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Adapting irrigated agriculture in the Middle Rio Grande to a warm-dry future

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A R T I C L E I N F O

Keywords:
Climate change
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Soil and Water Assessment Tool (SWAT)
Alternative crops
Groundwater depletion

A B S T R A C T

Study region: Middle Section of the Rio Grande Basin (MRG), U.S.
Study focus: Long-term tradeoffs of technologically possible land and water management interventions were analyzed to adapt irrigated agriculture to growing water scarcity in a desert environment under a projected warm-dry future. Nineteen different intervention scenarios were investigated to evaluate potential watershed-scale agricultural water savings and associated water budget impacts in the MRG. The interventions are based on (i) management innovations of growers in implementing deficit irrigation and changing cropping patterns using existing crops, (ii) changing cropping patterns by introducing new alternative drought- and salt-tolerant crops, and (iii) limitations of the soil and water assessment tool (SWAT) model to perform scenario simulations.
New hydrological insights for the region: (1) status quo irrigation management cannot sustain the current crop mix in the face of dwindling river water and likely fresh groundwater depletion within the 21st century; (2) existing cropping and irrigation interventions create limited water savings; and (3) deficit irrigation of alfalfa or removing it from the crop mix allows moderate water savings to sustain high-value perennial pecan crops but the region will remain vulnerable to intensive, prolonged droughts. Strategies for future agricultural water sustainability in the study area could include transitioning to relatively drought- and salt-tolerant crops, desalinating brackish groundwater for irrigation, and developing water markets to increase flexibility in water use.

1. Introduction

Increasing vulnerability to water shortages in arid/semi-arid regions of the world underscores the importance of adaptive management strategies to sustain agricultural production in these regions (Jury and Vaux, 2005; Al-Ghobari and Dewidar, 2018; Aliyari et al., 2021). Water conservation and increasing the resilience of the agricultural sector support both food security and the economy,

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especially in the face of uncertainties related to water shortages (English et al., 2002). Adaptive irrigation practices such as deficit irrigation, partial root zone drying, mulching, and crop pattern change facilitate coping with growing water scarcity (Sadras, 2009; Eberbach et al., 2011; Nouri et al., 2019). Technological advances such as surface and sub-surface drip irrigation, along with using remote sensing data and on-farm monitoring (e.g., soil moisture and evapotranspiration (ET)), now allow precise scheduling and application to minimize unnecessary irrigation (Li et al., 2007; Koech and Langat, 2018; Taghvaeian et al., 2020). Furthermore, water savings are possible during the periods of crop growth when the plant is less sensitive to water stress, allowing implementation of practices such as deficit irrigation or partial root-zone drying without significantly impacting yields (Sadras, 2009; Geerts and Raes, 2009). Other options include breeding new drought-tolerant crops (Condon et al., 2004), growing known drought-adaptive crops, and land leveling to improve water distribution (Knutson et al., 1998; Thompson et al., 2009; Perry, 2011; Mir et al., 2012; Li et al., 2013; Ganjegunte and Clark, 2017).

The impact of different cropping and water management strategies on irrigated agriculture's resilience to diminished and less reliable water availability in arid regions such as the Middle Rio Grande (MRG) basin (Fig. 1) is reported in this paper. Increasing aridity in the southwestern U.S. (Dettinger et al., 2015; USGCRP, 2018; Hicke et al., 2022), where a significant proportion of the U.S. irrigated lands are located, is expected to negatively impact the quantity and quality of water available for agricultural production. MRG typifies water-scarce agricultural watersheds in desert environments where heavily irrigated croplands face the risk of increasing water shortages and salinity due to growing demand and extreme variability of renewable water (Elias et al., 2015; Chavarria and Gutzler, 2018). From 1994–2013, the region experienced a 25% increase in the area of pecan orchards, which is the highest-value crop and the most vulnerable to water shortages and quality decline (Miyamoto et al., 1995; Miyamoto and Storey, 1995; Miyamoto, 2007). Adaptive agricultural water management approaches like irrigation scheduling, deficit irrigation, and land use management do not require major changes in infrastructure and are already practiced to some extent by farmers in the region (Skaggs and Samani, 2005). In recent severe droughts (e.g., 2003–2004 and 2011–2012), producers have typically decreased the acreage of other crops, especially alfalfa and cotton, or stopped growing them altogether to save water for pecan orchards. Other methods such as drip irrigation would create a heavier economic burden on farmers due to fundamental changes in irrigation infrastructure along with a variety of challenges to irrigation districts. Likewise, substituting vulnerable high-value commodity crops with climate-compatible drought-tolerant crops has been applied as an adaptation strategy in arid regions (Herrera, 1997; Wang et al., 2015).

The objectives of the paper are two-fold: 1) simulate a series of agricultural interventions using a calibrated Soil and Water Assessment Tool (SWAT) watershed hydrology model; and 2) evaluate the water conservation potential of each scenario, as well as opportunities for agricultural water savings using a combination of the analyzed interventions. Water conservation potential is defined

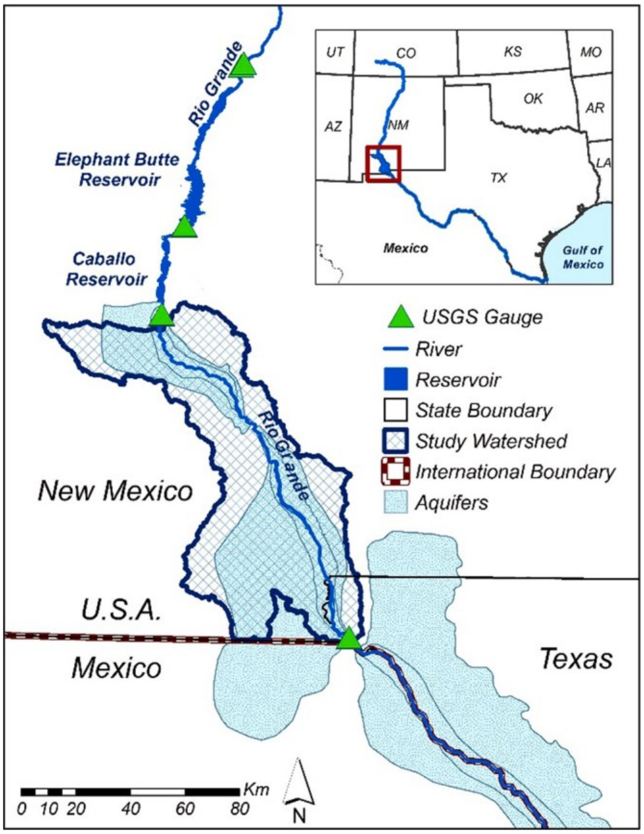

Fig. 1. Study watershed in the New Mexico-Texas portion of the Rio Grande Basin.

in this study as the percentage of reduction in watershed-scale irrigation water applied by the model under different intervention scenarios. The implications of the modeled interventions (e.g., deficit irrigation, changing current cropping pattern, and growing alternative high-value crops) for sustaining agricultural production in the MRG within the constraints of projected decreases in water supply are discussed. The results inform model-based evaluation of agricultural water management interventions in the MRG and hydro-climatically similar agricultural watersheds to adapt to growing risks of water shortages due to climate-induced future water scarcity.

2. Materials and methods

2.1. Study area

The study area (watershed area: ~ 6000 km²; agricultural area: ~ 400 km²), located in the New Mexico-Texas portion of the Rio Grande basin (Fig. 1), is arid/semi-arid with an average annual precipitation of approximately 270 mm (less than one-third of global average). The Rio Grande streamflow is regulated at the Elephant Butte (EB) and Caballo reservoirs. The EB reservoir (capacity: > 2.5 billion cubic meters (BCM)) is the principal surface water storage in the region. Caballo reservoir (capacity: 424 million cubic meters (MCM)) located 40 kilometers downstream of the EB Dam regulates the releases from the EB reservoir. Two USGS gauging stations (USGS 08358300 Rio Grande conveyance channel at San Marcial and USGS 08358400 Rio Grande Floodway at San Marcial) measure inflow to the EB reservoir. USGS gauges 08361000 Rio Grande below EB and 08362500 Rio Grande below Caballo record the reservoirs' releases. The USGS gauge 08364000 Rio Grande at El Paso measures the outflow from the watershed (Fig. 1).

The main irrigated agricultural activities in this portion of the Rio Grande occur within Elephant Butte Irrigation District (EBID), which extends from downstream of the Caballo reservoir to the El Paso Gauge. Surface water availability for agriculture depends on upstream reservoir releases, and storage in EB Reservoir is derived almost entirely from Rio Grande inflow as measured at San Marcial (Holmes et al., 2022). To compensate for surface water shortages during the irrigation season, farmers pump groundwater from the Mesilla Bolson aquifer, one of the main aquifers in the region (Sheng, 2013). As a result, the groundwater resources are declining due to increasing withdrawal (Sheng, 2013; Fuchs et al., 2018).

In normal years, Caballo reservoir releases water from March to September to meet the irrigation water demands in the EBID. Three diversion dams, Percha, Leasburg, and Mesilla, and five main canals distribute water among irrigated farms. Historical changes in crop patterns reflect adjustments based on water availability (Fig. 2). Traditional flood irrigation (basin irrigation) is commonly practiced in the EBID leading to significant non-beneficial consumptive use via surface evaporation and because irrigation schedules typically do not account for crop water demand at different growth stages (Skaggs and Samani, 2005; Samani and Skaggs, 2008). While some fields within the irrigation district over-irrigate, others fail to meet their water requirements (Skaggs and Samani, 2005).

As freshwater availability declines, there is mounting concern about increasing salinity in groundwater and river water. Salinity monitoring from 2014 to 2016 indicated freshwater (TDS < 1000 mg/L) flow in the river channel during the reservoir release period, and fresh to slightly saline groundwater with TDS values ranging 300–2000 mg/L in sampled wells along the main stem of the river (Ma et al., 2019). Overdraft of fresh groundwater is expected to cause intrusion or upwelling of brackish water, deteriorating the quality of water in the aquifer (Ashworth and Hopkins, 1995; Sheng, 2013). As such, agricultural producers are concerned about the

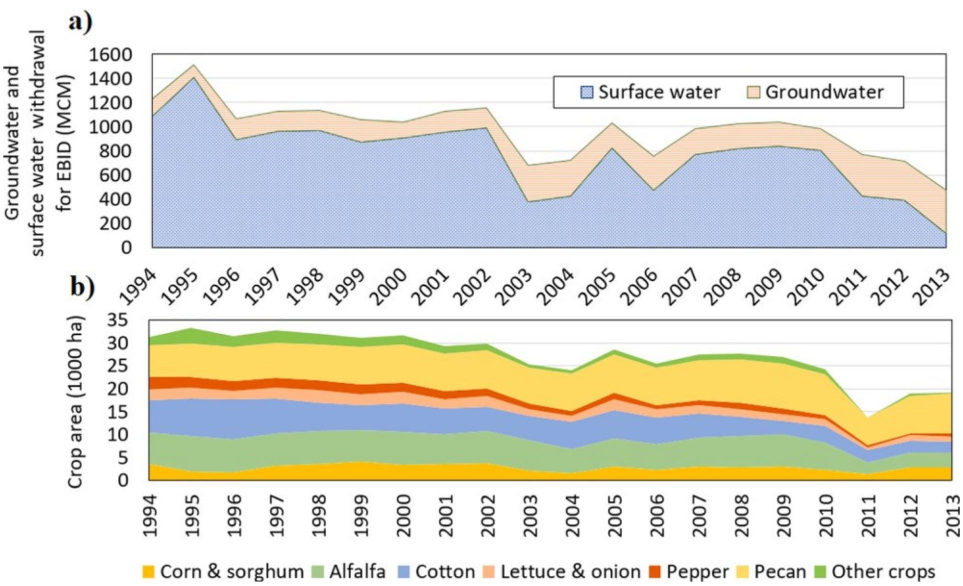

Fig. 2. Water withdrawal and irrigated farmlands in EBID: (a) conjunctive use of surface water and groundwater; and (b) historical changes in the cultivated area of major crops.

prospect of reduced fresh water availability, especially the sustainability of irrigated pecan production (Hargrove and Heyman, 2020). Water stress can impact the quality of nuts, affect plant growth, and in the long run kill the pecan tree. Saline water with TDS more than 700–1000 mg/L impacts the growth of pecan trees and shrinks the size of leaves and nuts. Growth decline starts at EC of 2.5–3.0 dS/m in the soil saturation extract, while tree die-back starts at higher EC (6–8 dS/m) (Miyamoto, 2007).

2.2. Watershed modeling: accounting for Irrigation

Soil and Water Assessment Tool (SWAT) was used to model the MRG basin, including heavily irrigated croplands. SWAT is a semi-distributed model that simulates watershed hydrology using a water balance approach (Arnold et al., 1998). The model has been widely applied in arid/semi-arid areas with irrigated agriculture to simulate the impacts of changes in climate and agricultural management (Samimi et al., 2020). The USGS 10 m × 10 m DEM (Digital Elevation Model)(USGS, ND), 2008 cropland data layer, SSURGO soil map (USDA, ND), and precipitation and temperature data from NOAA stations were used as input data. The USDA (2008) cropland data for the study area was assumed to represent average cropping conditions in the region since it was a near-normal year with the standardized precipitation index (SPI) of 0.9 (Samimi et al., 2022). The watershed was first divided into hydrological response units (HRU) based on similar land use/land cover type, soil characteristics, and slope in each subbasin. The water balance in each HRU was subsequently calculated based on weather data, management practices (irrigation, fertilization, harvest, etc.), and plant growth information. SWAT's built-in databases provide weather data, land use, and plant growth (Neitsch et al., 2011). The upstream reservoir releases are introduced to the model with an inlet inflow, which marks the upstream boundary of the watershed.

SWAT model was calibrated and validated for different water budget components (described below), as well as irrigation amounts. The model was first calibrated and validated for monthly observed river flow at the watershed outlet using the SUFI2 algorithm in SWAT-CUP (Abbaspour, 2015) and then it was manually calibrated with the available data for average annual irrigation and ET, as well as groundwater recharge. In each step, the main components (streamflow, crop ET, groundwater recharge, and applied irrigation) were cross-compared to find a realistic calibrated parameter set for the heavily managed watershed (Table 2). The calibration period (1995–2004) covers both high and low flows in the historical period preceded by two years of warm-up (1993–1995) to initialize the model. The model's performance was evaluated for the period of 2005–2013. Due to limited irrigation data, range of values were used based on measurements reported in the literature to evaluate the model performance with respect to irrigation (e.g., Abdul-Jabbar et al., 1983; Samani et al., 2005, 2009, 2011, 2013).

SWAT's auto-irrigation function was used to simulate the irrigation timing and amount based on default or user-defined parameter values because detailed information about the irrigation schedules of each farm were unavailable for manual irrigation simulation. The start of irrigation season is defined on a specific day and month or based on the amount of crop heat units. The model assumes irrigation continues until soil water content reaches the field capacity (Neitsch et al., 2011). Irrigation events are triggered based on plant water demand (fraction of decline in plant growth due to water stress) or soil water content (soil water deficit in mm). The specific date and soil water content threshold was selected for auto-irrigation of each crop based on agricultural practices in the region. The soil water deficit threshold (mm) for auto-irrigation was defined based on total available water content (AWC- fraction) for plant uptake in the soil calculated as the difference between the field capacity (fraction) and wilting point (fraction), which depends on the soil type. The readily available water (RAW - fraction) in the soil is the portion of the AWC that can be easily used by plants without any water stress. RAW varies between 0.3 and 0.7 of AWC. Smaller RAW values are typically used for dry and hot climates and more stress-sensitive crops (Allen et al., 1998). RAW has been estimated to be 0.45–0.50 for pecan, 0.65 for cotton, 0.55 for oat and alfalfa, and 0.30 for onion and vegetables (Allen et al., 1998; Kallestad et al., 2008). The RAW for each crop was calculated based on soil AWC from the SSURGO soil map (mostly 0.13–0.14 in the study area) and the effective rooting depth of plants. The final values of thresholds were determined based on the AWC of each HRU, individually. The effective rooting zone is where 80% of all roots are present and maximum water uptake occurs (USDA, 1997). The model also uses irrigation efficiency as an input. The on-farm irrigation efficiency in several EBID farms has been estimated to be between 60%− 83% (Samani et al., 2005; Ahadi et al., 2013). The higher efficiencies (70%−83%) are attributed to deficit irrigation and the high water demand of pecan. The auto-irrigation parameters were calibrated separately for each crop. The water stress threshold for soil moisture deficit was calculated based on the soil and crop characteristics. The amount of water application for each irrigation event (IRR_MAX) was set based on the irrigation application rates commonly found in the region (e.g., about 4900 m^3 or 4 acre-feet) for mature pecan trees during the irrigation season.

2.3. Climate-based future water scarcity

To investigate the efficiency of the selected water and land management practices under plausible future water scarcity conditions, MRG surface water availability was simulated using a 21st Century scenario for projected San Marcial inflows developed by Townsend and Gutzler (2022). This scenario, based on a CMIP5 climate model projection (ACCESS1–0) driven by the high-emissions RCP8.5 greenhouse gas pathway, was transformed by the US Bureau of Reclamation into a Rio Grande streamflow projection by applying downscaled climate model output to the VIC surface water model (Reclamation, 2016). Townsend and Gutzler (2020) then took Reclamation's annual flow projections for Rio Grande flow and statistically adjusted them to account for upstream water diversions, by determining the fractional constant values required to force the simulated flows at San Marcial to match first and second moments of the observed flow during a simulated historical epoch.

This procedure was carried out for 97 simulations in the Reclamation archive. The spread of these simulations in future decades is large, although future declines in San Marcial inflow occur in the majority of the projections. The ACCESS1–0_RCP85 simulation chosen for this study is one of the "driest" simulations, typically near the 25th percentile of the ensemble of projected flows in future decades (Townsend and Gutzler, 2020). This simulation was used for the present study to provide something close to a worst-case scenario that would require very significant water use adjustment by downstream irrigators.

The ACCESS1–0_RCP85 inflow scenario has been used in previous assessments of 21st Century EB Reservoir management (Holmes et al., 2022) and groundwater depletion (Samimi et al., 2022). Annual inflow at San Marcial in this simulation delivers on average just about 2/3 of the historical average throughout the 21st Century (Townsend and Gutzler, 2020), which prevents EB Reservoir from ever reaching, or even approaching, full capacity (Holmes et al., 2022). There is a modest long-term downward trend in San Marcial flow throughout the second half of the 21st Century but no appreciable acceleration in declining flow is apparent. Samimi et al. (2022) projected reservoir releases into the study watershed and developed a regression relation to characterize conjunctive use of reservoir release and groundwater. Projected groundwater withdrawals under warmer and drier conditions indicate a high likelihood that fresh groundwater (TDS < 1000 mg/L) in the MRG would be depleted in the second half of the 21st century (Samimi et al., 2022), reducing the annual probability of fulfilling EBID's full river water allocation to below 20%.

2.4. Intervention scenarios

Nineteen intervention scenarios were analyzed (Table 1) to sustain irrigated agriculture, in general, and high-value pecan crops, in particular, to mimic the risk aversion behavior of pecan producers in the study area. The interventions are based on (i) management innovations of growers in implementing deficit irrigation and changing cropping patterns using existing crops, (ii) changing cropping patterns by introducing new alternative drought- and salt-tolerant crops, and (iii) limitations of the SWAT model to perform the scenario simulations. Potential agricultural water savings and associated water budget impacts were evaluated by comparing the corresponding changes in total water consumption at the watershed level and average annual water availability for major crops under each intervention scenario.

2.4.1. Deficit Irrigation

Deficit irrigation is applied in water-scarce regions around the world to increase water use efficiency with minimal loss in crop yield (Martin et al., 1989; Costa et al., 2007). Common ways to implement deficit irrigation include reducing the irrigation amount, increasing the RAW coefficient, and reducing the number of irrigation events, especially during growth stages when plants are less

Table 1
Description of selected intervention scenarios to cope with dwindling river water and potential fresh groundwater depletion in the MRG by mid-21st century.

Scenario		Name	Description
Status quo		Baseline	Recent historical period (1994–2013)
Projected status quo		Projected baseline	Current condition under projected surface water in the warm-dry future (up to 2100); fresh groundwater is depleted by 2050
Deficit irrigation	Regulated	Early irrigation termination for alfalfa	Irrigation of alfalfa stops at the end of July
		Early irrigation termination for cotton	Irrigation of cotton stops at the end of July
	Unregulated	Alfalfa 50% of ET_{base}	Deficit irrigation of alfalfa represented by reducing alfalfa ET to 50% of alfalfa ET_{base}
		Alfalfa 65% of ET_{base}	Deficit irrigation of alfalfa represented by reducing alfalfa ET to 65% of alfalfa ET_{base}
		Corn 65% of ET_{base}	Deficit irrigation of corn represented by reducing corn ET to 65% of corn ET_{base}
		Cotton 50% of ET_{base}	Deficit irrigation of cotton represented by reducing corn ET to 50% of cotton ET_{base}
		Alfalfa 50% of ET_{base} and cotton 85% of ET_{base}	Deficit irrigation of alfalfa and cotton represented by reducing alfalfa ET to 50% of ET_{base} for alfalfa and reducing cotton ET to 85% of ET_{base} for cotton
Modifying current crop pattern		Pecan acreage increased by 4%	Acreage of flood irrigated pecan orchards increased by 4% in 2020; Irrigation requirements for young pecan trees considered
		No alfalfa after 2050	Alfalfa farms removed from the crop mix after 2050
		Alfalfa acreage reduced by 50%	Alfalfa acreage reduced by half after 2050
		No cotton after 2050	Cotton farms removed from the crop mix after 2050
		Cotton farms removed and corn area reduced by half	Cotton farms removed from the crop mix and corn cultivation area is reduced by half after 2050
		Only pecan after 2050	All crops except pecan removed from the crop mix after 2050
Alternative crops		Cotton replaced with pistachio	Flood irrigated pistachio orchards replace cotton farms by 2030
		Cotton replaced with pomegranate	Flood irrigated pomegranate orchards replace cotton farms by 2030
		Pecan replaced with pistachio later	Pistachio trees replace pecan orchards in 2050.
		Pecan replaced with pistachio now	Pistachio trees replace pecan orchards in 2022.
		Pecan replaced with pomegranate later	Pomegranate trees replace pecan orchards in 2050.
		Pecan replaced with pomegranate now	Pomegranate trees replace pecan orchards in 2022.

* ETbase = Average annual ET of alfalfa/cotton/corn farms (1994–2013).

vulnerable to water stress (i.e., regulated deficit irrigation) or throughout the growing season (i.e., unregulated deficit irrigation) (Kirda, 2002; Onder et al., 2009; Payero et al., 2009; Bauder et al., 2011; Chai et al., 2016; Liu et al., 2017; Himanshu et al., 2019; Djaman et al., 2020). Regulated deficit irrigation requires knowledge of plant growth periods and the corresponding accumulated heat units. It is most practical with center pivot, trickle, and drip irrigation systems where the timing and amount of irrigation can be controlled (Kirda, 2002; Costa et al., 2007).

Seven deficit irrigation scenarios were simulated, including five scenarios representing different levels of unregulated deficit irrigation of alfalfa, corn, and cotton and two scenarios of regulated deficit irrigation in which water application to alfalfa and cotton is stopped towards the end of the growing season (Table 1). The impact of water stress on different crop yields is varied. Alfalfa is a high water-demand crop that is relatively adaptable to water stress because of its deep roots and the ability to go dormant during droughts (Bauder et al., 2011; Lindenmayer et al., 2011). ET and yield reduction of alfalfa in unregulated deficit irrigation is greater than partial-season regulated deficit irrigation (Bauder et al., 2011; Djaman et al., 2020; Smeal et al., 1991). Regulated deficit irrigation of alfalfa can be implemented by stopping irrigation after the first, second, or the third harvest (Bauder et al., 2011; Lindenmayer et al., 2011; Djaman et al., 2020). Cotton under unregulated deficit irrigation with lower levels of water stress (i.e., reducing crop ET by 15–30%) has resulted in acceptable yield reductions considering water sustainability challenges and the rising cost of water in arid regions (Dağdelen et al., 2009; Singh et al., 2010). Regulated deficit irrigation of cotton during the initial and final stages of plant growth was reported as the most efficient (Himanshu et al., 2019).

The average annual simulated ET of farms under deficit irrigation were compared with the average annual calibrated and validated ET of the same farms during the historical period of 1994–2013 (namely ET_{base}) to represent watershed-scale crop water stress due to deficit irrigation. On the farm scale, water stress through deficit irrigation can be defined by the percentage of crop's ET relative to potential ET or pan evaporation (Onder et al., 2009; Payero et al., 2009; Bauder et al., 2011; Liu et al., 2017). On the watershed scale, many farms already experience some levels of deficit irrigation due to water shortages in this desert environment. Water stress was defined by increasing the soil water deficit threshold or reducing irrigation water in SWAT's auto-irrigation function. It was assumed that changes in watershed-scale ET represent the water stress level in deficit irrigation. For example, in one scenario (alfalfa 65% of ET_{base}), alfalfa farms are irrigated such that their average annual ET reaches 65% of the average annual historical ET of alfalfa farms in the study area (i.e., ET_{base} of alfalfa).

2.4.2. *Modifying crop pattern using current crops*

Six scenarios were simulated to investigate the impact of crop pattern changes on irrigation water consumption based on general agronomic practices in the region. Four scenarios examine the effects of water conservation associated with taking all or part of the less valuable crops (e.g., alfalfa, cotton, and corn) out of production (Table 1). Producers reduce alfalfa and cotton acreage or stop their cultivation altogether (Ganjegunte and Clark, 2017), depending on surface water availability while they rely on fresh groundwater to sustain pecans, the most vulnerable perennial crop. Corn, pepper, and vegetables had the maximum acreage decline (30%−56%) during the 2003–2004 period compared to the acreage in the previous year (2002–2003). The largest single-year acreage decline in major crops in the study area was recorded for alfalfa in 2011 during an exceptional drought (D4 intensity based on US Drought Monitor), which was 56% less than 2010 alfalfa acreage. The decline in cotton fields during the same year was about 26% less than 2010 cotton acreage. Similarly, corn, pecan, alfalfa, and vegetables reached their minimum cultivation area in 2011. A scenario was defined to investigate the current increasing trend of pecan acreage (i.e., 4% relative to 2012–2013) with a corresponding reduction in the acreage of other crops based on the fixed water allocation of the EBID. A combination of the water demand of young to mature trees was used for the new orchards in the simulation (2022–2099). Further, an extreme pecan-only scenario was considered to reflect the risk aversion behavior of the producers to save pecan trees during severe droughts (Table 1).

2.4.3. *Alternative crops*

Pistachio and pomegranate were considered as alternative crops. It was assumed that instead of expanding pecan orchards, irrigated lands are replaced with new pomegranate or pistachio orchards. For example, cotton fields (<10% of EBID) are changed to flood irrigated pistachio and pomegranate orchards by 2030. In recent years, some New Mexico farmers have expressed interest in growing pistachio and pomegranate as potential alternatives to pecan (Wang et al., 2015; Carreon, 2019). Thus, in an extreme scenario, pistachio and pomegranate trees could replace pecan orchards in 2050 (Table 1). Pistachio is relatively resistant to salinity (e.g., TDS up to 4000 mg/L), and water stress (needs about 610–1180 mm of water annually) compared to pecan (water demand of up to 1400 mm/year, e.g. Miyamoto, 1983). It has been cultivated in the U.S. as a commercial crop since 1929 (Herrera, 1997; Goldhamer and Beede, 2004; Geisseler and Horwath, 2016). The tree starts to bear fruit after 5–10 years while the full fruit production takes up to 15 years. Despite being a drought-adaptive crop, enough soil moisture during late winter, spring and early summer is required to produce a quality crop for commercial purposes with maximum water demand from June to August (Herrera, 1997; Goldhamer et al., 1985; Doster et al., 2001). Deficit irrigation at certain stages of crop growth may have minimal impact on pistachio yield (Goldhamer and Beede, 2004). Pomegranate is gaining attention as a competitive commodity crop due to its growing use in the food and medicine industries (Çam et al., 2009; Lansky and Newman, 2007; Carreon, 2019). The water use in surface or flood irrigation of pomegranate is 1250–1500 mm/year (Glozer and Ferguson, 2008) and in subsurface and surface drip irrigation is 53–953 mm/year, based on the tree age and irrigation method (Wang et al., 2015; Aseri et al., 2008; Volschenk, 2020). It takes 3–5 years for a young pomegranate tree to become productive (Glozer and Ferguson, 2008). The salinity tolerance threshold of pomegranate is reported to be up to 2560 mg/L (2.5–4 dS/m) of TDS (Holland et al., 2009).

3. Results and discussion

3.1. SWAT calibration and validation

Parameter values obtained by the SUFI-aided calibration are summarized in Table 2. The model performed well both during calibration (Nash-Sutcliffe Efficiency (NSE) = 0.68, percent bias (PBIAS) = 1.5% and R-squared= 0.86) and validation (NSE=0.70, PBIAS= −7.0%, and R-squared=0.84), although some peak flows (e.g., 2003 and 2004) and low flows during validation are over-estimated (Fig. 3). The annual average groundwater recharge was simulated at 25 mm, which is close to the results of other modeling applications in the study (e.g., Ahn et al., 2018). Calibration of crop ET and irrigation values improved model performance to assess water availability at the watershed scale.

The initial auto-irrigation settings, based on the field RAW, resulted in lower average annual irrigation amounts than expected based on the literature for crops, especially pecan and alfalfa (e.g., Abdul-Jabbar et al., 1983; Sammis et al., 2004; Samani et al., 2009, 2011, 2013). In reality, some farms are over-irrigated to leach out the salt, or because most farmers do not schedule irrigation based on RAW (Ganjegunte and Clark, 2017). Calibrating the irrigation amounts by adjusting the auto-irrigation parameters based on individual HRU characteristics improved simulated streamflow. At the completion of calibration, some HRUs remained over-irrigated by the model while others were under-irrigated based on water availability to each HRU and subbasin at each time step in the SWAT model. To ensure realistic irrigation water consumption at the watershed scale, the average simulated irrigation, ET, and yield of major crops were compared with available reported values (Table 3). The reported values are in ranges based on the different sources and years of reports (e.g., Abdul-Jabbar et al., 1983; Samani et al., 2004, 2009, 2011; Kannan et al., 2011; USDA, 2018). The range of simulated values refers to the minimum and maximum values obtained among the HRUs.

The model performance for crop irrigation and ET was acceptable (Moriasi et al., 2007) during calibration and validation. While the model has limitations in simulating detailed spatial distribution of water among HRUs, the average amount of irrigation of each crop at the watershed scale is within the range of reported crop irrigation in the region. The range of simulated crop irrigation and ET in SWAT for major crops, especially for pecan, is comparable with the range of reported irrigation values (Table 3). The model underestimates the average annual irrigation simulated for corn, which comprises 1.2% of the EBID. The irrigation and ET of onion matches the reported values in the literature (Kannan et al., 2011). Although the calibration approach focused on the hydrologic aspects rather than agronomic processes, the ranges of simulated yields are reasonable compared with reported crop yields except for onion yield and to a lesser extent corn (Table 3).

Pecan and alfalfa are the most water-demanding crops in the basin, covering about 74% of the EBID cultivated area, so the accuracy of simulated water consumption by these crops can largely influence the regional water budget calculations. For this reason, the irrigation and ET for these crops were calibrated with a higher precision on a monthly basis. Table 4 presents results of the comparison of four years of measured irrigation data from a flood-irrigated pecan orchard (Sammis et al., 2004; Wang et al., 2007) with historical maximum and average irrigation of pecan simulated by SWAT. It is noteworthy that the trees in the experimental orchards did not experience any water stress throughout the experiment due to groundwater supply from two wells (Sammis et al., 2004; Wang et al., 2007). Although irrigation data from a single well-watered farm are not necessarily representative of the pecan irrigation practices across the study area, the closeness of the simulated and measured pecan irrigation amounts increases the confidence in the model simulation performance. The higher measured irrigation data in 2003, a severely dry year (Samimi et al., 2022), indicates increased groundwater withdrawal, and possibly additional irrigation in the experimental orchards, to avoid adverse drought impacts.

The HRU-level irrigation amount and the resulting ET vary across the watershed. The semi-distributed nature of the SWAT model and the limited irrigation schedule for each farm complicates capturing the spatial distribution of water across various farms. EBID farms do not receive similar amounts of water; some farms apply deficit irrigation forced by limited available surface water and groundwater. Expectedly, as shown in Fig. 4, average monthly SWAT-simulated ET is consistently lower than measured ET at a well-

Table 2
Calibration parameters in the SUFI-aided calibration.

Parameter	Definition	Default Range/Value	Final Estimate
ALPHA_BF	Base flow recession constant (days)	0–1	0.4
GWQMN	Return flow threshold depth (mm)	0.01–5000	1500
CANMX	Maximum canopy storage (mmH_2O)	0	1–3
OV_N	Manning's "n" value for overland flow	0.008–0.5	0.02
EPCO	Plant uptake compensation factor	0.01–1	0.9
ESCO	Soil evaporation compensation factor	0.01–1	0.8
GW_REVAP	Groundwater "revap" coefficient	0.02–0.2	0.08
CH_N2	Manning's n value for the main channels	0.008–0.5	0.03 (Rio Grande literature)
GW_delay	Groundwater delay time (days)	31	Ag.: 20; non-Ag.: 115
CN2	SCS curve number for moisture condition II	35–98	varies (40–75)
LAI_INIT	Initial leaf area index	varies	4
REVAPMN	Threshold water level in shallow aquifer for "revap" or deep percolation (mmH2O)	varies	800
RCHRG_DP	Deep aquifer percolation fraction	0–1	0.1
AUTO_WSTRS	Water stress threshold that triggers irrigation (mm for soil water deficit)	varies	30–100
SURLAG	Surface runoff lag coefficient (days)	4	2–4
HVSTI	Harvest Index	varies	0.13–1.25

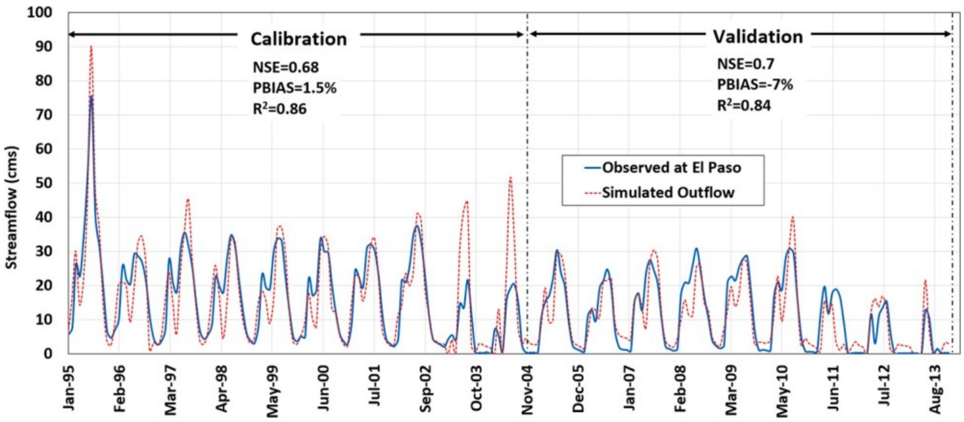

Fig. 3. Streamflow calibration and validation.

Table 3
Calibration results for crop irrigation, ET, and yield.

Crop (% EBID acreage)	Irrigation (mm)		ET (mm)		Yield (tons/ha)	
	Reported[a] (Average)	Simulated[b] (Average)	Reported[c] (Average)	Simulated (Average)	Reported[c] (Average)	Simulated (Average)
Pecan (37)	368–2300 (1300[c])	224–2970 (1700)	825–1400 (1113)	369–1460 (1060)	2.5	0.3–2.3
Alfalfa (37)	900–2100 (1500)	127–1713 (983)	390–1240 (900)	312–1140 (850)	5–19	0.7–14
Cotton (9)	508–950 (729)	170–1920 (736)	650–890 (770)	370–1260 (947)	1.1–1.5	0.02–7
Corn (1.2)	508–1300 (904)	127–930 (580)	685 (NA)	214–1045 (740)	0.5–13	2–20
Pepper (1.3)	1050–1400 (1225)	570–1900 (1260)	900 (NA)	614–1310 (1098)	5	2–16
Onion (10)	350–1040 (695)	190–1560 (667)	1010 (NA)	360–1055 (782)	50–57[d]	0.02–14.5

a Irrigation range is based on reported irrigation in the study area (Miyamoto, 1983; Abdul-Jabbar et al., 1983; Al-Jamal et al., 2000; Sammis et al., 2004, 2013; Andales et al., 2006; Wang et al., 2007)
b The ranges of simulated irrigation and ET include the minimum and maximum results amongst the HRUs during the simulation period (1994–2013)
c The range is based on reported values for ET (Sammis et al., 2004, 2013; Wang et al., 2007), and yield (Smeal et al., 1991; Al-Jamal et al., 2000; Samani et al., 2013; USDA, 2018) in the study area for different years.
d USDA (2000)

Table 4
Comparison of monthly measured pecan irrigation in a well-watered experimental orchard with SWAT-simulated irrigation across the watershed.

Month	**Pecan Monthly Irrigation (mm)**					
	Measured *				**Simulated* * (1994–2013)**	
	2001	**2002**	**2003**	**2004**	**Average**	**Maximum**
March	88	115	120	NA	–	–
April	112	114	135	146	117	164
May	357	326	416	231	152	211
June	361	354	467	421	178	236
July	350	303	394	343	167	223
August	293	357	323	347	126	199
September	202	188	284	127 * *	97	151
October	176	196	190	147	68	111

* Measured water application in a flood-irrigated pecan orchard with no water stress throughout the experiment for 2001–2002 (Sammis et al., 2004) and for 2002–2003 (Wang et al., 2007). Both studies used the same farm.
* * The experimental orchard was irrigated twice during September 2003 but the irrigation amount for the first application was not reported.
* **Irrigated twice in May and October and three times a month from June to September.

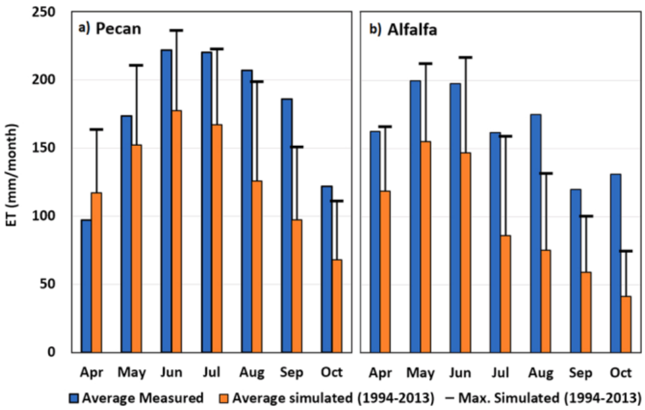

Fig. 4. Comparison of monthly average measured ET for (a) pecan and (b) alfalfa for well-watered experimental farms and SWAT-simulated average monthly and maximum ET (1994–2013) for pecan/alfalfa. Average measured ET data were obtained for well-watered pecan monitored from 2001 to 2004 (Sammis et al., 2004; Wang et al., 2007) and well-watered alfalfa monitored in 2008 (Samani et al., 2013).

irrigated farm that experiences no water stress (e.g., Sammis et al., 2004; Wang et al., 2007; Samani et al., 2013). The maximum simulated ET values for pecan and alfalfa for an HRU that receives sufficient water are comparable with the measured ET values at well-watered experimental farms (Fig. 4), indicating that the model is performing well in terms of representing watershed-scale irrigation and crop ET for regional water budget assessments. Overall, the disproportionate irrigation of HRUs by SWAT model is reasonable due to unequal irrigation of farms.

3.2. Assessment of intervention scenarios

The long-term tradeoffs of technologically possible land and water management interventions were analyzed to adapt irrigated agriculture in order to continue producing high-value perennial crops in the face of growing water scarcity in a warm-dry future. Table 5 summarizes the results of total water consumption and average annual irrigation water availability compared with the projected status quo for six example scenarios. The results for all the nineteen intervention scenarios are reported in Table S1 in Supplementary Material. Both regulated (i.e., early termination of irrigation) and unregulated deficit irrigation of alfalfa resulted in increased water availability for pecan. Moderate to severe deficit irrigation of alfalfa farms reduced the total water consumption of the farmlands across the watershed (based on average annual ET) more than other interventions. Combining the severe deficit irrigation of alfalfa and mild deficit irrigation of cotton (e.g., Alfalfa 50% of ET_{base} and cotton 85% of ET_{base}) slightly improved the water conservation potential compared to the severe deficit irrigation of alfalfa farms alone (Table S1). Under this scenario, the amount of water available to irrigate pecan orchards could be increased by about 19% (Table S1). Moderate deficit irrigation of alfalfa (i.e., curtailing the irrigation of this crop to lower alfalfa ET to 65% of its ET_{base}) increased pecan water availability by 14%. The deficit irrigation of other crops alone does not produce the same level of water saving, because of lower area and water demand. For example, reducing the irrigation to lower the consumptive use of water in cotton fields by 50% resulted in only about a 2% increase in pecan water availability (Table 5). As expected, regulated deficit irrigation of cotton had less impact on pecan water availability compared to the unregulated deficit irrigation with high water stress of up to 50% of ET_{base} for cotton.

Table 5
Average watershed outflow (MCM) and crop irrigation (MCM) in the growing season for example scenarios.

Scenario	Outflow	EBID Irrigation	EBID ET	Crop Irrigation				
				Pecan	Alfalfa	Corn	Cotton	Pepper
Projected status quo	143.2	349.0	267.7	179.8	116.5	2.5	15.6	6.2
Early irrigation termination for alfalfa	147.0	347.8	266.2	191.6	102.1	2.6	16.7	6.2
Change (%)*	2.7	-0.4	-0.6	6.6	-12.4	3.1	6.8	0.4
Alfalfa 50% of ET_{base}	182.0	316.9	247.1	213.2	44.9	2.7	19.0	6.2
Change (%)	27.0	-9.2	-7.7	18.6	-61.4	7.1	21.7	0.7
Cotton 50% of ET_{base}	148.4	356.6	262.1	181.6	128.9	2.5	8.8	6.1
Change (%)	3.6	-0.4	-1.8	2.2	0.6	0.2	-42.6	0.1
No Alfalfa after 2050	165.5	341.0	242.0	228.0	50.0	3.0	21.0	6.2
Change (%)	15.6	-2.3	-9.5	27.0	-56.9	10.6	35.9	0.8
Only pecan after 2050	198.0	339.4	212.6	259.0	–	–	–	–
Change (%)	38.0	-5.2	-20.4	45.7	–	–	–	–
Pecan replaced with pomegranate now	152.5	300.0	273.0	–	130.0	2.6	16.4	6.1
Change (%)	6.5	-14.0	2.0	–	12.0	2.4	5.0	-0.3

[*] Percent change compared to projected status quo

Removal of alfalfa from the crop mix had a much larger effect on increasing pecan water availability than removing cotton. In an extreme case, removing alfalfa farms in 2050 increased pecan water availability up to 27%. Under this scenario, corn and cotton also received about 11% and 35% more water than the projected status quo while watershed outflow increased by 16%. Overall, however, even the aggressive scenario of completely removing alfalfa from the crop mix after 2050 will not provide sufficient water to maintain the ET level for pecan orchards, which might result in crop loss during major prolonged droughts (Fig. 5).

Growing pistachio and pomegranate instead of cotton (about 9% of EBID farmlands) after 2050 resulted in a small to moderate reduction (up to −12%) of irrigation water availability for other crops because the water requirements of these alternative crops are comparable to pecan. Replacing current pecan orchards with pistachio or pomegranate trees after 2050 would increase alfalfa water availability by about 10% and the watershed outflow up to 2%. The water availability changes for other crops are insignificant while the annual irrigation water consumed across the watershed would be about 5–14% less than the projected status quo. Replacing all pecan orchards with pistachio or pomegranate after 2022 would not change the results significantly compared to replacing the trees after 2050. This can be explained by the small difference between the water demands of pecan and pistachio and pomegranate trees.

Under status quo irrigation management in a warmer and drier future (2022–2099) characterized by falling reliability of full water allocation from EB reservoir due to dwindling river water and risk of fresh groundwater depletion (Samimi et al., 2022), the current level of pecan production would require significant loss of other crops. Besides the extreme scenarios of removing all alfalfa farms by 2050 and only pecan grown after 2050, which led to minimal water stress for pecan orchards, other scenarios result in pecan irrigation demand being met about 30% of the time (see Fig. S1 in Supplementary Material). Given the risk of fresh groundwater (TDS<1000 mg/L) depletion in the region in the coming decades (Samimi et al., 2022), only the extreme scenarios would save adequate water to maintain the current acreage of pecan orchards (Fig. 6). However, pecan orchards are expected to remain vulnerable to significant water stress during severe prolonged droughts (e.g., 2070–2079) even under the extreme intervention scenarios.

Decreasing the acreage of pecan orchards is not economically viable without some sort of compensation to growers due to the significant loss of pecan trees that are usually productive for several decades. It will also be challenging to expand the acreage of pecan orchards in the face of dwindling agricultural water supply and increasing salinity due to growing likelihood of fresh groundwater depletion. Even a slight increase in the acreage of pecan (i.e., a 4% increase in 2020) results in significant water shortage for other crops. Pecan production is negatively affected by water stress and salinity (Miyamoto et al., 1995; Miyamoto, 2007). Using more irrigation water to leach out salt from the root zone, diluting the saline water with available fresh water, switching to drip irrigation, on-farm desalinization units, and growing more salt-tolerant crops are example strategies to deal with the impacts of salinity.

Deficit irrigation and reducing the acreage of water-intensive crops like alfalfa allow modest water savings in the study area but not enough to drastically change the vulnerability of pecan farms to future severe droughts. However, reducing the acreage or removing other crops is also challenging due to a strong sense of ownership of water (Hargrove and Heyman, 2020). Alternative crops, such as pistachio and pomegranate, might not generate significant water savings, especially in surface irrigation, but they offer a potential strategy to improve the resiliency of the agricultural sector in this region, along with using deficit irrigation, drip irrigation, or irrigation with marginal quality water. The time required for the new alternative crops to reach commercial fruiting should be considered in the planning of this adaptation strategy.

The effectiveness of deficit irrigation depends on climate, water retention potential of the soil, and plant physiology and mechanisms to cope with water stress (Aydinsakir et al., 2013; Witt et al., 2020). Although some studies have reported that deficit irrigation may decrease crop productivity to some extent (Bauder et al., 2011; Djaman et al., 2020), other studies have shown increased crop quality or improvements in the yield under deficit drip irrigation such as increased boll weights and opened boll numbers in cotton (Onder et al., 2009; Liu et al., 2017). Regulated deficit irrigation of crops like alfalfa could have less negative impact on their yield (Bauder et al., 2011; Djaman et al., 2020; Smeal et al., 1991). In some cases, the yield reduction associated with deficit irrigation was negligible (Costa et al., 2007). In areas facing growing water scarcity and rising economic value of water, the increase in water use efficiency may justify the yield reduction. The yield reduction and optimum time for deficit irrigation in arid and semi-arid regions depend on many factors that vary from year to year (Payero et al., 2009). Deficit drip irrigation of cotton during the initial and final stages of growth were most efficient in the Southern High Plains with 350–450 mm rainfall (Himanshu et al., 2019). Moderate water stress without decreasing irrigation events had minimum yield loss in cotton in the arid climate of Central Asia (Pereira et al., 2009). Mixing deficit irrigation with other measures like mulching to manage soil water might be more effective (Pereira et al., 2009). There is a dearth of literature on deficit irrigation of pecan orchards, although it is generally known that pecan is highly sensitive to water stress (Miyamoto et al., 1995; Miyamoto and Storey, 1995).

3.3. Limitations of the modeling approach

The results should be interpreted in light of the spatial scale of the analyses and limited data. Despite extensive calibration of the model to realistically simulate irrigation alongside streamflow, ET, and groundwater recharge, the results from the watershed-scale model are not directly generalizable to field scale. This is because of the model's semi-distributed nature, which hinders explicit simulation of the spatial variability of water availability on the farm with varying crop types and soil characteristics. SWAT distributes the saved water under different irrigation interventions among all other crops. For example, despite the decrease in cotton irrigation by deficit irrigation, the available water for pecan and alfalfa did not change significantly as the model distributed the conserved water across all other cultivated areas (Fig. S2). In reality, farmers can leverage the conserved water to prioritize the irrigation of higher-value crops. In addition to the irrigation of other crops by the conserved water, a portion of the saved water leaves the watershed as outflow (Table 5). Although this may be considered as a desirable outcome from the standpoint of surface water availability for downstream users, this could also be an artifact of using the auto-irrigation function of SWAT. The largest outflow belonged to

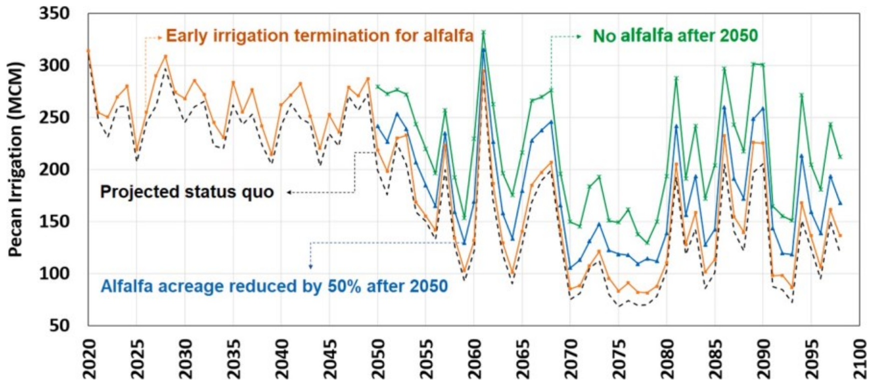

Fig. 5. Projected pecan irrigation under different cropping and deficit irrigation interventions.

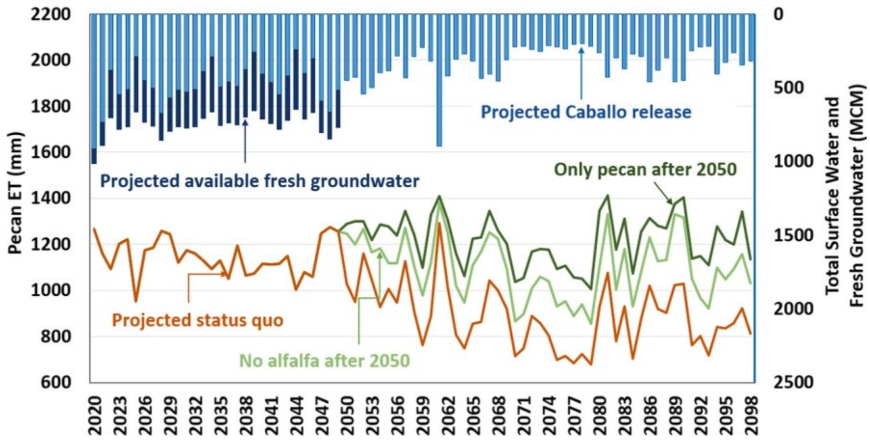

Fig. 6. Simulated pecan evapotranspiration for scenarios of no alfalfa after 2050, and only pecan after 2050 compared to projected status quo in a warm-dry future with fresh groundwater (TDS < 1000 mg/L) depletion in 2050.

scenarios of deficit irrigation of alfalfa while other crops in some farms remained under-irrigated, likely due to differences in soil types, crops, and soil moisture variation in the farms, which affects auto-irrigation timing. Farm-level analyses of water saving potential and likely impacts on crop yield require detailed field-scale measurements and modeling to reduce uncertainties in model setup and parametrization. Drip irrigation of the alternative crop orchards or existing crops could create additional water conservation opportunities, but this scenario could not be explicitly simulated due to the limitation of the current SWAT model.

3.4. Need for holistic analysis of policy implications

This study focused on the water budget implications of the analyzed interventions as a first step toward a more holistic analysis of the broad, important policy implications of leveraging agricultural water conservation and cropping change to adapt to a warmer and drier future in the MRG. Effective planning and implementation of the discussed interventions would facilitate additional evaluation of the interventions considering the required infrastructure, crop yield loss/gain, finding/establishing markets for alternative crops, and social and environmental considerations compared to business as usual. It is expected that the modeled interventions result in reductions in net profitability for growers to varying degrees, and they will not be implemented voluntarily without policy interventions that would somehow compensate growers through financial incentives or catalyze change through disincentives. To this end, there is a critical need to better understand "what would each intervention scenario cost to implement", "what is the cost-benefit ratio of each scenario", and "what are the opportunities and hurdles to develop the infrastructure and markets for new crops". If irrigated agriculture is to be sustained, viable policy interventions are necessary to preempt the end of agriculture in the region due to depletion of fresh groundwater and loss of economic competitiveness.

4. Conclusions

Nineteen land and water management interventions were investigated to evaluate potential watershed-scale agricultural water savings to sustain high-value crop production and associated tradeoffs in the middle section of the Rio Grande basin in a warm-dry future. The intervention scenarios were developed focusing on deficit irrigation and changing cropping patterns using existing crops or introducing new alternative crops, taking into account the limitations of the SWAT model to perform scenario simulations. Results demonstrate that maintaining the current crop mix with status quo irrigation management will be challenging due to declining river water availability and likely fresh groundwater depletion within the 21st century. The water conservation potential of existing cropping and irrigation interventions will be limited in a warm-dry future. Extreme interventions such as aggressive deficit irrigation or stopping the cultivation of alfalfa generate moderate water savings for perennial pecan crops. It is timely to prepare for scenarios of reduced freshwater availability and intensive, prolonged droughts. Some examples of potential technologies that hold promise include desalination of brackish groundwater for irrigation, developing water markets to increase flexibility in water use, and transitioning to high-value crops that are relatively drought- and salt-tolerant to increase the resiliency of irrigated agriculture. Detailed study of crop growth stages and yield reduction due to water stress is necessary for planning more sustainable deficit irrigation with minimal loss of crop yield and the introduction of alternative high-value crops. There is also a need for more holistic analysis of the policy implications of more aggressive agricultural water conservation and cropping change from socio-economic, agronomic, and environmental standpoints.

CRediT authorship contribution statement

M. Samimi and **A. Mirchi** conceived of the ideas, performed the experiments, analyzed the results, and prepared the first draft of the manuscript. **D. Moriasi, Z. Sheng, D. Gutzler, S. Taghvaeian, S. Alian, K. Wagner, and W. Hargrove** contributed to scenario development and interpretation of the results, and helped finalize the manuscript for publication.

Declaration of Competing Interest

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.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101307.

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