NM WRRI Student Water Research Grant (NMWRRI-SG-2018)

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2. **Project title:** Optimizing fertilizer application and leaching under abiotic stresses within and below the Root Zone of Pecan Orchards

3. Research problem and objectives

Nitrogen (N) is an essential element for plant growth, and pecan needs N fertilizer during the nut enlargement and nut filling stages. N application rates are usually much higher than rates for other nutrients (Wells, 2013), which increases the risk of N leaching in irrigated pecan orchards. The recommended rate of N fertilizers is about 200 kg/ha (Byford, 2005). Excess N fertilization in irrigated fields contaminates groundwater (Cepuder and Shukla, 2002) because NO_3-N is a weakly absorbed ion that moves quickly through soil (González–Delgado and Shukla, 2014). NO_3-N leaching to groundwater is affected by the type of irrigation system (Sharma et al., 2012a) and the soil texture, and it can be high in arid and semiarid areas such as southern New Mexico, especially in surface-irrigated areas with sandier soils (Sharma et al., 2012b).

Measurements of water and NO_3-N in pecan orchards are limited because they are time- and labor-intensive, and the cost of instrumentation and analysis can also be high (van der Laan et al., 2010). On the other hand, solute transport in and out of the root zone can be simulated using a variety of numerical models. These models can provide deeper insight into the transport behavior as well as leaching of the applied chemicals and fertilizers toward the groundwater table with irrigation.

Monitoring volumetric soil water content (θ) and N variations, which are key factors in crop productivity, is essential for gaining a deeper understanding of soil–plant–atmosphere water relations. Simulations can provide additional information, such as on N leaching that may cause groundwater contamination. However, there are no studies reporting NO_3-N leaching in irrigated pecan orchards of southern New Mexico, and most available studies are only for lighter-textured soils. To the best of our knowledge, there are only two studies that focused on modeling water fluxes in the root zone of a flood-irrigated pecan tree (Deb et al., 2011, 2013). This research was therefore conducted (i) to determine soil water and NO_3-N dynamics within and below the root zone, (ii) to simulate water and NO_3-N variations and root NO_3-N uptake, and (iii) to compute NO_3-N balance during two growing seasons in a pecan orchard.

4. Methodology

This research was carried out in a pecan orchard located at the Leyendecker Plant Science Research Center (PSRC) of New Mexico State University. The orchard has been under similar management with regard to tillage operations since 2007. The orchard was flood irrigated. The fertigation was scheduled by the farm manager. To determine volume of water per application, the rate of inflow was multiplied with the duration of pumping. The groundwater table was 7 m below the soil surface, and the sources of irrigation were surface water and groundwater. Soil is classified as Harkey (coarse-silty, mixed, calcareous, thermic Typic Torrifluvents)-Glendale (fine-silty, mixed, calcareous, thermic Typic Torrifluvents).

The HYDRUS-1D model (version 4.16.0110) was used to simulate the one-dimensional movement of soil water and solutes in variably saturated porous media (Šimůnek et al., 2016). The orchard was flood irrigated; therefore, it is reasonable to use 1D model. However, for this study, we have used average root length density (RLD) from three different quadrants of a Pecan tree. HYDRUS-1D uses the Richards equation to predict the redistribution of water in soil. HYDRUS-1D provides simulations of multiple solutes, which can be either independent of each other or linked using the first-order degradation (or hydrolysis) pathway, which can be applied to N species. The solute transport equation describes advective-dispersive transport in the liquid phase and diffusive transport in the gaseous phase. In this study, urea, NH_4-N, and NO_3-N were the N species considered in simulations.

The type and amounts of fertilizers applied are given in Table 1. Soil physical properties, including particle size, bulk density, and the saturated hydraulic conductivity, are presented in Table 2. Diurnal variations of θ at five different depths (10, 20, 40, 60, and 80 cm) were measured using five TDR sensors installed horizontally. For HYDRUS-1D modeling, the average RLD was obtained by depth from the northwest, southwest, and southeast quadrants of the pecan canopy. Replicated soil samples were collected four to five days after the scheduled irrigation from canopy area. The NO_3-N (mg/kg of soil) (EPA 353.2) was measured six times, in February, June, and October in both 2015 and 2016, with three sample replications. NO_3-N measurements were carried out at five depths (10, 30, 50, 70, and 90 cm).

Regarding solute transport parameters, urea and NO_3-N were assumed to be present only in the dissolved phase ($k_d = 0$ cm^{3}g^{-1}). NH_4-N was considered to adsorb to the solid phase using a k_d value of 3.5 cm^3 g^{-1} for all soil depths (Hanson et al., 2006). The longitudinal dispersivity was considered equal to one-tenth of the profile depth for all soil depth intervals (Cote et al., 2003; Hanson et al., 2006; Phogat et al., 2012). Molecular diffusion was neglected because it was considered negligible relative to hydrodynamic dispersion (González-Delgado and Shukla, 2014; Deb et al., 2015). The first-order decay coefficient μ_a for urea was considered to be 0.38 d^{-1} for all soil depth intervals (Hanson et al., 2006). The nitrification and denitrification rates were initially set to be the same in all soil depth intervals (namely $\mu_{nit} = 0.2$ d^{-1} and $\mu_{dnit} = 0.02$ d^{-1}) and then adjusted for each soil depth interval according to observed data. Note that volatilization of NH_4-N and subsequent NH_4-N transport by gaseous diffusion was neglected in this study. Under flood irrigation, urea is reported to be washed into soils and is not available to be nitrified significantly (Hu et al., 2008). Unlimited passive uptake of NO_3-N was considered by specifying the c_{max} value larger than dissolved simulated concentrations, which allowed all dissolved nutrients to be taken up by plant roots with root water uptake (Šimůnek and Hopmans, 2009). For root water uptake (RWU), the piece-wise model of Feddes et al. (1978) was chosen.

HYDRUS-1D requires separate values of potential evaporation (Ep) and potential transpiration (Tp) with time. The soil cover fraction (SCF) was determined monthly in the pecan orchard (Samani et al., 2013). Meteorological parameters were taken from a climate station located at the PSRC. HYDRUS-1D calculated the daily reference evapotranspiration (ET_0) based on the Penman-Monteith equation and then divided it into Ep and Tp using measured SCF. Model performance was assessed using the following quantitative measures (Shen et al., 1998; Willmott, 1981):

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(S_i - M_i)^2}{N}} \qquad (7)$$

$$d = 1.0 - \frac{\sum_{i=1}^{N}(S_i - M_i)^2}{\sum_{i=1}^{N}\left(|S_i - M_{avg}| + |M_i - M_{avg}|\right)^2} \qquad (8)$$

where RMSE is the root mean square error, d is the index of agreement, N is the number of paired measured and simulated values, S_i is the ith simulated value, M_i is the ith measured value, and M_{avg} is the average of measured values. RMSE is the mean difference between measured and simulated results, and d shows the agreement between measured and simulated values.

Table 1. Dates of irrigation, fertigation, and amounts in the pecan orchard during 2009, 2010, 2015, and 2016. During each irrigation, 13.29 cm of water were applied.

Irrigation/ Fertigation	Type	N applied (kg/ha)	Total applied N (kg/ha)	Irrigation/ Fertigation	Type	N applied (kg/ha)	Total applied N (kg/ha)
14 May 2009	Urea (46% N)	51.75		28 June 2015		-	
21 June 2009	Urea (46% N)	103.5		23 July 2015		-	
2 Aug. 2009	Ammonium sulfate (21% N)	35.5		23 Aug. 2015	Ammonium sulfate (21% N)	35.5	
2 Sept. 2009		-		15 Sept. 2015		-	
10 Oct. 2009		-	190.75	8 Oct. 2015		-	320.15
7 Apr. 2010	Urea (46% N)	129.4		21 Mar. 2016		-	
27 May 2010	Urea (46% N)	51.75		12 Apr. 2016	UAN (32% N)	118.8	
22 June 2010	Urea (46% N)	103.5		19 May 2016	UAN (32% N)	118.8	
18 July 2010		-		7 June 2016	UAN (32% N)	118.8	
23 Aug. 2010	Ammonium sulfate (21% N)	35.5		23 June 2016		-	
7 Oct. 2010		-	320.15	17 July 2016		-	
23 Mar. 2015		-		12 Aug. 2016		-	
21 Apr. 2015	Urea (46% N)	129.4		28 Aug. 2016		-	
17 May 2015	Urea (46% N)	51.75		21 Sept. 2016	UAN (32% N)	118.8	
9 June 2015	Urea (46% N)	103.5		14 Oct. 2016		-	475.2

Table 2. Soil physical properties at the study field.

Soil depth	Particle size distribution (%)			Bulk density	K_s[a]
(cm)	Sand	Silt	Clay	(Mg m^{-3})	(cm min^{-1})
0–20	22.84 ± 1.92	51.00 ± 1.47	26.16 ± 0.71	1.53 ± 0.04	0.001 ± 0.000
20–40	10.84 ± 1.29	59.00 ± 1.29	30.16 ± 0.82	1.28 ± 0.05	0.001 ± 0.001
40–60	49.34 ± 12.99	37.25 ± 10.88	13.41 ± 3.59	1.24 ± 0.08	0.0174 ± 0.0108
60–100	37.84 ± 11.52	51.00 ± 10.74	11.16 ± 2.00	1.11 ± 0.05	0.0097 ± 0.0028

[a] K_s = saturated hydraulic conductivity

5. Results

5.1. Calibration and Validation for Water Flow

All measured θ in 2009 were used to calibrate water flow in HYDRUS-1D and to obtain optimized water flow parameters by inverse modeling. Water flow parameters were optimized using measured θ for a 247-day period from DOY 91 through DOY 337 (April 1 to December 3) in 2009 for each material separately. HYDRUS-1D was validated using measured θ for a 233-day period from DOY 132 through DOY 364 (May 12 to December 30) in 2010.

Figures 1 and 2 illustrate differences between measured and simulated daily mean θ at five depths (10, 20, 40, 60, and 80 cm) during the calibration (DOY 91 through DOY 337, 2009) and validation (DOY 132 through DOY 364, 2010) periods. Generally, there was good agreement between measured and simulated θ during both calibration and validation periods (the calibration period in particular). For instance, during the calibration period, RMSE fluctuated between 0.03 and 0.04 $cm^3 cm^{-3}$, and d between 0.57 and 0.73 (Fig. 1). During the validation period, RMSE varied between 0.04 and 0.06 $cm^3 cm^{-3}$, and d between 0.44 and 0.66 for different soil depths (Fig. 2). HYDRUS-1D simulated both rapid rises in θ immediately after irrigation (Table 1) and gradual declines during drying periods. Model-predicted θ_s matched well ($0.01 \leq RMSE \leq 0.03$) with measured values at all depths except for 60 and 80 cm during the calibration period (Fig. 1), and 40 and 60 cm during the validation period (Fig. 2). However, some under-predictions during the validation period at the depth of 60 cm were likely associated with the soil water retention behavior of the heavy textured soil as well as measurement errors associated with sensors. Differences between simulated and measured θ were also reported by Abbasi et al. (2004) and Deb et al. (2012, 2013), among others.

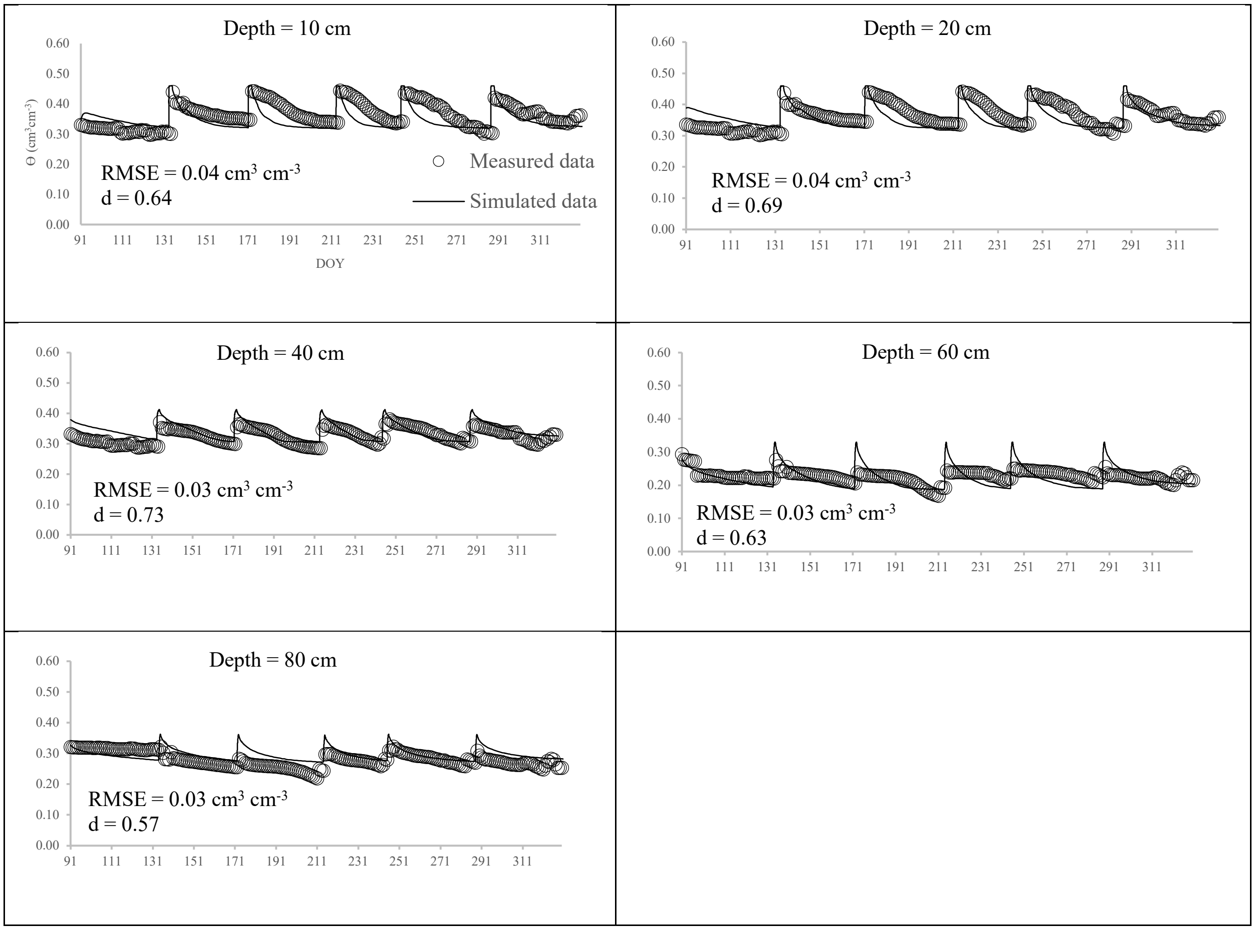

Fig. 1. Temporal variations in the simulated and measured θ at different soil depths during the calibration time period from DOY 91 (1 Apr. 2009) to DOY 337 (03 Dec. 2009).

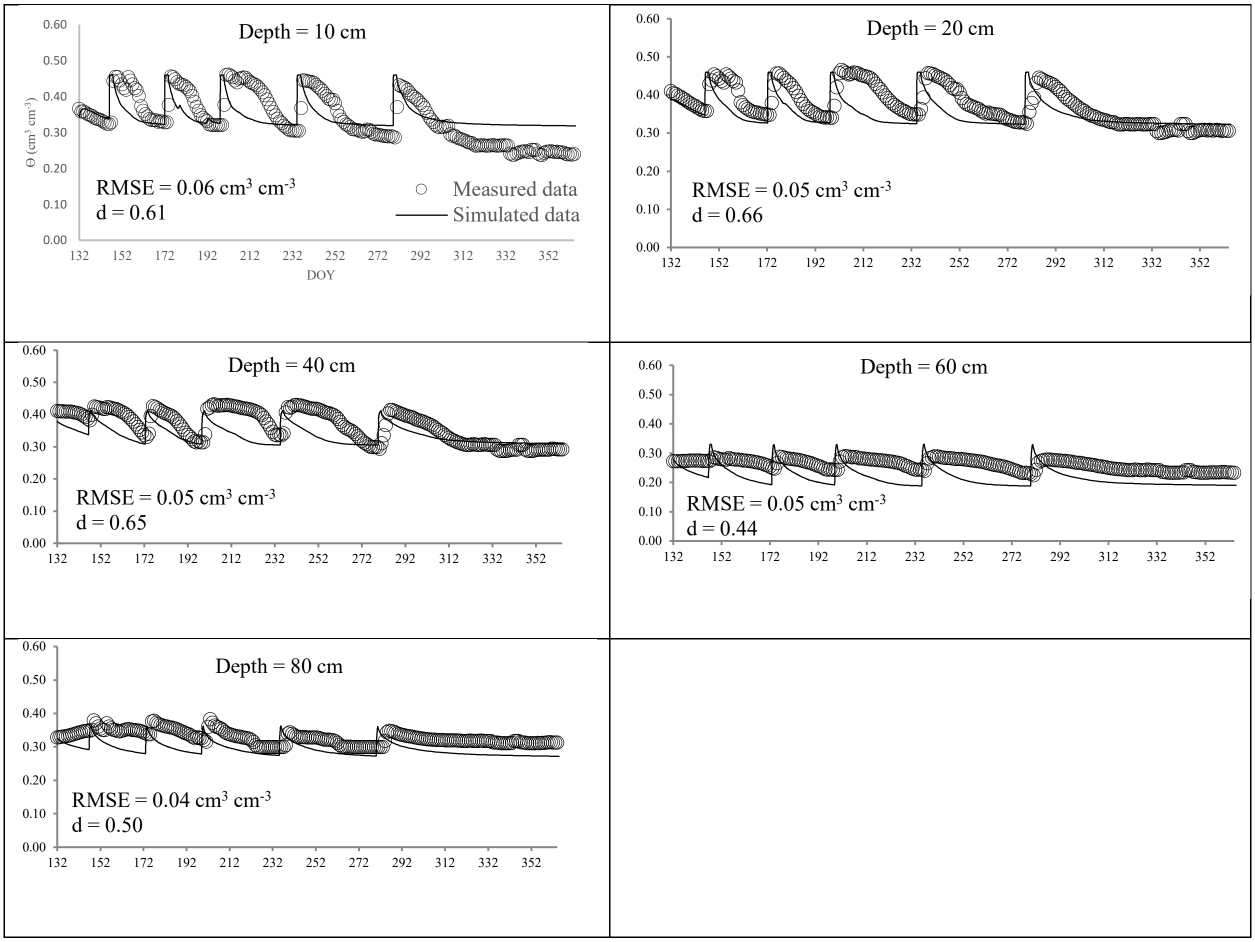

Fig. 2. Temporal variations in the simulated and measured θ at different soil depths during the validation time period from DOY 132 (12 May 2010) to DOY 364 (30 Dec. 2010).

5.2. Calibration and Validation for Solute Transport

Optimized water flow parameters (Table 3) and measured NO_3-N concentration profiles during 2015 were used for calibration. In this study, nitrification and denitrification parameters were adjusted and optimized for each soil depth separately (Table 3). The measured NO_3-N concentration profiles during 2016 were used for model validation.

Simulated and measured depth distributions of NO_3-N concentrations during two growing seasons, which represented calibration and validation periods, are presented in Fig. 3. Generally, Fig. 3 illustrates that the optimized set of solute transport/reaction parameters considered in model simulations (Table 3) was reasonable and applicable for simulating the N transport and transformations in the pecan orchard. Fluctuations in the measured and simulated NO_3-N concentration profiles at specified times showed that HYDRUS-1D simulated well ($0.36 \leq d \leq 0.79$) the patterns of NO_3-N concentration profiles for both 2015 and 2016 (Fig. 3). Predictions of depth distributions of NO_3-N concentrations were the best at all depths during the calibration period of June 2015 with d = 0.74 (Fig. 3b). However, simulated NO_3-N values had a relatively low d and high RMSE during the validation period of June 2016 (Fig. 3e). The model simulated very well ($0.99 \leq RMSE \leq 5.16$) NO_3-N concentrations below the rooting zone (approximately 60 cm for pecan) in all months during both years (Fig. 3). Since root nutrient uptake occurs in the rooting zone, NO_3-N below the rooting zone could leach to the groundwater.

Table 3. Optimized parameters of the calibrated flow and nitrogen-species transport model.

Material #	Depth interval (cm)	Water flow parameters (van Genuchten, 1980)				Nitrogen reaction parameters	
		θ_r	θ_s	n	K_s (cm d^{-1})	μ_{nit} (d^{-1})	μ_{dnit} (d^{-1})
1	0–20	0.09	0.46	1.11	5	0.13	0.015
2	20–40	0.1	0.42	1.11	5	0.11	0.017
3	40-60	0.15	0.34	1.4	25	0.22	0.006
4	60–100	0.24	0.37	1.4	25	0.21	0.002

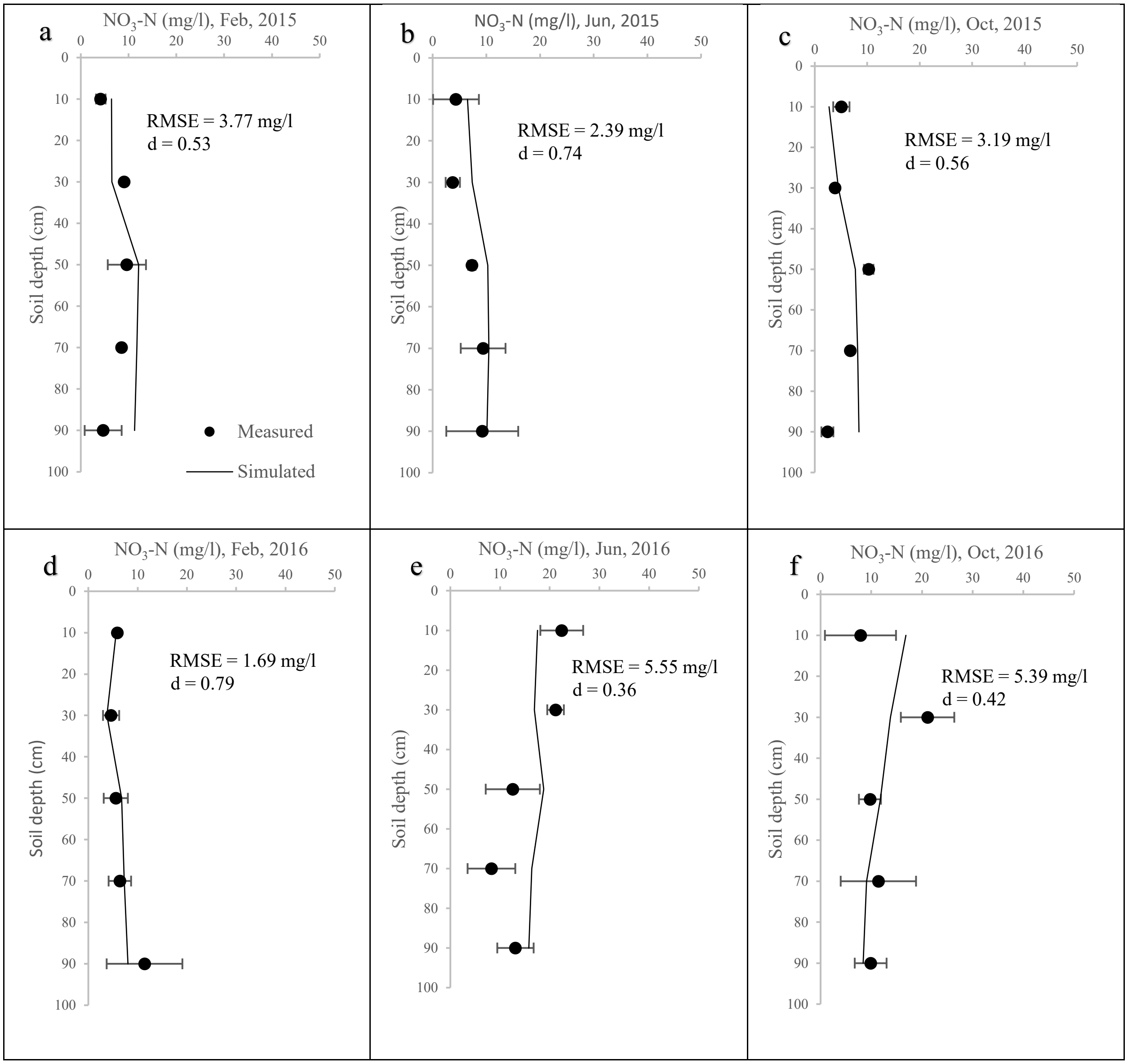

Fig. 3. Simulated and measured NO_3-N concentration profiles for days of soil sample collections during the calibration (a, b, c) and validation (d, e, f) periods of 2015 and 2016, respectively.

5.3. Root NO_3-N Uptake

A comparison of root NO_3-N uptake in 2015 and 2016 showed an increase of about 27 kg/ha in 2016, which was in agreement with approximately 48% more N fertilizer applied in 2016 than 2015 (Table 1). More N uptake was reported for rapeseed and maize when higher N application rates were applied (Tafteh and Sepaskhah, 2012). The growing season of 2016 was the alternate bearing or “off” year, when a higher fertilizer application and soil N increased root NO_3-N uptake in June 2016 (Fig. 4b; DOY 154–183). A 48% increase in the N fertilizer application (Table 1) resulted in a 72% increase in NO_3-N uptake in 2016 compared to that in 2015 (Fig. 4 and Table 4).

The nitrogen demand of pecan is high in June during the nut enlargement period and stays high during the subsequent nut filling stages (Acuña-Maldonado et al., 2003). The timing of fertilizer applications influences N absorption and partitioning as well as nut yield; therefore, the fertilizer application during the entire growing season should be taken into consideration. The first N application should be done before the bud break because absorption apparently takes place during the dormancy, followed by rapid N absorption during the shoot and leaf development (Acuña-Maldonado et al., 2003). A 5-year study assessed in pecan orchards showed that applying just 125 kg/ha N per year (less than one-third times the average N rate applied in our study) led to roughly 80 kg/ha of total N uptake (Acuña-Maldonado et al., 2003). The high N uptake efficiency could be explained by the difference in the type of irrigation system (drip irrigation vs. flood irrigation). Obviously, fertilizer management is more efficient in drip irrigation compared to flood irrigation.

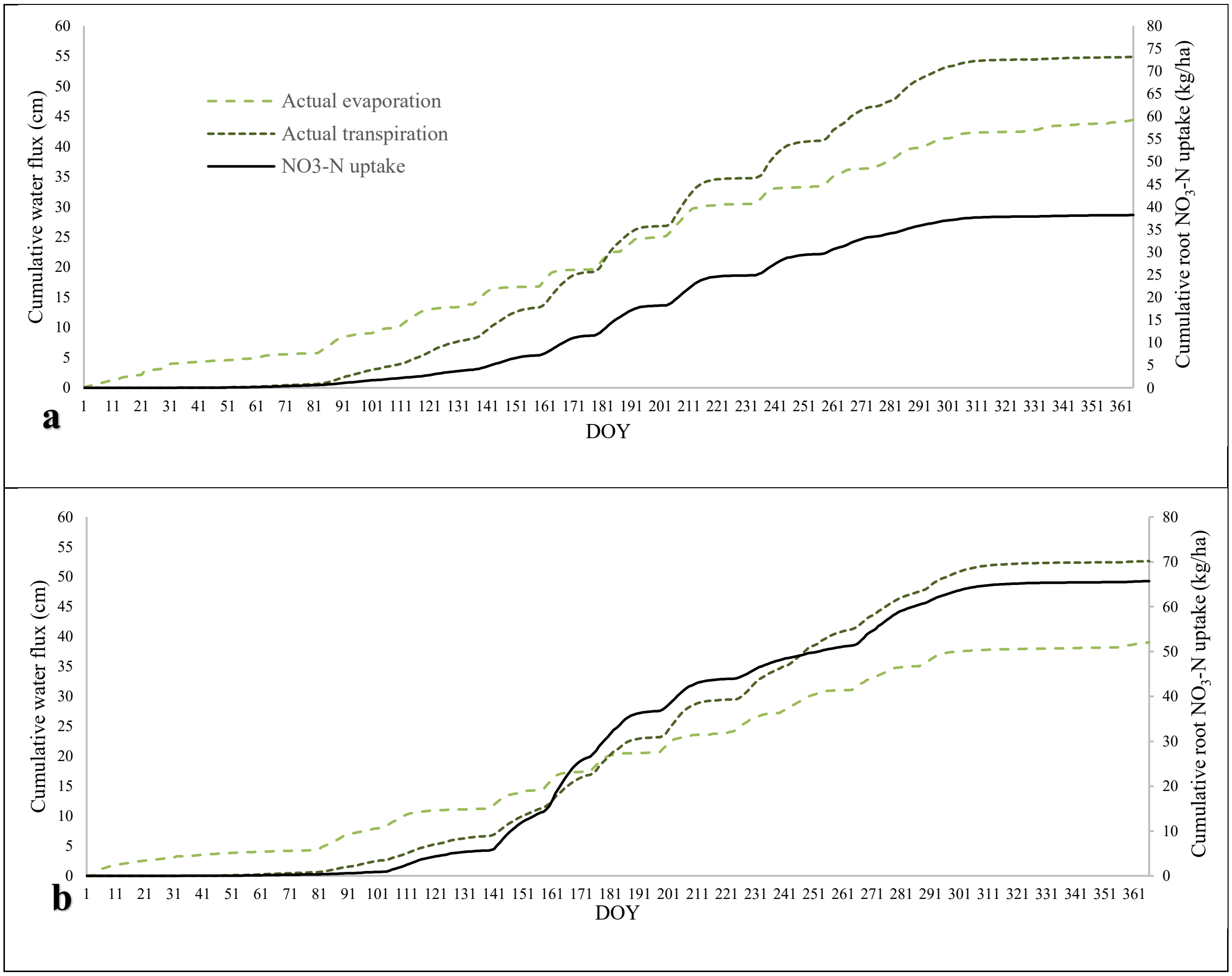

Fig. 4. Simulated cumulative total water fluxes (total actual evaporation and transpiration) (cm) and cumulative NO_3-N (kg/ha) removed from the flow domain by root uptake during the time periods DOY 1 (Jan. 1) to DOY 365 (Dec. 31) in (a) 2015 and (b) 2016.

5.4. NO_3-N Balance

The importance of the NO_3-N balance is to gain deeper understanding about fertilizer efficiency and fertilizer losses due to various processes. Table 4 shows simulated cumulative components of the NO_3-N balance (kg/ha) across the 100-cm soil profile during 2015 and 2016. The two inputs of NO_3-N were from applications of NO_3-N fertilizers and nitrification of NH_4-N to NO_3-N as a result of urea fertilizer applications (Table 1). From Table 4, all components of NO_3-N outputs were different between years because of differences in the amount and type of fertilizer applications (Table 1). Denitrification had a large contribution to the NO_3-N loss from the soil profile in both years, accounting for approximately 40% of applied NO_3-N each year (Table 4). NO_3-N leaching accounted for 32% and 26% of applied NO_3-N in 2015 and 2016, respectively.

To reduce NO_3-N leaching, more frequent but lighter applications of N fertilizers are highly recommended in flood-irrigated orchards. The soil NO_3-N storage increased on average by 14.15 kg/ha during both years. Total NO_3-N balance errors with HYDRUS simulations were less than 1% during both years.

Table 4. Cumulative components of the NO_3-N balance (kg/ha) across the 100-cm soil profile during 2015 and 2016.

Year	Input NO_3-N	Leaching	Denitrification	Root uptake	Change in soil storage	Total NO_3-N balance error
2015	+172.92	-56.03	-68.67	-38.2	-11.64	-1.62
2016	+254.43	-66.86	-105.47	-65.69	-16.65	-0.24

6. Presentations

Poster presentation titled as “Special Variability of Root Distributions in the Pecan Orchard” to the 63rd Annual New Mexico Water Conference

Poster presentation titled as “Modeling water and solute fluxes in a Pecan Orchard in Mesilla Valley” to the SSSA International Soils Meeting (January 6-9, 2019)

7. Publications

This report was published by Soil Science Society of America Journal: Published online May 23, 2019: Mokari,E., MK Shukla, J Simunek, and J Fernandez. 2019. Soil Sci Soc Am J, doi:10.2136/sssaj2018.11.0442

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