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Groundwater impacts of adding carrot to corn-peanut rotations in North Florida

Dogil Lee [a,*], Jason Merrick [b], Sagarika Rath [c], Michael Dukes [a,d], David Kaplan [e], Wendy Graham [a,f]

[a] Department of Agricultural and Biological Engineering, University of Florida, Gainesville, FL, USA
[b] Natural Resources Conservation Service, United States Department of Agriculture, Chestertown, MD, USA
[c] Blackland Research and Extension Center, Texas A&M University, Temple, TX, USA
[d] Center for Land Use Efficiency, University of Florida, Gainesville, FL, USA
[e] Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL, USA
[f] Water Institute, University of Florida, PO Box 116601, Gainesville, FL 32611-6601, USA

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ABSTRACT

The Upper Floridan aquifer underlying the Suwannee River Basin in Florida has experienced increased groundwater pumping and nitrate leaching over the last half century resulting in violation of water quantity and quality standards, largely due to row crop production. Increasingly carrot is being added as a winter cash crop to the traditional corn-peanut rotation in the region which may further increase pumping and nitrogen leaching. Establishing carrot nitrogen and irrigation best management practices is therefore critical to help growers meet yield goals while minimizing groundwater quantity and quality impacts. In this study, a carrot cultivation field experiment was conducted to evaluate the effects of a range of irrigation and nitrogen fertilizer practices on irrigation demand, nitrogen uptake and carrot crop growth and yield. Results showed that soil moisture sensor-based irrigation reduced the amount of water used for carrot cultivation by approximately 30% over the calendar-based irrigation without statistically significant reductions in yield, and fertilization rates above 224 kg ha^{-1} showed no statistically significant increase in yield. A field-scale SWAT carrot model was calibrated using the field experiment data and validated using previously published experimental results. The carrot parameters were then incorporated into a watershed-scale SWAT model of the Santa Fe River Basin, a tributary of the Suwannee River, and used to assess groundwater recharge and nitrate leaching impacts of adding carrot into corn-peanut rotations across all row crop lands in the watershed. Modeling results showed that adding carrot cultivation to the rotation will increase irrigation by 32–43% and decrease net groundwater recharge from row crop land by 9–28%. Moreover, it will increase nitrate leaching from row crop land by 60–100%. These results indicate that adding carrot cultivation to the conventional corn-peanut rotation will make water quantity and quality standards in the region more difficult to achieve.

1. Introduction

Global groundwater demand has increased significantly over the last century due to increasing human population and associated agricultural and industrial development (Scanlon et al., 2023). In the United States (US), groundwater withdrawals increased from 128,700,000 m^3 day^{-1} to more than 310,400,000 m^3 day^{-1} between 1950 and 2015, an increase of approximately 140% (Dieter et al., 2018). This rapid increase in abstraction has caused groundwater decline and depletion in many US aquifers, including the Ogallalla, Atlantic Coastal Plain, West-Central Florida, and Gulf Coastal Plain aquifers, among others (Bartolino and Cunningham, 2003; Bierkens and Wada, 2019; Konikow, 2013; Konikow and Kendy, 2005; Scanlon et al., 2012). Negative societal effects of groundwater depletion include reduced or eliminated well yields, reduced groundwater flows to surface water bodies, irreversible land subsidence, damage to aquatic ecosystems, and desiccation of wetlands (Alley et al., 1999; Bartolino and Cunningham, 2003; Harrington et al., 2007; Konikow, 2015).

Contemporaneous with groundwater depletion, aquifer contamination from human activities such as urbanization, industrial activity, and

* Corresponding author.
E-mail address: lee.d@ufl.edu (D. Lee).

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intensive agriculture production further threatens groundwater sustainability. Along with other land uses, agricultural systems are a major source of nutrients leaching to groundwater (Burkart and Stoner, 2002; Fowler et al., 2013; Lemaire and Gastal, 1997; Pratt, 1984). For example, it was estimated that more than 70% of nitrogen delivered to the Gulf of Mexico originates from agriculture (Alexander et al., 2008), and approximately 96% of groundwater nitrate in the Tulare Lake Basin and Salinas Valley originates from crop lands (Viers et al., 2012). Nitrate entering surface water bodies can cause eutrophication that may lead to mass morality of fish and algae blooms (Cameron et al., 2013). Furthermore, nitrate can easily leach into groundwater due to its high solubility in water, and this can cause critical health issues such as methemoglobinemia where the groundwater is the major source of drinking water (Brender et al., 2013; Bryan et al., 2012; Fewtrell, 2004; Ward et al., 2010).

The Floridan aquifer (FA) underlying the southeastern US is one of the most productive aquifers in the world (Miller, 1990). The Upper Floridan aquifer (UFA) provides drinking water for nearly 10 million people and supports an agricultural economy valued at $7.5 billion (Martin, 2017). Total groundwater withdrawals from the FA increased by more than 5 times between 1950 and 2015 (Marella, 2020). Increased groundwater withdrawals in Florida have caused reduced flows or water levels in many groundwater-fed aquatic ecosystems, requiring the implementation of recovery plans under the state-mandated Minimum Flows and Levels (MFL) program (FS 373.042/FAC 62–40.473; Munson et al., 2005). At the same time, pollutant loads to the aquifer from human activities have increased nutrient concentrations both in the FA and in the freshwater springs it feeds. As a result, in some springs nitrate (NO_3) concentrations have increased by as much as 250% in the past few decades (The Howard T. Odum Florida Springs Institute, 2017). Twenty-four out of 30 Outstanding Florida Springs fed by the FA do not meet the Florida Department of Environmental Regulation (FDEP) Numeric Nutrient Criteria (NNC) of 0.35 mg NO_3-N L^{-1} set for Florida springs (FDEP, 2018a).

Increasing aquifer withdrawals and nutrient contamination are linked with agricultural production in northern Florida, which is economically vital to the region and state. In 2014, agricultural sales from Florida counties within the Suwannee River Basin (SRB; Fig. 1) totaled over $1.1 billion. In Suwannee County alone, agriculture was responsible for supporting 45% of all employment and producing $350 million in farm receipts (BEA, 2014). Agricultural land uses in the Florida portion of the SRB consist mostly of row crops (typically corn and peanut in rotation; Marella et al., 2016), with smaller areas of fruit crops, field crops, plant nurseries, and sod farms. Approximately 18% of these crop lands are irrigated (almost exclusively via groundwater), representing a 100% increase over the last 20 years. The percentage of irrigated crop land is expected to increase by an additional 40% by 2040 (FDACS, 2019). Agricultural production systems have been identified as the primary source of nitrogen loading to the FA in the region (FDEP, 2018a, 2018b). It is estimated that meeting the mandated NNC will require a load reduction of nearly 2 million kg N $year^{-1}$, largely from agricultural lands (Division of Environmental Assessment and Restoration, 2018b).

Increasing water and fertilizer use to support agricultural production makes it more difficult to meet regulations intended to protect groundwater and surface water quantity and quality (i.e., MFL and NNC regulations). Nevertheless, with recent drought and expanded groundwater regulations in the western United States, and the availability of new processing infrastructure in Florida, carrot production is gaining popularity as a winter cash crop among row crop producers in north

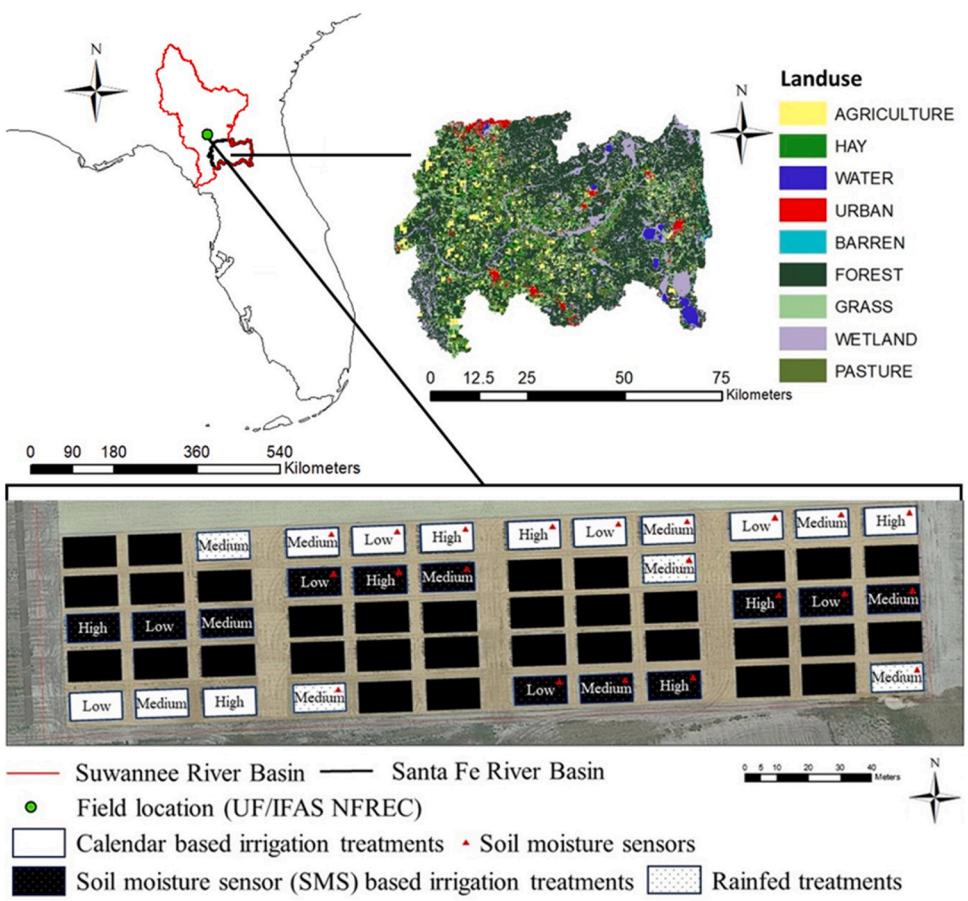

Fig. 1. Santa Fe River Basin land use (top right), and carrot plots and treatment locations for randomized complete block design. High, Medium, and Low designate Low, Medium, High fertilization treatments, respectively (bottom).

Florida (Treadwell, 2017; Hochmuth et al., 2021; Rusnak, 2021). The region's deep, sandy soils and moderate winter temperatures are well suited to carrot production, and many producers already have center pivot irrigation systems that can be used to irrigate carrots incorporated into a corn-peanut rotation.

The conventional corn-peanut rotation, which is the most common row crop rotation in the SRB, consists of planting corn in March and harvesting it in August one year, followed by planting peanut in May and harvesting it in September of the next year, sometimes with a cover crop between the two (Rath et al., 2021). Increasingly, farmers are adding carrot cultivation between corn and peanut, planting in November and harvesting in April (Hochmuth et al., 2021). While the addition of this winter cash crop benefits farmers' revenue, it has the potential to increase groundwater pumping and nitrogen leaching to the FA. Establishing carrot best management practices (BMPs) with respect to nitrogen and irrigation management is therefore critical for helping growers meet yield goals while minimizing the water quantity and quality impacts of adding an additional crop to the traditional corn-peanut rotation.

Establishing carrot BMPs for the region requires new field research and modeling efforts to quantify the impacts of water and nutrient management practices on carrot yields, irrigation requirements, net recharge and nitrate leaching to the UFA. In this study a BMP experiment was conducted at the North Florida Research and Education Center-Suwannee Valley (NFREC-SV) to evaluate the effects of range of irrigation and nitrogen fertilizer practices on carrot irrigation requirements, crop growth, nitrogen uptake, and yield. In turn, these observations were used to calibrate carrot growth parameters for a field-scale Soil and Water Assessment Tool (SWAT) model, which was used to estimate crop yields and water and nutrient budgets for experimental irrigation and nitrogen management practices. After calibration and validation of the field-scale carrot model, a previously calibrated watershed-scale SWAT model (Rath, 2021) was used to estimate nitrate leaching and groundwater recharge impacts of incorporating carrot into the traditional corn-peanut rotation across all row crop lands in the Santa Fe River Basin, a spring-fed tributary of the Suwannee River. The study had two primary objectives: quantify the impacts of alternative water and nutrient practices on carrot yield, nitrate leaching and groundwater recharge using field experiments and a field-scale SWAT model and; assess the regional nitrate load and groundwater recharge impacts of adding a winter carrot crop to the corn-peanut rotation throughout all row crop lands in the Santa Fe River basin using a watershed-scale SWAT model.

2. Materials and methods

2.1. Field experiment

The carrot BMP field experiment was conducted at the North Florida Research and Education Center – Suwannee Valley (NFREC), located near Live Oak, Florida (3018′22″ N, 8254′00″ W). Carrot was planted in November 2018 and harvested in May 2019, between a corn crop cultivated from March to August 2018 and a peanut crop cultivated from May through September 2019. Whole-plot treatments were four carrot irrigation scheduling methods and subplots were six carrot fertilization rates, each with four replicates (one in each of four blocks). The experiment used a randomized complete block design with split, 1.5-ha plots (Fig. 1). Each plot was 12 m long and 6 m wide with 6 m lanes separating the plots and 12 m lanes separating the blocks. For this study, we focused on a subset of seven treatments with the most available field data: two irrigation scheduling methods, each with three fertilization rates, and one non-irrigated (rainfed) control treatment, described in detail below.

2.1.1. Irrigation

Irrigation was applied by a Valley linear end feed 8000 (Valley, NE) with two spans, a variable rate controller, and ten banks of sprinklers controlled by separate solenoids. Irrigation was supplied by a dedicated well installed into the UFA. The three irrigation treatments included in this study were Calendar, Soil Moisture Sensor (SMS), and Rainfed.

The calendar-based irrigation treatment represented regional grower irrigation practices and was scheduled by the NFREC farm manager. The general strategy was to add 0.75 cm every three days, in the absence of precipitation, from day of planting until the plants were established and no longer in danger of being injured by blowing sand. From 90 days after planting (DAP) to maturity, 1.25 cm of irrigation was applied every three days in the absence of precipitation over 0.65 cm. In the Soil Moisture Sensor (SMS) based irrigation treatment, soil water was monitored with 26 Sentek, TriScan "drill&drop" soil moisture sensors (Stepney South, Australia). These instruments contain nine capacitance-type sensors spaced 5 cm apart down to 1 m, each of which integrates soil moisture, volumetric ion content (a proxy for EC), and soil temperature over 10 cm (5 cm above and below the sensor). Irrigation was applied at a maximum allowable depletion (MAD) of 50% of plant available water (PAW) for the duration of the growing season. Sensors were monitored via a web portal daily. When the 25th percentile of the aggregated sensor readings in the SMS treatment was below the MAD, 10 mm of water was applied to all plots in that treatment. The rainfed treatment was a non-irrigated control treatment and irrigation was only applied as necessary to establish the plants and incorporate any applied fertilizers into the soil.

2.1.2. Fertilization

Three nitrogen fertilization treatments were selected to bracket the University of Florida Institute for Food and Agricultural Sciences (UF/IFAS) recommendations for carrot (Hochmuth et al., 2021): 112 (Low), 224 (Medium), and 336 (High) kg N ha^{-1} (Table 1). The rainfed treatment received the medium fertilizer rate. Granular fertilizer was applied in nine separate applications starting at 30 DAP, with subsequent applications approximately every two weeks. A preplant application of 0–15–0 (P_2O_5) was applied prior to forming beds. Fertilizer application dates, amounts, and types are summarized in Table 1.

Table 1
Fertilizer application dates and amounts.

Date	Nitrogen fertilizer (kg N ha^{-1})			Potassium fertilizer (kg K_2O ha^{-1}; all treatments)
	Low	Medium	High	
Preplant (11/07/18)	28	28	28	70
12/11/18	10.5	24.5	38.5	0
12/22/18	10.5	24.5	38.5	0
01/07/19	10.5	24.5	38.5	70
01/17/19	10.5	24.5	38.5	0
01/30/19	10.5	24.5	38.5	70
02/14/19	10.5	24.5	38.5	0
03/04/19	10.5	24.5	38.5	70
03/20/19	10.5	24.5	38.5	0
Total	112	224	336	280

2.1.3. Agronomic practices

A previous corn crop was harvested on 8/23/18 and fields were disced twice with a Landoll harrow, once on 8/29/18 then again on 9/26/18 to prepare for bottom plowing the following day. Telone II was applied on 10/3/18 at a rate of 131 liters/ha. Treflan herbicide and Diazinon insecticide were applied and incorporated on 11/5/18. A John Deere leveling disc was used the following day to smooth the field and prepare for forming beds.

All preplant fertilizers were incorporated into the plots with a KMC rototiller on 11/8/18. After rototilling, 1-m wide beds were formed in an East-West direction with a spacing of 1.8 m. This spacing was required due to equipment limitations on the research farm, however the amount of fertilizer and seed placed on the bed-top was calculated based on a standard bed spacing of 1.3 m. On 11/19/18, a Seed Spider (sponge type 1) high-density planter outfitted with two metering units with four lines per unit was used to plant Maverick variety carrots at a density of 12,350,000 seeds ha^{-1}. The beds were then sprayed with Ridomil, Quadris, and Macho fungicides. Harvest occurred on 4/30/19. A 12-m length of the center plant bed was machine harvested with a Nobels 3.15 bed-lifter type harvester. Average carrot weight, diameter, and length was recorded from a sub-sample of 20 representative carrots from each bag.

2.1.4. Soil and Tissue Sampling

The site is comprised of Hurricane, Chipley, and Blanton soils that all consist of more than 90% of sand (USDA, 2019), with clay contents of 2% or less. Field capacity, permanent wilting point, available water content and saturated hydraulic conductivity of the fields ranged from 1.8% – 15.1%, 0.1%– 8.7%, 0.03 cm cm^{-1}-0.13 cm cm^{-1}, and 15 cm hr^{-1}-51 cm hr^{-1}, respectively (USDA, 2013).

Soil moisture was measured with soil moisture sensors installed in blocks 2, 3, and 4 of each treatment. Soil moisture sensors collected soil moisture data at 10-cm intervals up to 90 cm below the soil surface every 30 min. Daily soil moisture data was aggregated by summing soil moisture of the active root zone in the soil profile by each time step and averaging them daily.

Soil nitrate samples were collected at 0–15 cm, 15–30 cm, 30–60 cm, and 60–90 cm for each sampling location, stored in plastic sample bags, and placed on ice until they were transported to the lab. In the lab, soil samples were divided into two 100-g samples. The first was placed in the drying oven at 105 ℃ for 48 h then re-weighed to calculate gravimetric water content. The second was allowed to air dry for 48 h, sieved to 2 mm, bagged, and sent to the University of Florida/IFAS Analytic Research Laboratory (ARL) on the UF campus for Total Kjeldahl Nitrogen (TKN) analysis. A potassium chloride extractant was used to recover ammonium and nitrate, quantified using colorimetry in accordance with EPA Method 351.2 (USA EPA, 1993).

Tissue samples were collected in Medium N sub-plots within the Calendar, SMS and Rainfed irrigation treatments three times during the growing season and once just prior to harvest. The final sampling event was scheduled during the same week as harvest, when all plots were sampled. A row length of 1 m in one of the non-harvest rows was sampled and individual carrots were counted and separated from the above ground biomass. Samples were placed in a forced-air drying room for 48 h or until completely dry. As carrots matured it became necessary to cut them into smaller pieces and allow up to 72 h for drying.

Carrot samples were then ground in a Wiley mill with a 1-mm mesh screen, placed in in plastic bags, and sent to the IFAS Forage Evaluation Support Laboratory where TKN content (reported as elemental N as a percentage of total dry matter), was measured using a modified version of the TKN method. Samples were digested using a modified, aluminum block digestion procedure as outlined by (Gallaher et al., 1975). A catalyst of 1.5 g of 9:1 K_2SO_4:$CuSO_4$ was added to a 0.25 g sample. Digestion occurred for at least 4 h at 375 ℃ using 6 ml of H_2SO_4 and 2 ml of H_2O_2. Nitrogen content of the digestate was determined by semiautomated colorimetry (Hambleton, 1977).

Statistical analysis of experimental yields across treatments was completed using one-way ANOVA with Bonferroni post-hoc test (Bland and Altman, 1995) to evaluate potential interactions among irrigation treatments and fertilization treatments and post-hoc Tukey's Honest Significant Difference (HSD) method of multi-comparisons (Tukey, 1949) to evaluate differences among treatments. A confidence interval of 95% was utilized for all comparisons.

2.2. Field-scale Model

The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is a continuous, semi-distributed, physically based model which is widely used throughout the world to simulate surface and subsurface water, crop growth, and nutrients and sediment transport. SWAT has operations that can represent many water and nutrient management practices, so it is often used to evaluate the impacts of alternative agricultural practices on water, nutrients, and crop yield (Arabi et al., 2008; Karki et al., 2020; Khalid et al., 2016). In SWAT, a watershed is delineated into sub-basins based on a Digital Elevation Model (DEM), and each sub-basin is delineated into a number of Hydrologic Response Units (HRUs), which are unique combinations of soil, slope, and land use (Arnold et al., 2012; Neitsch et al., 2011). Overall hydrologic and nutrients balances are simulated for each HRU, and thus each HRU can be used to simulate the effects of alternative crop, water and nutrient management practices on groundwater recharge, evapotranspiration, nitrate leaching and crop yield at the field scale (Arnold et al., 2012; Gassman et al., 2007; Gitau et al., 2004).

The plant growth algorithm in SWAT uses a simplified version of Environmental Impact Policy Climate (EPIC) plant growth model (Williams et al., 1984). Phenological plant development is based on daily accumulated heat units, and plant growth can be hindered by water, temperature, nitrogen, or phosphorus stresses. Once the accumulated heat unit reaches potential heat unit of the plant, the plant attains maturity and stops growing (Neitsch et al., 2011).

In this study, a field-scale SWAT model was built to calibrate the crop growth parameters for carrot using observed carrot biomass over time, nitrogen content in biomass over time, and final yield from the field experiment. The field-scale model was set up with seven HRUs, one for each treatment. Management information such as planting and harvest dates, fertilizer application and irrigation schedules used in the experiment was directly used to set up the SWAT model. The irrigation source for the model was set to an unlimited source outside of the simulation domain since the irrigation source for the experiment was the UFA located approximately 3 m below the land surface, with no interaction between root zone and the aquifer (Hunn and Slack, 1983).

Daily weather data (precipitation, maximum temperature, minimum temperature, average wind speed, and solar radiation) were acquired from the Florida Automated Weather Network (FAWN) Live Oak station, which is located at the experimental site. Soil characteristics such as soil bulk density, soil texture and organic carbon content were taken from measurements made by Zamora-Re et al. (2018) for a corn-peanut BMP field experiment previously conducted at the same site from 2015 to 2017. Rath et al. (2021) developed a field-scale corn-peanut rotation SWAT model using the data from the Zamora-Re et al. (2018) experiment. The soil parameters calibrated by Rath et al. (2021) were adopted for the field-scale carrot SWAT model developed in this study since the Zamora-Re et al. (2020) field experiment was conducted at the same site where the carrot experiment reported in this study was performed. The calibrated soil parameters were further evaluated by comparing predicted soil moisture and soil nitrate concentrations to the experimental data obtained in the carrot experiment.

Critically, two bugs were identified in SWAT2012 ver. 664 when simulating the carrot experiment and long-term scenarios. First, in SWAT, accumulated heat units are reinitialized on the first day of a year even for cool season crops that are planted before and harvested after this date. This reinitialization affected carrot growth substantially and

resulted in inaccurate nitrate leaching and yield estimates. The second bug identified was that root vegetables, which typically have a HVSTI (harvest index for optimal growing conditions) parameter greater than 1.0, can result in a large amount of residue after harvest, which can cause unrealistically high mineralization (i.e., the amount of residue can be greater than final biomass). This bug can result not only in high nitrate leaching but also in higher biomass and yield of peanut in the following season. We thus modified the SWAT2012 rev. 664 source code to address these issues (code modification included in Appendix A).

Calibration of carrot plant parameters was conducted with the Sequential Uncertainty Fitting (SUFI-2) algorithm (Abbaspour et al., 2004) in the SWAT Calibration and Uncertainty Procedures (SWAT-CUP) software (Abbaspour, 2011) using the Nash-Sutcliffe Efficiency (NSE) as the objective function. Calibrated carrot parameters were then validated using carrot yields from a previous experiment conducted at the same location, which compared carrot yields under eight fertilizer rates ranging from 56 to 448 kg N ha^{-1}. (Hochmuth et al., 2021). The model was also validated using soil moisture and soil nitrate data from the field experiment. Three statistical indices were used to assess model results in the context of variability and uncertainty in observed values: the modified Nash Sutcliffe Efficiency (NSE_M; Harmel et al., 2010; Harmel and Smith, 2007), modified Root Mean Squared Error ($RMSE_M$), and percent bias (PBIAS). Statistical analysis was conducted using FITEVAL (Ritter and Muñoz-Carpena, 2013), and evaluation criteria suggested by Moriasi et al. (1995, 2007) were used to describe model performance.

2.3. Watershed-scale Model

Rath (2021) developed a watershed-scale SWAT model for the Sante Fe River Basin, a tributary of the SRB, and used the model to assess the impacts of land use and land management practices on streamflow and stream nitrate in the Santa Fe River. Rath (2021) used the USGS National Elevation Dataset DEM, USDA Soil Survey Geographic Database (SSURGO) soils data, National Agricultural Statistics Service (USDA NASS) 2017 Cropland Data Layer land cover data, North American Land Data Assimilation System (NLDAS) weather data, and crop and forest growth parameters from previous experimental and modeling research studies to develop the model. The model was calibrated and validated using available streamflow and stream nitrate measurements in the Santa Fe River, as well as USGS SEEBop actual evapotranspiration estimates from remote sensing measurements (Senay et al., 2013). In this study, this previously calibrated Santa Fe River Basin SWAT model was used to assess nitrate leaching and groundwater recharge impacts of incorporating carrot into the traditional corn-peanut rotation on all row crop land in the watershed (Fig. 1).

Three corn-peanut and corn-carrot-peanut rotation Management Systems (MSs) were developed to span the range of current cultivation practices in the region (Table 2). MSs were co-developed in consultation with agricultural stakeholders and Extension professionals through a participatory modeling process (Bartels and Furman, 2023). Fixed planting dates, harvest dates and fertilizer application dates were adopted through all 39 years of simulation period for ease of simulation. Ammonium nitrate fertilizers were applied using a split application method, and the amount of fertilizer per application and application dates used in the Zamora-Re et al. (2018) corn-peanut field experiment and the carrot field experiment reported here were adopted for the long-term simulations.

Soil moisture sensor-based irrigation in MS 1 and MS 2 was simulated using the auto-irrigation operation in SWAT based on plant water demand. Based on the SMS-based irrigation treatments in the field experiment, the threshold plant demand used to trigger carrot irrigation was estimated to be 0.60, and irrigation volumes of 10 mm per application were used. Based on Rath et al. (2021), a threshold plant demand of 0.65 was used for both corn and peanut, and irrigation volumes per application were 12.70 mm for corn and 10.16 mm for peanut. Calendar-based irrigation schedule rules for corn, carrot and peanut were developed in consultation with University of Florida Extension Specialists.

The Santa Fe River Basin SWAT model was used to simulate corn-peanut and corn-carrot-peanut rotations on all 2017 mapped row-crop land uses, using weather data from 1980 to 2018. A three-year warmup period from 1977 to 1979 was utilized incorporating weather data from the SWAT weather generator (Neitsch et al., 2011). Each of the three management systems was simulated for each rotation and crop yields, nitrate leaching, and net recharge to groundwater (percolation minus irrigation water pumped) were compared. One-way ANOVA with post-hoc Tukey's HSD test and a confidence interval of 95% was utilized for all comparisons.

3. Results and discussion

3.1. Field Experiment Results

Cumulative precipitation during the 2018–2019 carrot cultivation period was 522.0 mm, and the depth of irrigation water applied was 248.9 mm, 170.2 mm, and 58.4 mm in the calendar, SMS, and rainfed treatments, respectively (Fig. 2). There was no interaction effect between irrigation treatments and fertilization treatments according to the results of the Bonferroni post hoc test. Therefore in Fig. 3 irrigation treatments were lumped, including all fertilization levels within each irrigation treatment, and fertilizer treatments were lumped, including calendar- and SMS-based irrigation treatments within each fertilization level (the rainfed treatment was excluded since it only incorporated the Medium-N treatment). There was no significant difference in harvested yield dry weight (hereafter referred to as "yield") between the Calendar and SMS treatments based on Tukey's HSD test (Fig. 3a). SMS-based irrigation scheduling thus used 32% less water than calendar scheduling with no statistical difference in final yield. The Low-N treatment had significantly lower average yields (6488 kg ha^{-1}) than the Medium-

Table 2
Corn-carrot-peanut management systems for watershed scale model.

Management System (MS)	Water management	Nitrogen management	Cover crop
MS 1 (low input with fall/winter cover crop)	SMS-based irrigation with 85% irrigation efficiency	247 kg N ha^{-1} for corn 224 kg N ha^{-1} for carrot 0 kg N ha^{-1} for peanut	Rye planted in October after peanut is harvested
MS 2 (medium input with winter cover crop)	SMS-based irrigation with 80% irrigation efficiency	291 kg N ha^{-1} for corn 280 kg N ha^{-1} for carrot 7 kg N ha^{-1} for peanut	Oats planted in December after peanut is harvested
MS 3 (high input with no cover crop)	Calendar based irrigation with 70% irrigation efficiency	336 kg N ha^{-1} for corn 336 kg N ha^{-1} for carrot 13 kg N ha^{-1} for peanut	No cover crop

SMS: soil moisture sensor

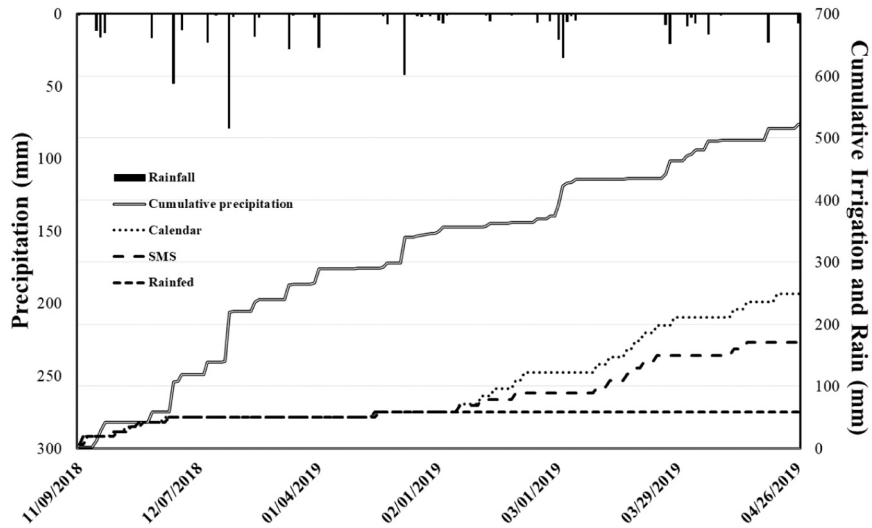

Fig. 2. Precipitation and cumulative irrigation during the carrot cultivation period.

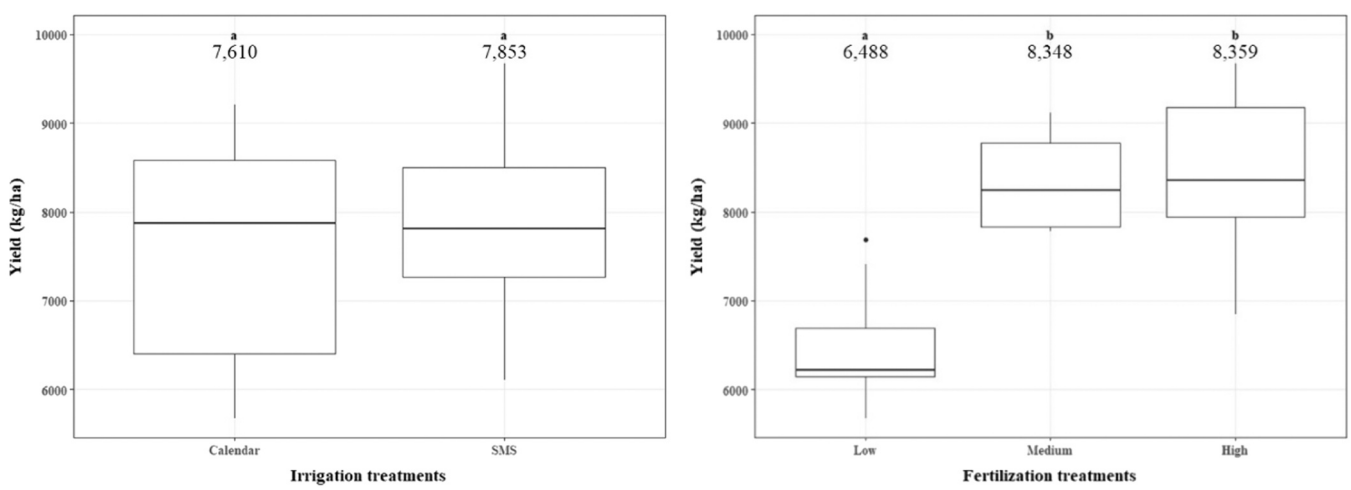

Fig. 3. Measured carrot dry biomass yield by treatments (left: measured carrot yield by irrigation treatments, right: measured carrot yield by fertilizer treatments; different letters indicate significant differences; numbers under the letters represent average yield).

and High-N treatments (8348 and 8359 kg ha^{-1}, respectively, Fig. 3b) which were found to be statistically similar. Average yields by N fertilization treatment showed less than 5% difference compared to the empirical equation for carrot yield response to N application developed in Hochmuth et al. (2021).

These results indicate that the lowest experimental nitrogen fertilization rate (112 kg N ha^{-1}) was not sufficient to produce optimal carrot yield at the study site, but that application of nitrogen fertilizer beyond the medium fertilization rate (224 kg N ha^{-1}) did not lead to a statistically significant increase in yield under the conditions tested. These results are consistent with carrot experiments previously conducted in the region, which reported total nitrate uptake of 213.6 kg N ha^{-1} (Hamilton and Bernier, 1975) and optimal N fertilizer application rate of 206 kg N ha^{-1} (Hochmuth et al., 2021). It should be noted that optimal N fertilizer application rates vary depending on soil mineral N content, soil characteristics, and the occurrence of large rainfall events that may leach N from the soil. The study site described here is composed of sandy soil prone to nitrate leaching, thus N applications exceeding the potential N uptake over time may be lost to groundwater causing environmental harm (Zamora-Re et al., 2020; Gholamhoseini et al., 2013).

3.2. Field-scale model calibration and validation results

3.2.1. Calibration

The most sensitive carrot crop growth parameters in SWAT were biomass-energy ratio (BIO_E), maximum potential leaf area index (BLAI), two parameters related to the optimal leaf area development curve (LAIMX2 and FRGRW2), and the base temperature for plant growth (T_BASE) (Table 3). Nitrogen uptake (calculated as the product of sample weight and tissue nitrogen content) and biomass were both predicted well, with $NSE_M > 0.95$ in all treatments (Table 4, Fig. 4). While the model slightly underpredicts the final observed mean biomass and nitrate uptake in the calendar-based irrigation treatment, and slightly overpredicts final observed mean biomass in the rainfed treatment, simulated values fell within the range of observed data. Using calibrated crop parameters, the model predicted carrot yield with $R^2 = 0.80$, $RMSE_M = 597.0$ kg ha^{-1}, and PBIAS = −1% across treatments (Fig. 5), indicating good performance, although as with total biomass, yields for the rainfed treatment were slightly overpredicted.

Like the field experiment, the model predicted substantially lower yields for the Low-N treatment than the Medium- or High-N treatments, which were very similar, and comparable yields between the calendar

Table 3
Calibrated carrot parameters in the SWAT model.

Parameters	Description	Default value	Calibrated value	p-value	t-stat
EPCO	Plant uptake compensation factor	1.00	0.21	0.23	-1.20
HVSTI	Harvest index for optimal growing conditions	1.12	0.96	0.21	-1.25
BIO_E*	The amount of dry biomass produced per unit intercepted solar radiation ((kg ha^{-1})/(MJ m^{-2}))	30.00	33.66	0.00	5.90
BLAI*	Maximum potential leaf area index	3.50	3.31	0.02	2.30
LAIMX1	Fraction of the maximum leaf area index corresponding to the 1st point on the optimal leaf area development curve	0.15	0.12	0.49	-0.69
LAIMX2*	Fraction of the maximum leaf area index corresponding to the 2nd point on the optimal leaf area development curve	0.50	0.57	0.00	-66.66
FRGRW1	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 1st point on the optimal leaf area development curve	0.01	0.01	0.95	0.06
FRGRW2*	Fraction of the plant growing season or fraction of total potential heat units corresponding to the 2nd point on the optimal leaf area development curve	0.95	0.82	0.03	-2.12
T_OPT	Optimal temperature for plant growth (℃)	24.00	25.47	0.70	0.39
T_BASE*	Base temperature for plant growth(℃)	7.00	6.36	0.00	-4.05
PLTNFR(1)	Normal fraction of nitrogen in plant biomass at emergence (kg N kgbiomass^{-1})	0.0550	0.0506	0.62	0.49
PLTNFR(2)	Normal fraction of nitrogen in plant biomass at 50% maturity (kg N kgbiomass^{-1})	0.0075	0.0238	0.55	0.60
PLTNFR(3)	Normal fraction of nitrogen in plant biomass at maturity (kg N kgbiomass^{-1})	0.0012	0.0174	0.80	0.26

If absolute value of t-stat of a parameter is larger than standard error, the parameter is sensitive. If the p-value is lower than 0.05, it was assumed that null hypothesis that the coefficient has no effect can be rejected.

* The parameters that are sensitive based on t-stats and p-values

Table 4
Statistical indices from calibrated carrot parameters.

Items	Treatments	NSE_M	$RMSE_M$ (kg ha^{-1}; kg N ha^{-1})	PBIAS (%)
Biomass	Calendar – Medium	0.98	731.06	-10.5
	SMS – Medium	1.00	94.60	-3.4
	Rainfed – Medium	0.95	552.66	17.2
Nitrogen uptake	Calendar – Medium	0.97	11.15	-5.5
	SMS – Medium	0.99	5.89	1.2
	Rainfed – Medium	0.93	11.11	17.2

SMS: soil moisture sensor

and SMS irrigation treatments. Based on the yield data illustrated in Fig. 5, it is apparent that carrot yield for the calendar-based irrigation – High-N treatment exhibited slightly (but not statistically significantly) higher yield compared to the SMS-based irrigation – High-N treatment, and higher yield than reported by other researchers conducting similar N rate experiments for carrots in the region (Hochmuth et al., 2021; Westerveld et al., 2006). This unexpected result could be the result of local-scale variation in soil characteristics across the experimental field that led to the calendar-based irrigation High-N treatment producing higher yields in some experimental plots but was not reproduced by the best-fit calibrated SWAT carrot parameters which assumed the same soil across the experimental field. Also, as six out of seven treatments were irrigated treatments, the calibration may have insufficiently accounted for water stress, leading to an overprediction of biomass in the rainfed treatment.

3.2.2. Validation

To validate the calibrated carrot parameters, the calibrated model was used to simulate yields from the Hochmuth et al. (2021) field experiment (Fig. 6). The NSE_M, $RMSE_M$ and PBIAS values for the two-year average yield predictions were 0.99, 44.63 and – 4.3%, respectively, indicating good model performance. Of note, neither the field experiment nor simulations showed a significant increase in yield at fertilizer application rates above 168 kg N ha^{-1}.

Next, the calibrated model was compared to soil moisture and soil nitrogen concentration data from the field experiment presented here. Simulated soil moisture time series showed the same overall temporal trends as observed values, however, model performance varied widely by treatment (Table 5, Fig. B.1 Supplemental Material). The Calendar-Low, Calendar-High, and Rainfed-Medium treatments simulations all showed large, negative bias during the early portion of the season (Fig. B.1 Supplemental Material), however the remaining treatments (Calendar-Medium and all SMS treatments) had daily NSE_M values ranging from 0.42 (acceptable) to 0.87 (very good). Similar to results shown by Rath et al. (2021) for a corn-peanut rotation at the same site, SWAT was unable to capture large peaks in soil moisture (e.g., March 2019), likely due to limitations of the simplified infiltration simulation processes in SWAT (Rajib et al., 2016; Yang et al., 2017; Zhang et al., 2017).

Model simulations of soil nitrate concentration were good, with NSE_M ranging from 0.08 to 0.96 (Table 5), however the model under-predicted soil nitrate for the low-N treatment during the mid- to late-season (Fig. B.2 Supplemental Material). The rainfed treatment showed higher simulated soil nitrate concentration than other irrigated treatments in the latter part of the carrot growing period, presumably due to less percolation leading to less nitrate leaching during the cropping season.

3.3. Watershed-scale Scenarios

3.3.1. Yield

Differences in simulated carrot yields among management systems were small (~6%), but statistically significant (Table 6, Fig. B.3 Supplemental Material), with highest yields for MS 3 (calendar irrigation, 336 kg N ha^{-1}), followed by MS 2 (SMS irrigation, 280 kg N ha^{-1}), and MS 1 (SMS irrigation, 247 kg N ha^{-1}). This result differs from the carrot field experiment, which found no significant yield difference between treatments that used 224 and 336 kg N ha^{-1}. However, it should be noted that watershed-scale simulation results represent the means of 19 carrot seasons across 1066 row crop HRUs, yielding more than 20,000 replicates, substantially more than the 4 experimental replicates in the field study. As such, it is likely that the large number of replicates in the watershed-scale simulation caused small differences in carrot yield across management systems to be statistically significant using Tukey's

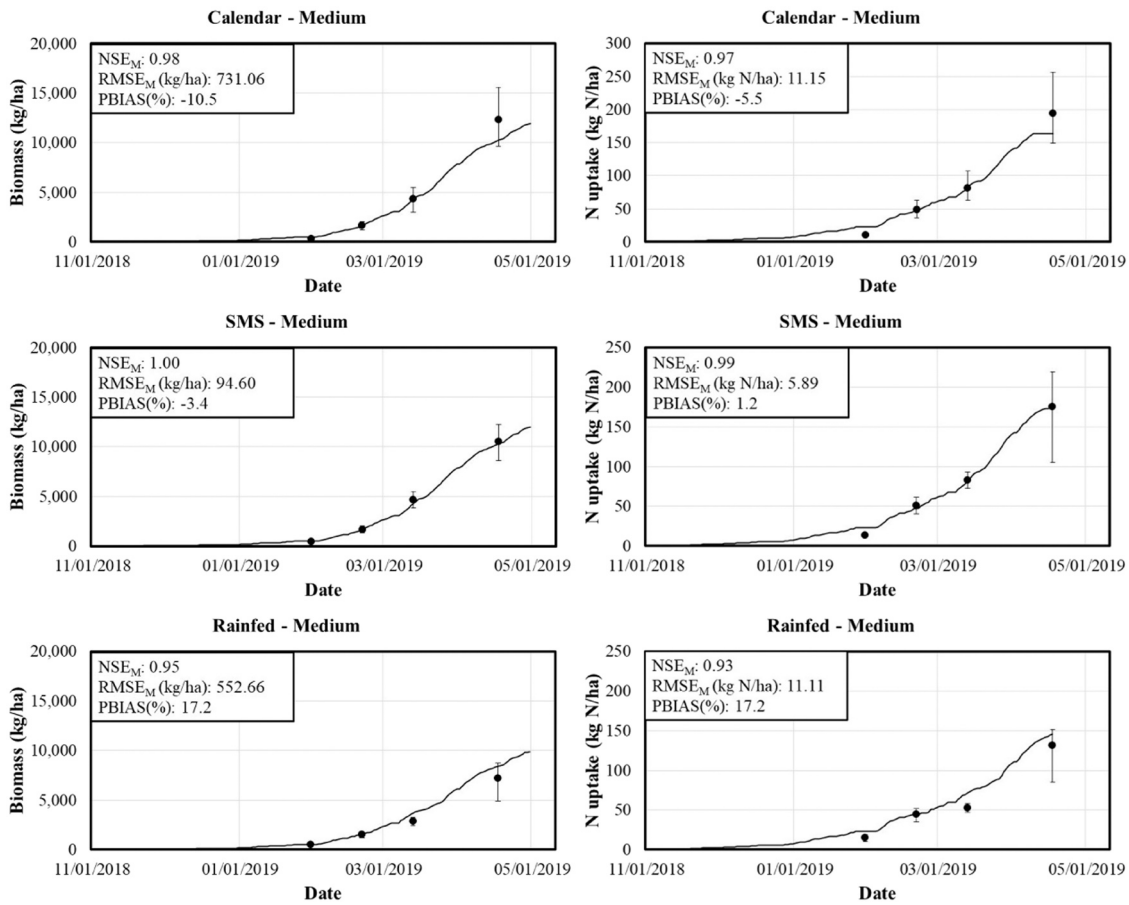

Fig. 4. Biomass (dry weight; left) and nitrogen uptake (right) of carrots by treatment.

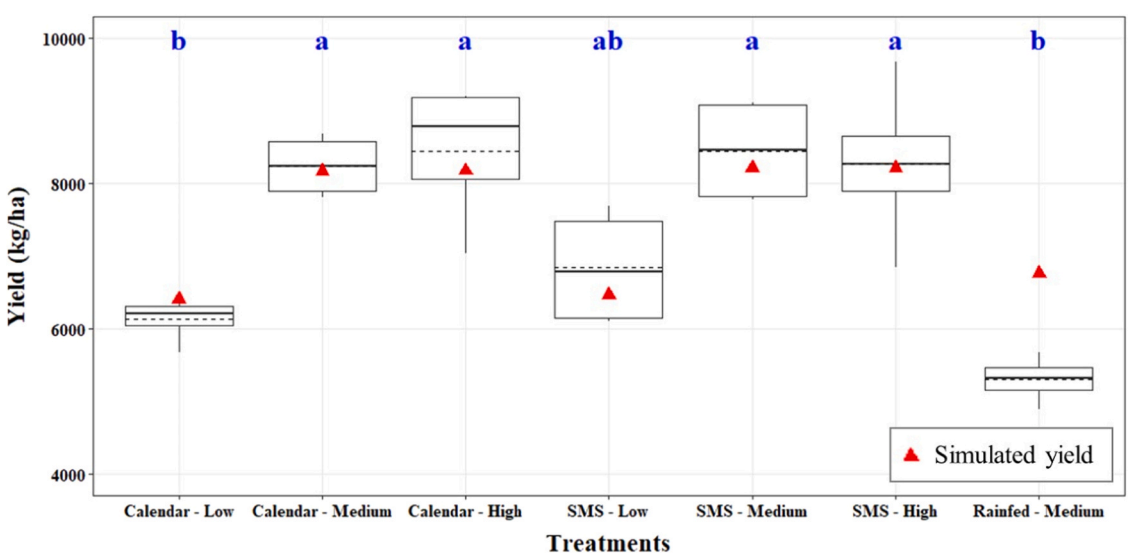

Fig. 5. Carrot yield (dry weight) from the field experiment by treatments (box plots: observed yield; alphabets: Tukey's HSD test results of observed carrot yields).

HSD test. To further explore this finding, Tukey's HSD test for differences in yield among MS was conducted individually for each HRU in the watershed, using each of the 19 carrot rotations as replicates. From this analysis, 986 HRUs (92.5%) showed no statistical difference in carrot yield among MS, while 80 HRUs (7.5%) showed small but significant differences.

Corn yields showed no significant differences between rotations (Table 6). However, as with carrot, there were small (~6%) but statistically significant corn yield differences between management systems, with the yield highest for MS 3 and lowest for MS 1. This result differs from the Zamora-Re et al. (2020) field experiment and the Rath et al. (2021) long-term simulation of that field experiment, which found no significant differences in corn yield across management systems over the range of N application rates and irrigation management practices

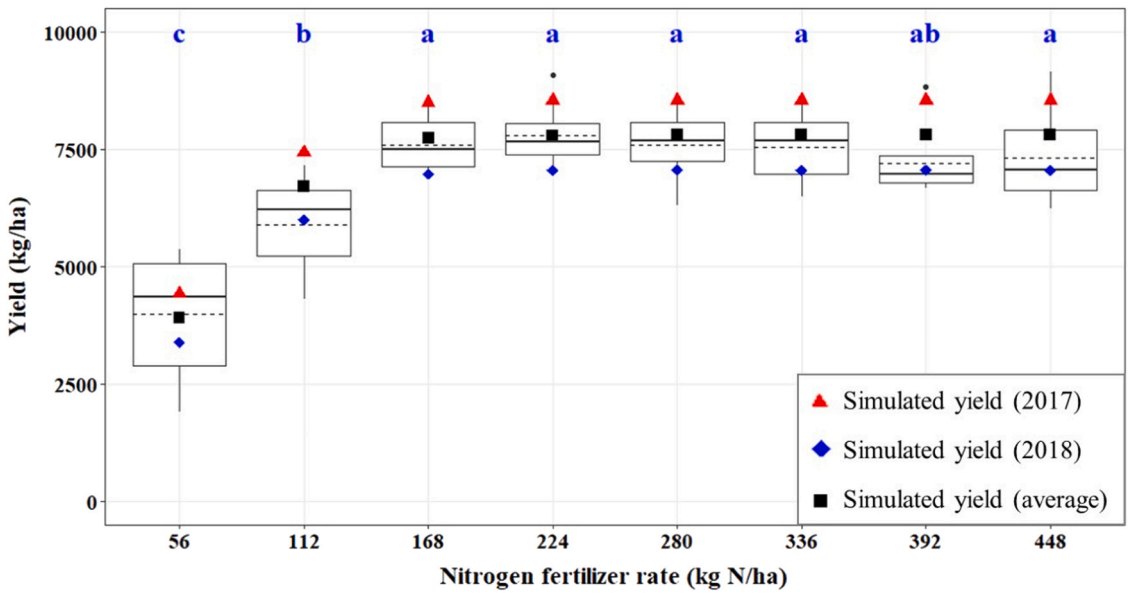

Fig. 6. Carrot yield (dry weight) from Hochmuth et al. (2021) experiment (box plots: observed yield; letters: Tukey's HSD test results of observed carrot yields).

Table 5
Performance measures for soil moisture and soil nitrate by treatment.

Items	Treatments	NSE_M	$RMSE_M$ (mm)	PBIAS (%)
Soil moisture (mm)	Calendar – Low	-1.82	21.28	-27.8
	Calendar – Medium	0.77	5.96	-8.6
	Calendar – High	-0.28	14.39	-16.1
	SMS – Low	0.42	8.42	7.4
	SMS – Medium	0.87	4.44	-11.8
	SMS – High	0.63	7.34	-5.9
	Rainfed – Medium	0.29	14.26	-17.9
Soil nitrate (kg N ha^{-1})	Calendar – Low	0.58	9.68	-59.7
	Calendar – Medium	0.96	5.82	-2.7
	Calendar – High	0.80	15.37	32.8
	SMS – Low	0.08	13.20	-65.9
	SMS – Medium	0.95	4.84	-5.6
	SMS – High	0.93	10.93	33.7
	Rainfed – Medium	0.94	3.28	38.1

SMS: soil moisture sensor

Table 6
Simulated average dry weight of crop yields.

Crops	Rotation	Yield (ton ha^{-1})		
		MS 1	MS 2	MS 3
Corn	Corn-Peanut	12.48c	12.94b	13.25a
	Corn-Carrot-Peanut	12.47c	12.92b	13.24a
Carrot	Corn-Carrot-Peanut	9.34c	9.41b	9.95a
Peanut	Corn-Peanut	7.64c	7.66b	7.85a
	Corn-Carrot-Peanut	7.66b	7.66b	7.85a

Different letters indicate significant differences at a p-value of 0.05; Statistical analysis was conducted within each crop group.
MS: management system

analyzed here. Again, the statistical differences found in our watershed-scale simulations are likely mainly due to the large number of replicates and more variation in soil type. Peanut yields showed very small (~2%), but statistically significant differences between rotations. For the corn-peanut rotation, there were small but statistically significant peanut yield differences between all management systems, while peanut yields in the corn-carrot-peanut rotation were only found to be statistically significantly different (higher) for MS 3.

3.3.2. *Irrigation, Net Recharge and Nitrate Leaching*

Among the three crops, corn required more irrigation than carrot or peanut (Table 7, Fig. B.4 Supplemental Material). Soil moisture sensor-based irrigation (MS 1 and MS 2) used statistically significantly less irrigation water than the calendar-based method for all crops (40% less for corn and carrot and 60% less for peanut). Adding carrots increased the amount of irrigation applied by 32% for MS 1 and MS 2% and 43% for MS 3, compared to the conventional corn-peanut rotation.

Tukey's HSD test results showed that net groundwater recharge was statistically significantly different between all management systems and cropping systems except corn-carrot-peanut MS 1 and MS2. For the corn-peanut rotation, net recharge was approximately 14% lower for MS 3 (calendar-based irrigation) compared to MS 1 (SMS-based irrigation), while for the corn-carrot-peanut rotation, this difference was about 33% (Table 8, Fig. B.5 Supplemental Material). Due to increased total

Table 7
The amount of water applied for irrigation by crops and management systems.

Crops	Irrigation (mm)		
	MS 1	MS 2[a]	MS 3
Corn	184.9b	186.3b	307.4a
Carrot	85.0b	85.2b	140.4a
Peanut	88.3b	88.3b	190.8a

Different letters indicate significant differences at a p-value of 0.05; Statistical analysis was conducted within each crop group.
MS: management system
[a] Due to the difference in irrigation efficiency MS 2 irrigation is ~1% higher than MS 1

Table 8
Estimated annual groundwater net recharge and nitrate leaching by rotations and management systems.

Items	Rotations	MS 1	MS 2	MS 3
Groundwater net recharge	Corn – Carrot – Peanut	406.4c	408.4c	274.0e
(mm year^{-1})	Corn – Peanut	445.2b	459.4a	381.7d
Nitrate leaching	Corn – Carrot – Peanut	28.8d	47.7b	58.4a
(kg N ha^{-1} year^{-1})	Corn – Peanut	14.4 f	28.1e	36.9c

Different letters indicate significant differences at a p-value of 0.05.
MS: management system

irrigation pumping, net recharge was also significantly lower for corn-carrot-peanut rotation compared to the corn-peanut rotation (9%, 11%, and 28% lower for MS 1, MS 2, and MS 3, respectively). Excess irrigation applied on the sandy soils where crops are grown in the study region directly recharges the unconfined FA. Nevertheless, due to evaporation and irrigation system losses, MS 3 had lower groundwater net recharge relative to MS 1 or MS 2.

Tukey's HSD test results showed that nitrate leaching was statistically significantly different between all management systems and cropping systems (Table 8, Fig. B.5 Supplemental Material). For the corn-peanut rotation, annual nitrate leaching was about 156% higher for MS 3 which used higher fertilization rates and calendar irrigation compared to MS 1 which used lower fertilization rates and SMS irrigation. For the corn-carrot-peanut rotation annual nitrate leaching was about 103% higher for MS 3 compared to MS 1. Annual nitrate leaching from the corn-carrot-peanut rotation increased substantially compared to the corn-peanut rotation for all management systems (MS 1 100%, MS 2 70%, MS 3 58%).

Although the corn-carrot-peanut rotation produces less net recharge and more nitrogen leaching than the corn-peanut within a particular management system, results show that the low input management system (MS 1) for corn-carrot-peanut produces more net recharge and less nitrate leaching than the high input management system (MS 3) for corn-peanut. This implies that if growers move from conventional practices to best management practices when adding carrots to their corn-peanut rotations, they have the potential to increase their incomes while also reducing environmental impacts.

4. Conclusions

As carrot cultivation is gaining popularity in North Florida, assessing crop production and its environmental impacts on the UFA is important to stakeholders in the region. In this work the impacts of alternative water and nutrient practices on carrot yield, nitrate leaching, and groundwater recharge were quantified using field experiments, a field-scale SWAT model calibrated to the experimental data, and a watershed-scale SWAT model.

The field experiment demonstrated that soil moisture sensor-based irrigation reduced irrigation demand by 32% over conventional calendar-based irrigation with no significant difference in carrot yield. Moreover, it revealed that low N fertilization (112 kg N ha^{-1}) resulted in significantly lower carrot yields, but there were no statistical differences between yields for medium (224 kg N ha^{-1}) and high (336 kg N ha^{-1}) fertilization rates. Long-term watershed-scale SWAT simulations across the Santa Fe River Basin overlying the UFA estimated that integrating winter carrot crops into the conventional corn-peanut rotation on all row crop land in the watershed would increase irrigation demand (32–43%), decrease net groundwater recharge (9–28%), and increase nitrate leaching (60–100%) across low-, medium- and high-input management systems. Thus, although beneficial to growers' revenue, incorporating carrot into the corn-peanut rotation will make achieving environmental regulations in the region more difficult. Nevertheless, this study showed that if growers who have been using conventional management practices for corn-peanut cultivation adopt soil moisture sensor irrigation and reduced N fertilization when adding carrot to their rotation, they can increase their revenue while increasing net groundwater recharge and reducing nitrate leaching.

Key findings of this study underscore the effectiveness of soil moisture sensors for reducing carrot irrigation, the validity of the UF/IFAS recommendation of 224 kg N ha^{-1} for carrots grown in the region, and the economic-environmental trade-offs associated with adding carrots to the corn-peanut rotation in the SRB overlying the UFA in North Florida. These insights offer valuable guidance for crop growers and environmental regulators seeking to promote both a robust regional agricultural economy and environmental protection of the UFA.

CRediT authorship contribution statement

Lee Dogil: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis. **Rath Sagarika:** Software, Resources, Formal analysis, Data curation. **Merrick Jason:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Kaplan David:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Data curation. **Dukes Michael:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Graham Wendy:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Wendy Graham reports financial support was provided by United States Department of Agriculture National Institute of Food and Agriculture.

Data availability

The experimental data and models used in this study will be uploaded to the Consortium of Universities for the Advancement of Hydrologic Science Inc. (CUAHSI) Hydroshare repository and made publicly available upon acceptance of the manuscript.

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Appendix A. SWAT code modification

a. Accumulated potential heat unit initialization error

```
- Original code (dormant.f).
if (idorm(j) = = 1.and. dayl(j)-dormhr(j) > = daylmn(hru_sub(j))).
& then.
select case (idc(idplt(j))).
!! end of perennial dormant period.
case (3, 6, 7).
idorm(j) = 0.
!! end of cool season annual dormant period.
case (2, 5).
idorm(j) = 0.
phuacc(j) = 0.
end select.
- Modified code.
if (idorm(j) = = 1.and. dayl(j)-dormhr(j) > = daylmn(hru_sub(j))).
& then.
select case (idc(idplt(j))).
!! end of perennial dormant period.
case (3, 6, 7).
idorm(j) = 0.
!! end of cool season annual dormant period.
case (2, 5).
idorm(j) = 0.
end select.
```

b. Residue Excessing Original Biomass Error

```
- Original code (harvkillop.f).
ff1 = (1-hiad1)/(1-hiad1 +rwt(j)).
ff2 = 1-ff1.
- Modified code:
!! to prevent hiad1 (actual harvest index) exceeding 1 +rwt(j) (fraction of biomass that is in roots).
elseif (hiad1 > 1 +rwt(j)) then.
hiad1 = 1 +rwt(j).
end if.
!! even though all the roots will be removed when carrots are harvested, but in SWAT world, it does not work like that. If actual harvest index is more than 1, we remove all the belowground biomass and some of aboveground biomass. The fraction of N or P in aboveground biomass and below ground biomass will be 1 and 0, respectively.
if (hiad1 >1) then.
ff1 = 1.
ff2 = 0.
else.
ff1 = (1-hiad1)/(1-hiad1 +rwt(j)).
ff2 = 1-ff1.
endif.
```

Appendix B. Validation results and watershed-scale modeling results

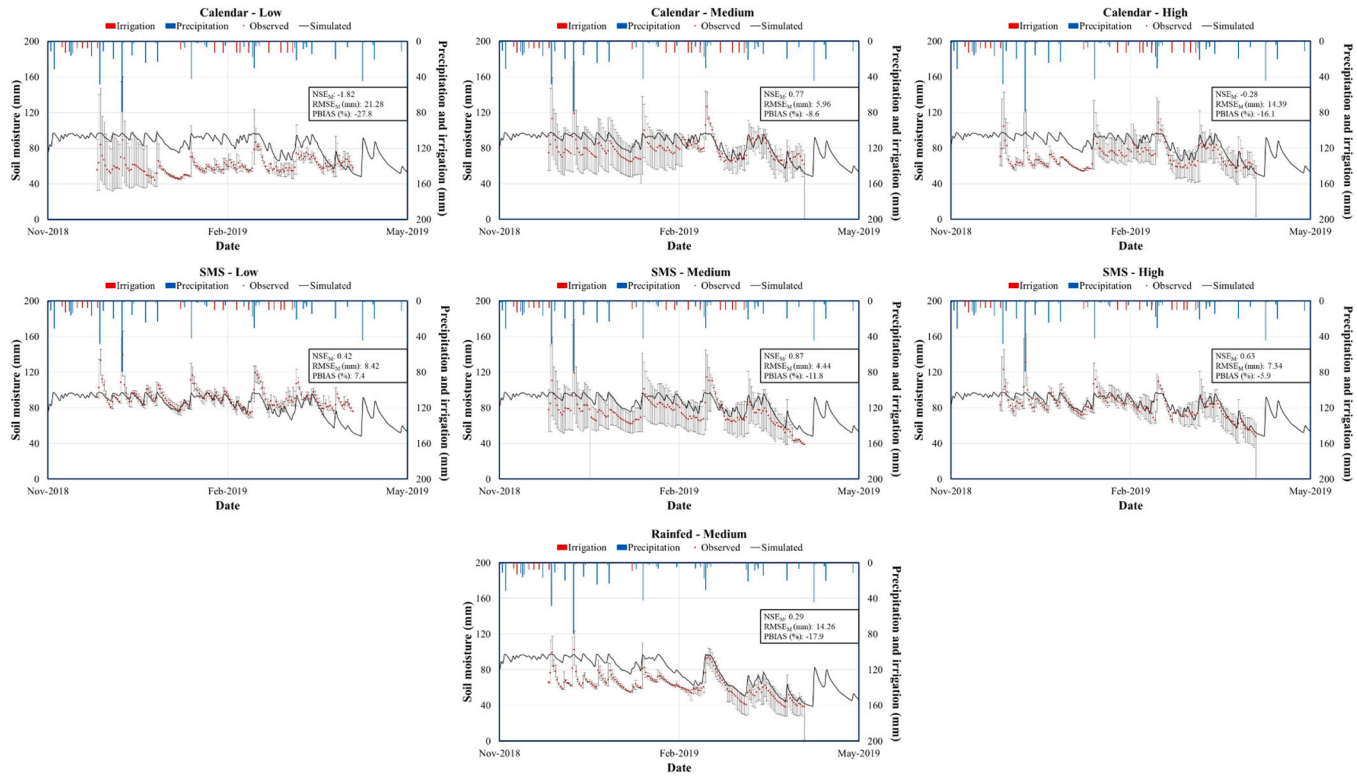

Fig. B.1. Soil moisture during carrot cultivation period.

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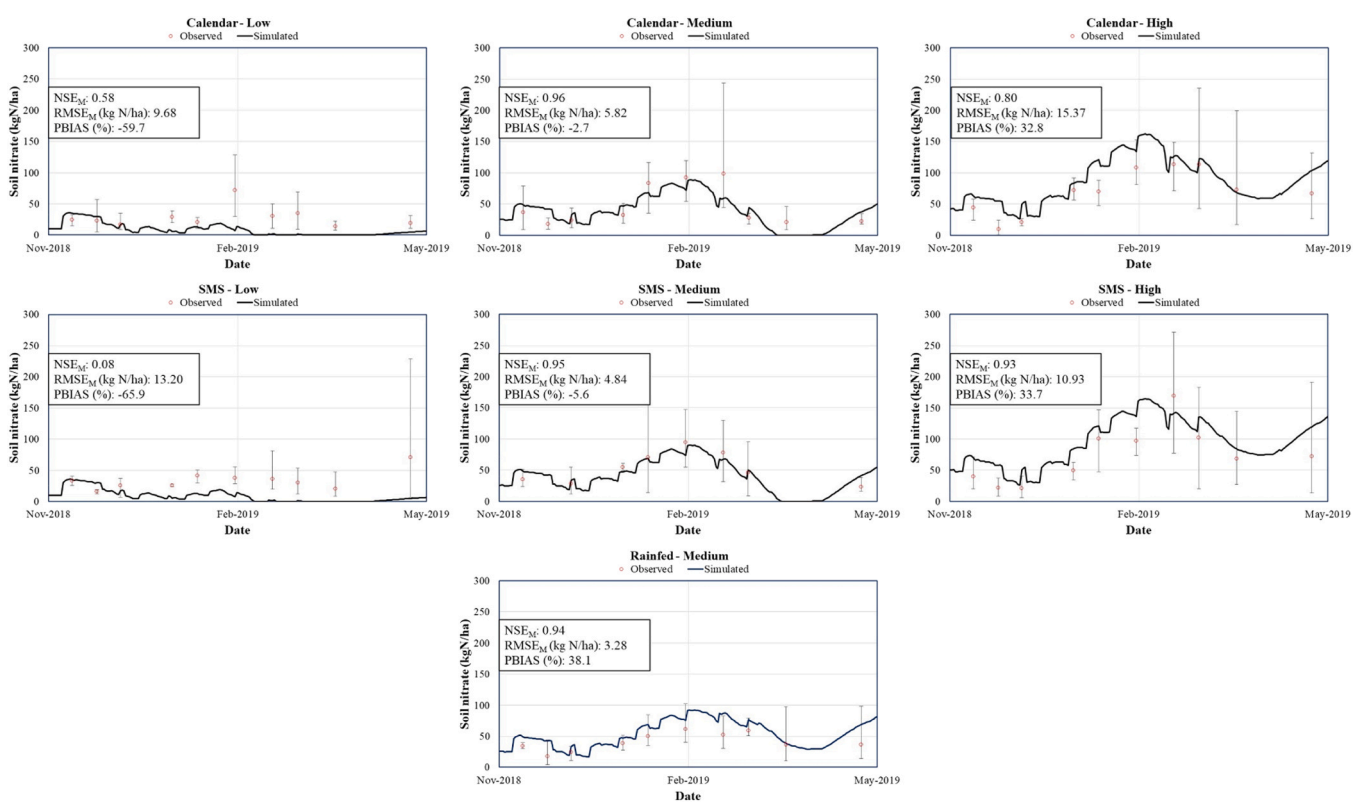

Fig. B.2. Nitrate in soil during carrot cultivation period.

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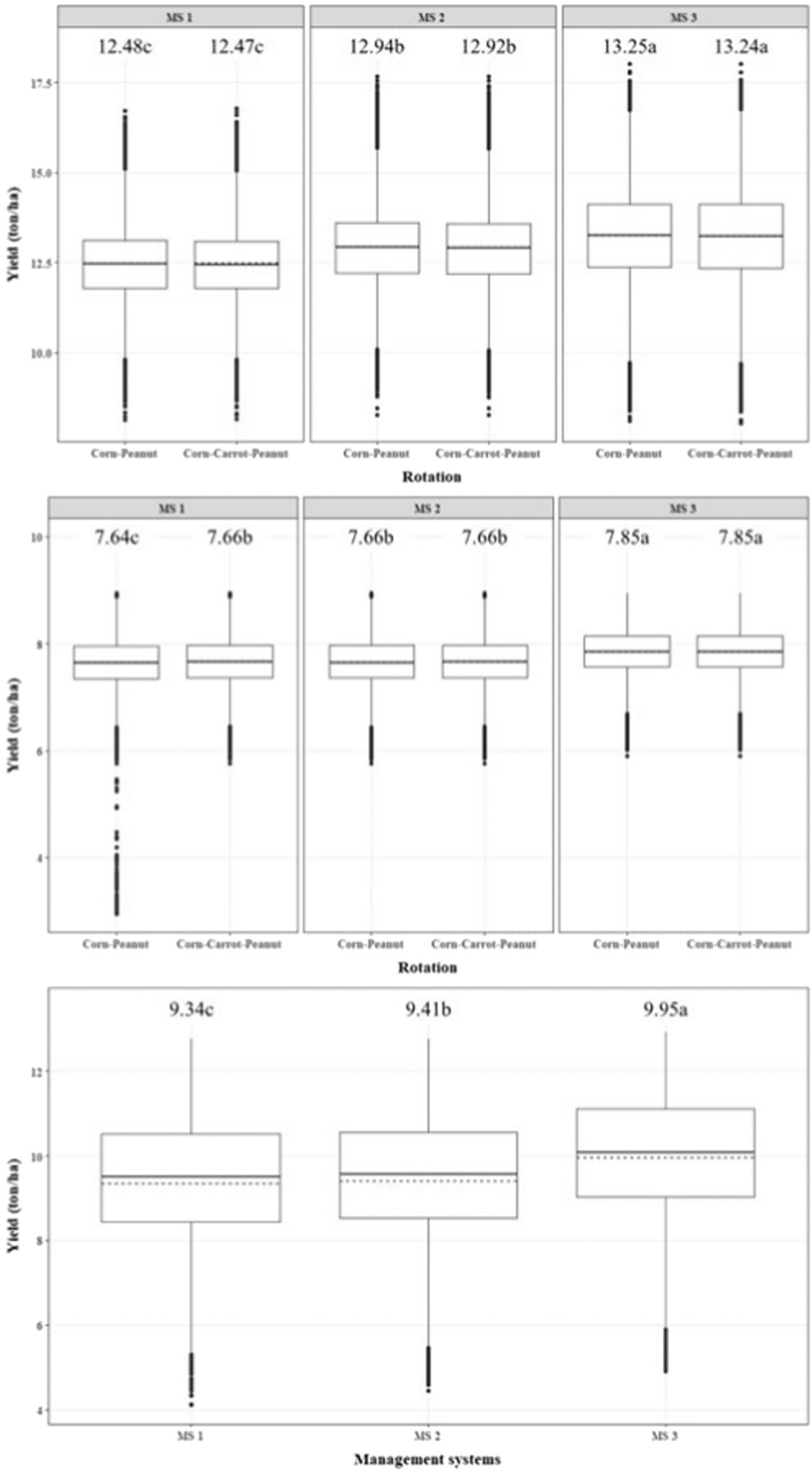

Fig. B.3. Simulated yields in the Santa Fe River Basin (top: corn yield; middle: peanut yield; bottom: carrot yield; numbers in the box plots represent average values; different letters indicate significant differences at a p-value of 0.05).

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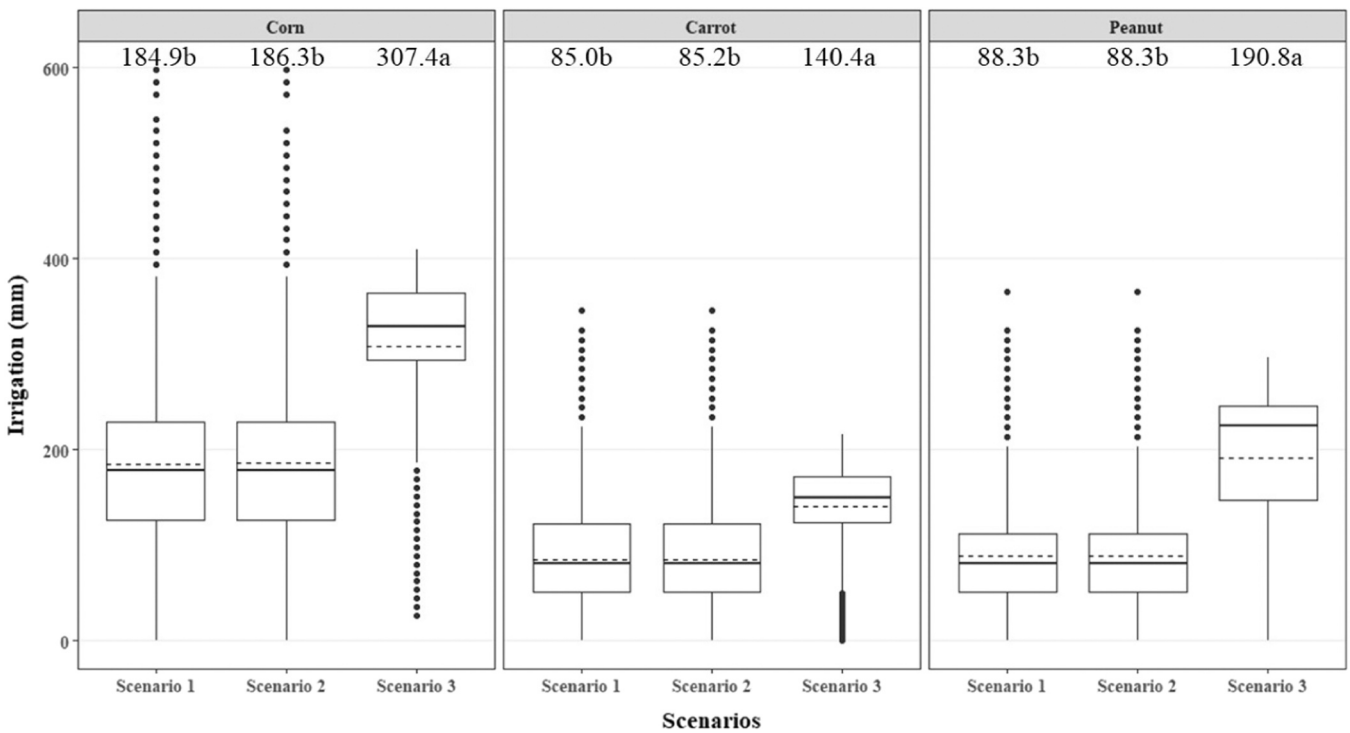

Fig. B.4. The amount of pumped water for irrigation by crops and management systems (numbers in the box plots represent average values; different letters indicate significant differences at a p-value of 0.05).

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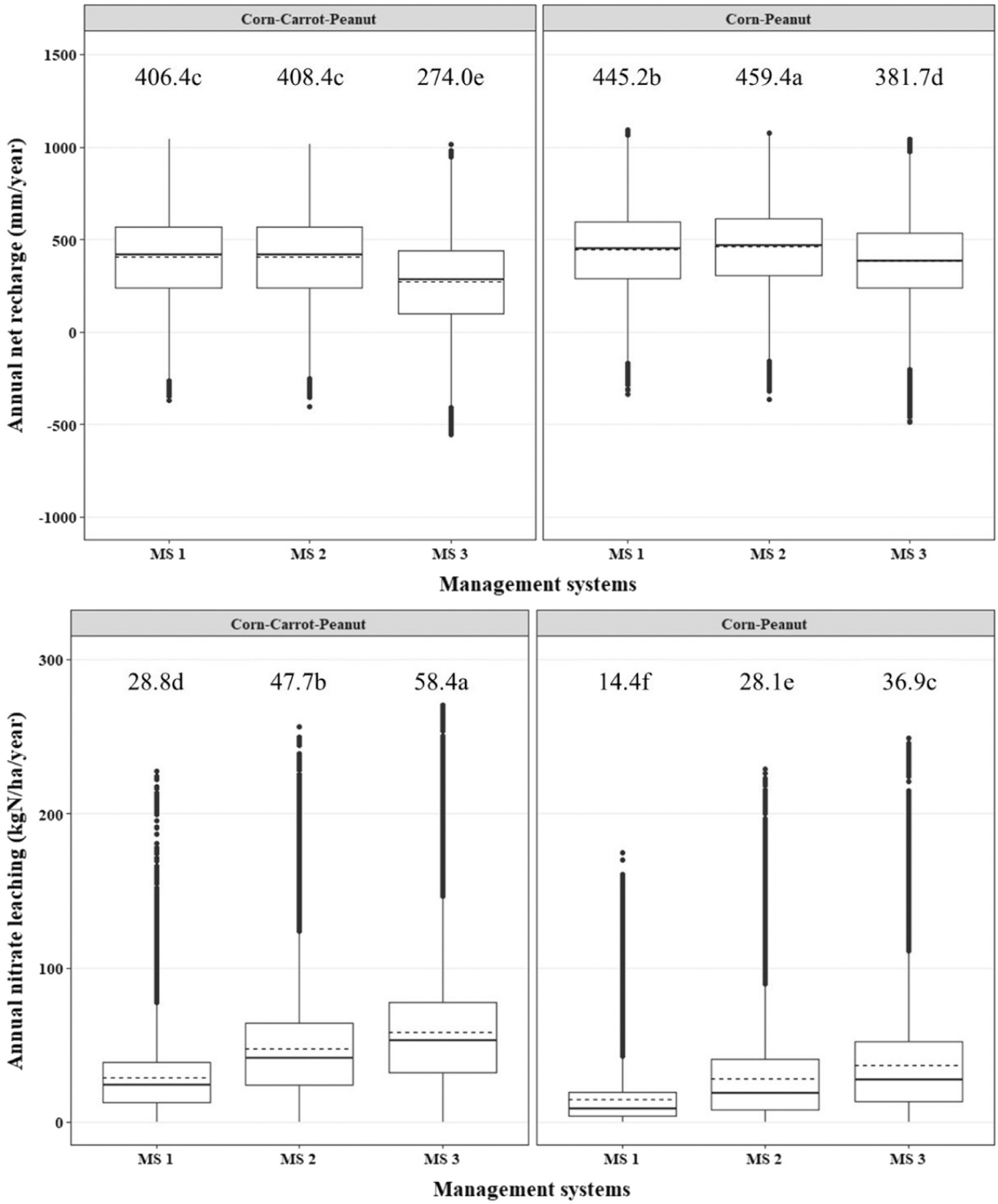

Fig. B.5. Annual groundwater net recharge and nitrate leaching by rotations and management systems (top: annual groundwater net recharge; bottom: annual nitrate leaching; numbers in the box plots represent average values; different letters indicate significant differences at a p-value of 0.05).

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