt and contaminants) are quickly flushed from the soil profile, particularly closer to the head of the field. This results in nonuniform distribution of nutrients and salt, which in turn can impact production negatively. Basin irrigation typically has an irrigation efficiency (when defined as the total ET as a fraction of water applied) of 55 to 65%.

Furrow irrigation applies water to wide furrows, each encompassing either a row of trees or the space between two rows of trees and shares some similarities with flood irrigation. With such a design, installation costs are likely to be higher, as more valves may be required. A plus is that furrow irrigation allows for greater flexibility and efficiency in applying inputs such as fertilizers or soil amendments (Cox et al. 2018; Deb et al. 2013). Furrow irrigation can result in irrigation efficiency of 65-75%.

Sprinkler irrigation is not common in pecan production in arid/semi-arid regions but can result in irrigation efficiency of 75-85%. One source of inefficiency in sprinkler irrigation is evaporation of water aerially sprayed from the sprinkler nozzle to the plant and soil surface.

Surface drip irrigation is a type of micro-irrigation system that distributes water through a network of valves, pipes, tubing, and emitters placed on the soil surface. The goal is to place water directly on the soil surface and minimize evaporation. With drip irrigation it is easier to maintain soil moisture in the root zone of plants closer to an ideal level during the growing season. Drip irrigation has been successfully used for several orchard crops, including almonds, peaches, pecans, and others (Stetson and Mecham 2011; Worley 1982). Poor-quality water can be used more successfully with drip than with sprinkler or surface irrigation, since less total salt is added with drip irrigation. In addition, a uniformly high soil moisture level is maintained in the root zone with drip irrigation, which makes more water available to trees and leaches the salts below the root zone. However, in regions with at least moderate annual rainfall (> 500 mm), irrigation efficiencies can be much lower due to poor timing of rainfall relative to irrigation, with consequences of significant amounts of DP. In such a case published by Darouich et al. (2022), DP amounted to 29-36% of the total water input of rain plus irrigation.

Sub-surface drip irrigation is like surface drip, except lines are placed below the soil surface. This offers some advantages in that evaporation levels can be less, and orchard maintenance is simpler with vital irrigation infrastructure buried below the soil surface. However, one recent study, comparing three subsurface irrigation designs and two micro-sprinkler systems for irrigated pecans, reported only minor differences in irrigation efficiency (Shalek-Briski et al. 2019).

Deficit irrigation/partial root drying is a strategy aimed at taking advantage of a plant's physiological response to water deficits, pioneered by Chalmers et al. (1981) for peaches and Dry and Loveys (1998) for vineyards. Partial root drying exploits the plant's response to water deficits, while still replacing the daily ET demand to a portion of the plant. This is achieved using dual drip lines placed on opposite sides of a tree row and only delivering water through a single side at a time. In this way, the tree's ET needs can be met while simultaneously provoking a drought response. One half of the tree's roots are irrigated while the other half are in drying soil. Typically, the side delivering water is alternated every 2-3 weeks. One primary benefit of alternating which side of the tree row receives irrigation is that by re-wetting the drier side promotes growth of high-order roots, which are best suited to access limited soil water. As with a standard drip-irrigation design, root growth will likely show bias towards the higher soil water content, where water is most available.

Drip irrigation is receiving growing interest as an alternative to flood or furrow irrigation in our region. It is commonly thought that drip irrigation will decrease E losses, but there is evidence that this might not always be true. Burt et al. (2001) summarized research in California on E under surface and subsurface drip systems and showed that the amount of E from drip irrigation is heavily dependent on the fraction of the soil surface that is wet. Although drip irrigation wets a smaller area, that area is wet for much of the growing season, whereas with flood or furrow irrigation, all if not most of the surface soil is wetted, but dries in relatively short periods of time, reducing the total E. This leads to the conclusion that some types of drip systems can result in at least as much and perhaps more E than flood or furrow irrigation, substantiated by several published studies (Evett et al. 1995; Dasberg 1995; Bresler 1975; Meshkat et al. 2000; and Burt and Styles 1999). Burt et al. (2001) summarized results for drip and furrow irrigation for several crops produced in California and showed that total ET for crops produced by drip irrigation compared to furrow irrigation are often similar, but the distribution of E and T for the two systems are quite different. Total ET averaged 940 mm/yr for both furrow and drip irrigation, but E was 63.5 mm/yr for furrow irrigation (6.75% of total ET) and 38 mm/yr for drip irrigation (4% of total ET), making the drip irrigation system more efficient in reducing non-beneficial consumption of water.

7. Summary

Based on results presented here, we developed a generalized water balance for flood-irrigated pecans in an arid climate (Table 3). This generalized water balance is for a mature orchard with at least 70% groundcover by the tree canopy. Values will change for more immature orchards.

The largest single component of the water balance in mature pecan orchards is usually T, which represents beneficial consumptive use. Individual measurements of E and T are difficult and thus scarce in the literature. Rates of ET or total ET are much more commonly reported. Daily rates of ET for mature orchards are as high as 7.5 mm/d during the middle of the season during high water demand. Immature orchards have lower daily rates due to the incomplete canopy (5-6 mm/d or less). Seasonal totals of ET for mature pecans with optimum management are often in the range of 1100-1300 mm. Younger orchards with incomplete canopy development have much lower values. Orchards that experience stress factors such as moisture deficiency, salinity, nutrient deficiency, diseases, and/or pests, also have lower ET values. Since the amount of water applied to pecans by flood irrigation is commonly about 1650-1800 mm/season, an ET of 1200 mm is about 67-73% of the total amount of irrigation water. If you consider only T, calculated irrigation efficiency for trees is about 65%. An irrigation efficiency of 65% compares poorly with other methods of irrigation such as sprinkler or drip irrigation in row crops, which often have efficiencies of 75-85% and can be as high as 90% for subsurface drip irrigation.

Table 3. Generalized water balance for flood irrigated pecans in arid environment.

Water balance component	**(I + P)[1]**	**Total ET**	**T**	**E**	**DP**
Reported range, mm	1500–1800	1095-1307	1020-1232	75-180	405-705
Best estimate, mm (% of applied)	1650	1200 (73)	1075 (65)	125 (8)	450 (27)
Reference to this document	Introduction	Section 3	Section 4 & 5	Section 5	Section 6

[1] Irrigation is generally 90% or more of this total. Total includes water applied to leach salts.

E losses of various kinds and T by non-target plants represent non-beneficial consumptive use and are usually small but significant (5-10% of applied water in mature orchards, more in younger orchards). This can be equivalent to one irrigation application per season. The largest source of E in flood-irrigated pecans is from the free water surface at the time of flooding and lasting for 2-3 days (Stage 1 E), followed by E from the wet soil surface as it dries (Stage 2), lasting about another 3-5 days. In Stage 3 E, rates are very low but steady, limited by the dry soil surface and lasting until the next irrigation event. E rates under a tree canopy are generally less than those outside, but this difference varies widely depending on several factors, most importantly the age of the orchard and the extent of the plant canopy. E rates under a canopy vary widely on a fine spatial scale due to the dynamic shading of the soil surface, which depends on the time of year and time of day. Shading impacts the temperature at the soil surface and thus the energy available to drive E. Because pecan orchards almost never have a completely closed canopy, it is difficult to measure or estimate cumulative E accurately over space and time.

Applied water that is not T or lost through E is either stored in the soil profile (S) or percolates below the root zone of the trees (DP). The change in S in the profile represents a useable reservoir of soil water for future crop use, but could still be lost to E, T by non-target plants, or DP. The amount of S is related to several soil properties, including soil texture, pore size distribution, and SOM content. SOM content can be modified through management and has been shown to have a positive impact on pecan production.

DP, either downward or laterally, represents recoverable flows that are considered non-consumptive use, and might be added to one or more of several "sinks", including drainage ditches, streams, ponds, and aquifers. Recoverable flows can be further characterized as "recharge" if it is a net addition of water to a sink other than its original source, or "return flows" if it represents water returned to its original source. For example, irrigation water from a stream source that percolates to the aquifer represents recharge, but irrigation water that is pumped from the aquifer and percolates back to the aquifer is return flow. DP can be non-intentional from excessive irrigation, or intentional if the purpose is to leach salt from the soil profile.

Micro-irrigation, such as surface or subsurface drip irrigation, is a highly efficient way of applying water to a crop by delivering water more directly to plants. With micro-irrigation, most of the water infiltrates to the plant root zone, while less water is lost to E. The application efficiency for a typical drip system is 80- 90%. Deficit irrigation is a way to reduce water inputs without significantly impacting yield. Simple reductions in applied water can result in significant increases in water use efficiency (defined by the yield per unit of water applied). Partial root drying is a method of deficit irrigation designed to affect plant responses to simulated drought while still trying to supply the ET demand to at least part of the plant, which ultimately might increase the plant's water use efficiency. This is achieved using dual drip lines placed on opposite sides of a tree row and only delivering water through a single side at a time.

8. Needed Research

The two largest components of the water balance that do not contribute directly to crop production and thus if reduced could improve water use efficiency, are E and DP. Although E in row crop agriculture has been rigorously studied and successfully modeled over the past fifty years, E in orchard crops, especially flood irrigated pecans, have been studied much less, and presents unique challenges. A major deficiency is our lack of understanding of the microclimate in pecan orchards and the dynamic nature, in space and time, of water and heat gradients and fluxes at relatively "fine" scales (i.e., hourly on one square meter grids). As pecan trees are most often planted in a grid pattern on a 9 or 12 meter spacing, the size of one grid is either 81 or 144 m^2. The details of water and heat gradients and fluxes are needed on a fine scale for each grid (i.e., hourly on a $1m^2$ basis).

Additionally, we need to improve our estimates of cumulative growing season E for different irrigation systems and for different ages and row spacing of orchards (that result in varying canopy cover). More importantly we need to evaluate different management practices that can reduce non-beneficial consumptive losses of water through E to make irrigation more efficient. Those might include uses of mulch, improved irrigation methods and management, closer tree spacing, and others. In this regard, a recent study by Kool et al. (2014) in grape vineyards represents a useful approach to measurement of E that is needed in pecan orchards.

More work is needed on optimum composting and use of pecan waste materials in pecan production. Proper composting can ameliorate pecan pathogen survival in organic materials to be returned to pecan orchards (Tsegaye et al. 2003). Effectively incorporating organic amendments into soil management for pecan production can be an important water conservation practice that is needed to better manage water on a landscape scale.

Research is needed that will help us better define the costs and benefits of DP in specific situations with different water sources, water quality, water availability, and climate. To accomplish this, it is necessary to quantify more precisely the water that passes the root zone vs. how much water is being used beneficially. More accurate estimations of DP could provide a basis for improving irrigation efficiency (Nassah et al. 2018) and provide better estimates of recharge from flood-irrigated pecan production (Beyene et al. 2018).

Preliminary testing of partial root drying as an irrigation technique showed that water inputs could be reduced significantly without reducing yield. It thus holds promise in making water use more efficient for irrigated pecan production. But, more research, especially over multiple growing seasons and varying conditions, is needed for this innovative technique.

In conclusion, our understanding of the water balance for irrigated pecans falls far short of our understanding of the water balance for annual row crops, which has progressed much in the past fifty years. As water for agriculture becomes more competitive, scarce, and expensive, it is imperative that we improve its management to maintain a viable pecan production industry.

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Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References Cited

Allen GA, Pereira LS, Raes D, Smith M. 1998. Crop Evapotranspiration. Food and Agricultural Organization of the United Nations (FAO-56), Rome.

Bawazir AS, King JP. 2004. Crop ET study for Dona Ana County, NM. Technical Report, NM Water Resour Res.

Bethune, MG, Selle B, Wang QJ. 2008. Understanding and predicting deep percolation under surface irrigation. Water Resour Res. 44, W12430. doi:10.1029/2007WR006380

Beyene A, Cornelis W, Verhoest NE, Tilahun S, Alamirew T, Adgo E, Nyssen, J. 2018. Estimating the actual evpotranspiration and deep percolation in irrigated solid of a tropical floodpain, northwest Ethiopia. Agric Water Manage, 42-56.

Boyko, K, Fernald A, Bawazir S. 2020. Improving Groundwater Recharge Estimates in Alfalfa Fields of New Mexico with Actual Evapotrasnpiration Measurements. J Agric Water Manage.

Bresler, Eshel. 1975. Two dimensional transport of solutes during nonsteady infiltration from a trickle source. Soil Sci Soc Amer J. 39(4):604-613. https://doi.org/10.2136/sssaj1975.03615995003900040014x

Brun LJ, Enz JW, Larsen JK, Fanning C. 1986. Springtime evaporation from bare and stubble-covered soil. J Soil Water Con 41:120-122.

Burt, CM, Styles SW. 1999. Drip and micro irrigation for trees, vines, and row crops. Irrig Train and Res Cntr. Cal Poly, San Luis Obispo, CA. 291 p.

Burt CM, Howes DJ, Mutziger A. 2001. Evaporation estimates for irrigated agriculture in California. Conf Proc of the Ann Irrig Assoc Meeting, San Antonio, TX. Pp 103-110. http://www.itrc.org/papers/evaporationest/evaporationestimates.pdf

Burt, C.M., A. Mutziger, D. Howes, and K. Solomon. 2002. Evaporation from Irrigated Agricultural Land in California. Irrigation Training & Research Center, California Polytechnic State University, San Luis Obispo, California, USA. ITRC Report No. R 02-001. 478 pp. http://www.itrc.org/reports/evaporationca.htm

Cahn M. 2015. *Managing Salts by Leaching*. Agriculture and Natural Resources. Richmond: University of California. Retrieved from http://creativecommons.org/licenses/by-nc-nd/4.0/ or

Chalmers, D.J., P.D. Mitchell, and L. van Heek. 1981. Control of peach tree growth and productivity by regulated water supply, tree density, and summer pruning. J Amer Soc Hort Sci 106:307–312.

Contor BA. 2004. *Percolation, Runoff, and Deficit irrigation*. Idaho Water Resour Res Inst.

Cox C, Jin L, Ganjegunte G, Borrok D, Lougheed V, Ma L. 2018. Soil quality changes due to flood irrigation in agricultural fields along the Rio Grande in western Texas. App Geochemistry 90:87-100. https://doi.org/10.1016/j.apgeochem.2017.12.019

Creegan, EG, Flynn R, Brewer CE, Heerema RJ, Darapuneni M, and Valasco-Cruz C. 2023 Pecan Biomass and Dairy Manure Utilization: Compost Treatment and Soil In-Situ Comparisons of Selected Pecan Crop and Soil Variables. Processes 11:2046.

Darouich H, Ramos TB, Pereira LS, Rabino D, Bagagiolo G, Capello G, Simionesei L, Cavallo E, Biddoccu M. 2022. Water Use and Soil Water Balance of Mediterranean Vineyards under Rainfed and Drip Irrigation Management: Evapotranspiration Partition and Soil Management Modelling for Resource Conservation. *Water* 14, no. 4: 554. https://doi.org/10.3390/w14040554

Dasberg S. 1995. Drip and spray irrigation of citrus orchards in Israel. *In* Proc. 5th Int. Microirrigation Congress: 281-287. Orlando, Florida, 2-6 April. ASAE, St. Joseph, Michigan.

Deb SK., Shukla MK, Sharma P, Mexal J. 2013. Soil water depletion in irrigated mature pecans under contrasting soil textures for arid Southern New Mexico. Irrig Sci 31:69-85

Dry PR, Loveys, B. R. 1998. Factors influencing grapevine vigour and the potential for control with partial rootzone drying. Aust J of Grape Wine Res. 4(3), 140-148. https://www.researchgate.net/publication/327321681_Influence_of_irrigation_management_as_partial_rootzone_drying_on_raspberry_canes

Eden, M, Gerke H, Houot, S. 2017. Organic waste recycling in agriculture and related effects on soil water retention and plant available water: a review. Agron Sustain Dev (Springer Science & Business Media B.V.), *37*(2), 1–21. https://libezp.nmsu.edu:2072/10.1007/s13593-017-0419-9

Egrinya A, Inanaga S, Li X, An P, Li J, Duan L, and Li Z. 2008. Effectiveness of mulching vs. incorporation of composted cattle manure in soil water conservation for wheat based on eco-physiological parameters. J of Agron and Crop Sci. 194(1):26-33.

Evett SR, Matthias AD, Warwick AW. 1994. Energy balance model of spatially variable evaporation from bare soil. Soil Sci Soc Amer J. 58:1604-1611.

Evett SR, Howell TA, Scheider AD. 1995. Energy and water balances for surface and subsurface drip irrigated corn. *In* Proc. 5th Int. Microirrigation Congress. Orlando, Florida, 2-6 April. St. Joseph, Michigan:ASAE. pp. 135-140.

Farahani HJ, Bausch WC. 1995. Performance of evapotranspiration models for maize bare soil to closed canopy. Trans of the ASAE 38:1049-1059.

Fernald AG, Cevik YS, Ochoa SM, Tidwell CG, King PJ, Guldan SJ. 2010. River Hydrograph Retransmission Functions of Irrigated Valley Surface Water-Groundwater Interactions. *Irrig and Drain Eng*, 823-835.

Gutierrez-Jurado KY, Fernald AG, Guldan, SJ, Ochoa CG. 2017. Surface water and groundwater interactions in traditionally irrigated fields in Northern New Mexico, U.S.A. MDPI water, 1-14.

Hares MA, Novak MD. 1992. Simulation of surface energy balance and soil temperature under strip tillage. II. Field Test. Soil Sci Soc Amer J. 56:22-29.

Hargrove WL, Heyman JM, Mayer A, Mirchi A, Granados-Olivas A, Ganjegunte G, Gutzler D, Pennington DD, Ward FA, Garnica Chavira LA, Sheng Z, Kumar S, Villanueva-Rosales N, Walker WS. 2023. The future of water in a desert river basin facing climate change and competing demands: A holistic approach to water sustainability in arid and semi-arid regions. J of Hydrology: Reg Stud. Vol. 46. https://doi.org/10.1016/j.ejrh.2023.101336

Johnson MS, Lyon SW. 2019. Improving agricultural water use efficiency with biochar – A synthesis of biochar effects on water storage and fluxes across scales. *Sci of the Total Environ*. *657*, 853–

862. https://libezp.nmsu.edu:2072/10.1016/j.scitotenv.2018.11.312

Katul GG, Parlange MB. 1992. Estimatioin of bare soil evaporation using skin temperature measurements. J of Hydrology 132:91-106.

Kaveeshwar AR, Ponnusamy SK, Reclame ED, Gang DD, Zappi ME, Subramaniam R. 2018. Pecan shell based activated carbon for removal of iron (II) from fracking wastewater: Adsorption kinetics, isotherm and thermodynamic studies. Process Safety & Environmental Protection: Transactions of the Institution of Chemical Engineers Part B, 114(Part B), 107–122. https://libezp.nmsu.edu:2072/10.1016/j.psep.2017.12.007

Klocke NL, Todd RW, Schneekloth JP. 1996. Soil water evaporation in irrigated corn. Appl Eng in Agric. 12:301-306.

Kool D, Ben-Gal A, Agam N, Simunek J, Heitman JL, Sauer TJ, Lazarovitch N. 2014. Spatial and diurnal below canopy evaporation in a desert vineyard: Measurements and modeling. Water Resour Res. 50(8):7035-7049.

Lascano RJ, Baumhardt RL, Hicks SK, Heilman. 1994. Soil and plant water evaporation from strip-tilled control: Measurement and Simulation. Agron J. 86:987-994.

Lelamanie, DAL, Manawardana CU. 2019. Soil hydrophysical properties as affected by solid waste compost amendments: seasonal and short-term effects in an Ultisol. J of Hydrology & Hydromechanics / Vodohospodarsky Casopis, *67*(3), 232–239. https://libezp.nmsu.edu:2072/10.2478/johh-2019-0007

Lepsch H, Brown P, Peterson C, Gaudin A, Khalsa SD. 2019. Impact of organic matter amendments on soil and tree water status in a California orchard. Agric Water Manag. Vol. 222, pp. 204-212.

Li Z, Schneider RL, Morreale SJ, Xie Y, Li C, Li J. 2018. Woody organic amendments for retaining soil water, improving soil properties and enhancing plant growth in desertified soils of Ningxia, China. Geoderma, *310*, 143–152. https://libezp.nmsu.edu:2072/10.1016/j.geoderma.2017.09.009

Mayer A, Heyman J, Granados-Olivas A, Hargrove W, Sanderson M, Martinez E, Vazquez-Galvez A, Alatorre-Cejudo LC. 2021. Investigating Management of Transboundary Waters through Cooperation: A Serious Games Case Study of the Hueco Bolson Aquifer in Chihuahua, Mexico and Texas, United States. Water 2021 (13): 2001.

Meshkat M, Warner RC, Workman SR. 2000. Evaporation reduction potential in an undisturbed soil irrigated with surface drip and sand tube irrigation. Trans of the ASAE 43:79-86.

Miyamoto S. 2006. Diagnosis and Management of Salinity Problems in Irrigated Pecan Production. Agric Res and Extension Center at El Paso. El Paso, Texas, United States of America: Texas Water Resources Institute.

Miyamoto S. 1983. Consumptive water use of irrigated pecans. J Am Soc Hortic Sci. 108(5):676-681.

Mokari E, Shukla MK, Šimůnek J, Fernandez JL. 2019. Numerical Modeling of Nitrate in a Flood-Irrigated Pecan Orchard. Soil Sci Soc Am J. 83, 555-564.

Mutziger A, Burt C, Howes DJ, Allen RG. 2005. Comparison of measured and FAO-56 modeled evaporation from bare soil. J Irrig Drain. 131:1(59). DOI:10.1061/(ASCE)0733-9437(2005)131:1(59)

Nassah H, Er-Raki S, Khabba S, Fakir Y, Raibi F, Merlin O, Mougenot, B. 2018.

Evaluation and analysis of deep percolation losses of drip irrigated citrus crops under non-saline and saline conditions in a semi-arid area. Biosystems Eng. 10-24.

Obalum SE, Uteau-Puschmann D, Peth S. 2019. Reduced tillage and compost effects on soil aggregate stability of a silt-loam Luvisol using different aggregate stability tests. Soil & Tillage Res. 189, 217–228. https://libezp.nmsu.edu:2072/10.1016/j.still.2019.02.002

Ochoa CG, Fernald AG, Guldan SJ, Shukla MK. 2006. Deep Percolation and its Effects on Shallow Groundwater Level Rise Following Flood Irrigation. Amer Soc Agric and Biol Eng. 73-81.

Parlange MB, Katul GG. 1992. Estimation of the diurnal variation of potential evaporation from a wet bare soil surface. J of Hydrology 156:21-45.

Pereira da Silva AJ, Ferreira E. 2014. Estimation of Water Percolation by Different

Methods Usign TDR. Revista Brasileira de Ciencia do Solo, 73-81.

Ritchie JT. 1972. Model for predicting evaporation from a crop with incomplete cover. Water Resour Res. 8:1204-1213.

Samani Z, Bawazir S, Bleiweiss M, Skaggs R, Longworth J, Tran V, Pinion A. 2009. Using remote sensing to evaluate the spatial variability of evapotranspiration and crop coefficient in Lower Rio Grande Valley (LRG), NM. Irrig Sci., doi:10.1007/s00271-009-0178-8.

Samani Z, S. Bawazir S, Skaggs R, Longworth J, Pinion A, Tran V. 2011. A simple Irrigation Scheduling approach for pecan. Agric Water Manage. 98(2011) 611-664.

Sammis TW, Mexal JG, Miller D. 2004. Evapotranspiration of flood irrigated pecans. J Agric Water Manage. 69(3):179-190.

Sauer TJ, Hatfield JL, Prueger JH. 1996. Corn residue age and placement effects on evaporation and soil thermal regime. Soil Sci Soc Amer J. 60:1558-1564.

Selle B, Minasny B, Bethune M, Thayalakumaran T, Chandra S. 2011. Applicability of
Richards' equation models to predict deep percolaton under surface irrigation. Geoderma, 569-578.

Shalek-Briski A, Brorson W, Biermacher JT, Rohla CT, Chaney W. 2019. Effect of irrigation method on tree growth, foliar nutrient levels, and nut characteristics of young pecan trees in the southern great plains. HortTechnology 29(2):109-113.

Shukla MK. 2014. *Soil Physics: an introduction.* Boca Raton: CRC Press.

Staggenborg SA, Lascano RJ, Krieg DR. 1996. Determining cotton water use in a semiarid climate with the GOSSYM cotton simulation model. Agron J. 88:740745.

Stetson LV, Meacham B. 2011. *Irrigation* 6th Edition. Irrig Assoc, Falls Church, VA, USA. 1089 pp.

Tahboub M, Lindemann WC. 2007. Nutrient availability in soil amended with pecan wood chips. HortScience. 42(2): 339-343.

Todd RW, Klocke NL, Hergert GW, Parkhurst AM. 1991. Evaporation from soil influenced by crop shading, crop residue, and wetting regime. Trans of the ASAE 34:461-466.

Torres DS, Hargrove WL, Kumar S, Chaganti VS, Heerema RJ, Ganjegunte GK. 2019. Water evaporation from the soil surface in flood-irrigated pecans. Soil Sci Soc Amer Annu Meet. Abstr.

Tsegaye TD, Ranatunga TD, Reddy KC. 2003. Variation of Soil Dielectric Constant, Moisture Holding Capacity, and Nitrate-Nitrogen as Influenced by Application of Fresh and Compost Poultry Litter on a Decatur Silt Loam Soil. J Sustain Agric, *22*(2), 55–73. https://libezp.nmsu.edu:2072/10.1300/J064v22n02_05

Upreti H, Ojha CSP, Hari Prasad KS. 2015 Estimation of Deep Percolation in Sandy-Loam Soil using Water-balance Approach. Irrig. Drainage Sys Eng S1:002. doi: 10.4172/2168-9768. S1-002

Vanden Nest T, Vandecasteele B, Ruysschaert G, Cougnon M, Merckx R, Reheul D. 2014. Effect of organic and mineral fertilizers on soil P and C levels, crop yield and P leaching in a long-term trial on a silt loam soil. Agric, Ecosyst Environ. *197*, 309–317. https://libezp.nmsu.edu:2072/10.1016/j.agee.2014.07.019

Wallace JS, Holwill CJ. 1997. Soil evaporation from tiger-bush in south-west Niger. J of Hydrology 188/189:426-442.

Wells ML. 2013. Pecan Response to Nitrogen fertilizer placement. HortScience. 48(3): 369-372.

Woodroof JG, Woodroof NC. 1934. Pecan root growth and development. *J Agric Res.* 511-530.

Worley R.E. 1982. Tree yield and nut characteristics of pecan with drip irrigation under humid conditions. J Amer Soc Hort Sci. 107:30–34.