Evaluating Sustainable Crop Management in Arid Conditions using System Dynamics Modeling of Soil Salinity, Root Water Uptake, and Yield Reduction

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Abstract - *In arid regions, where water scarcity and soil salinity significantly impact crop health, promoting soil-tolerant crops and robust salinity management practices is crucial for sustainable agriculture. This study aims to simulate transient soil water flow, root water extraction, and salt transport in the vadose zone to quantify the long-term effects of root water uptake and crop yield under conditions of salinity and water stress over a decade. Utilizing the SMITUV system dynamic model, five irrigation water source scenarios with varying salt content were simulated, observing the resulting reductions in root water uptake and crop yield for Pecan and Cotton under water and salinity stress. Prolonged drought conditions were replicated using rainfall data for a period of 10 year. Results reveal that Pecan, with lower salt tolerance, experienced significant decreases in root water uptake and crop yield, while Cotton, with higher salt tolerance, showed minimal reductions. These findings underscore the importance of selecting salt-tolerant crops and implementing salinity management strategies in drought-prone regions. The study advocates for desalination practices and crop variety selection to ensure sustainable agricultural productivity in arid areas. This research provides insights into resilient agricultural practices amid climate change-induced droughts, emphasizing the significance of desalination practices and crop variety to address water scarcity and soil salinization in arid regions.*

Key Words: System Dynamics, Osmotic Stress, Water Stress, Salinity, Desalination, Arid, Resilience, Drought, Agriculture

1. INTRODUCTION

Agriculture in the arid southwest of the United States depends on surface and groundwater irrigation. Often, water sources contain a significant amount of dissolved salts that accumulate in the agricultural soils over time. The interplay between natural factors such as the geological nature of the region, surface water hydrology, minerals in underground water, low rainfall, high temperature, high evaporation, extremely hot and dry winds, coupled with anthropogenic factors such as the use of fertilizers, results in high salinity in soils [1]. Managing salts and using salt-tolerant species is extremely important for the sustainability of agriculture in the region.

The prolonged impact of salinity on crops in arid regions is a critical concern, emphasizing the dynamics between environmental stressors and agricultural productivity. Arid regions, characterized by limited water availability and high evaporation rates, are particularly vulnerable to soil salinization due to the gradual accumulation of salts from irrigation and natural processes [2], [3], [4], [5], [6]. The persistence of elevated salinity levels significantly hampers crop growth and development over extended periods [7], [8], [9]. As salinity accumulates in the soil, it creates an osmotic imbalance that restricts water uptake by plant roots, impairs nutrient absorption, and disrupts vital physiological processes [2], [10]. This multifaceted stress adversely affects various facets of plant growth, including germination, root elongation, leaf expansion, and reproductive success [11], [12], [13]. Prolonged salinity exposure further amplifies the deleterious effects by compromising the overall vigour and health of crops, rendering them more susceptible to pest infestations, diseases, and other environmental stressors [14], [15]. Consequently, the cumulative impact of prolonged salinity poses a formidable challenge to sustaining agricultural productivity and food security in arid regions, warranting comprehensive research and adaptive strategies to mitigate its enduring repercussions.

Mitigating the prolonged effects of salinity on crops in arid regions necessitates a comprehensive approach that integrates advanced agronomic practices, innovative irrigation strategies, and the utilization of salt-tolerant crop varieties. One key aspect involves optimizing irrigation management to minimize the buildup of salts in the root zone [16], [17]. Implementing precision irrigation techniques, such as drip or subsurface irrigation, can help maintain a more uniform soil moisture profile and mitigate salt accumulation at the plant's root zone. Additionally, identifying and cultivating crop varieties with inherent salt tolerance or genetic modification techniques can enhance resilience against prolonged salinity [5], [8]. Breeding programs aimed at developing crops that exhibit improved salt tolerance mechanisms, such as efficient ion exclusion, osmotic adjustment, and antioxidant defence systems, hold promise for mitigating the protracted effects of salinity on crop performance [2], [18].

Collaborative efforts between researchers, agronomists, and local communities are imperative to devise context-specific strategies that integrate scientific insights with traditional knowledge, enabling sustainable agricultural systems in arid regions despite the persistent challenge of prolonged salinity impact.

Predictive models have emerged as instrumental tools for effectively managing salinity issues in crops within arid regions. These models harness the power of advanced computational algorithms to simulate and forecast the dynamics of soil-water-salt interactions, enabling proactive decision-making and precision management strategies [19], [20]. By integrating essential factors such as soil properties, irrigation practices, climate conditions, and crop responses, these models offer a comprehensive understanding of salinity-related processes [21], [22]. The utilization of predictive models empowers farmers, agronomists, and policymakers to assess the long-term impact of salinity on crop performance, anticipate potential stress periods, and devise optimized irrigation schemes that minimize salt accumulation in the root zone [23], [24]. Additionally, these models aid in identifying salt-tolerant crop varieties and guide the implementation of targeted mitigation measures [8], [25]. As climate change exacerbates the salinity challenge, predictive models serve as indispensable tools for informed and sustainable agricultural practices in arid regions, fostering resilience and ensuring food security in the face of persistent salinity stress. Several numerical models are available for analyses of salt accumulation in the soil layers, such as ENVIRO-GRO [26], SALTMED [27], SWAP [28], UNSATCHEM [29], [30] and HYDRUS [31], [32], [33], [34]. These models predict salt accumulation based on the numerical solutions to physically based formulations and empirical assumptions. In addition to the simulation of salt accumulation, HYDRUS and UNSATCHEM have an additional option for precipitation and dissolution of calcite, gypsum, nesquehonite, hydro magnesite and sepiolite that introduces the concept of an amendment to the soil for reducing the accumulated salts [29]. The DRAINMOD model, conceived by [35], serves as a valuable tool for simulating soil profile salinity, salt distribution, and water movement, particularly in areas equipped with drainage systems. In addition to DRAINMOD, the DRAINMOD-S and Aqua Crop models have gained prominence in simulating a diverse array of crops [36], [37], [38]. Recently, a United States Department of Agriculture (USDA) funded SMITUV model, developed to simulate one-dimensional water infiltration in unsaturated soil using Richard's equation, offers a sophisticated tool for capturing the dynamic interplay between soil moisture, salt distribution and their impact on plant root systems [21], [22]. Unlike other models that are developed using FORTRAN and require significant expertise to integrate and modify various components, SMITUV is designed to engage and educate growers and allow for easy modification to the problem at hand with a graphical system dynamic development environment. The inherent systems approach allows the user to understand the system connections better, for example, how salinity, hydraulic conductivity, and crop uptake are interlinked. This study leverages the capabilities of the SMITUV model to explore the prolonged effects of salinity on crops in arid regions.

2. Model Description

Leveraging the collaborative and adaptable attributes of the SMITUV model, it was employed in this study to assess the prolonged impact of salinity on crops under drought-like conditions. Using Richard's equation, the SMITUV model simulates the dynamics of 1D water infiltration in unsaturated soil. It simulates the dynamic relation between soil moisture, salt distribution, and their interaction with plant root systems. SMITUV stands out as a participatory tool that was calibrated against the benchmark results of the HYDRUS 1D model, ensuring its reliability using the results based on Pecan and Cotton [22], [39]. A distinctive feature of SMITUV lies in its inherent versatility, made possible by utilizing a stock-converter framework embedded within the STELLA Architect software. This adaptability enables researchers and practitioners to readily modify and fine-tune the model parameters per their study's specific requirements. SMITUV can conveniently be accessed on the GitHub platform (https://github.com/skp703/SMITUV).

SMITUV uses feedback loops to dynamically relate the systems to each other through reinforcing (positive feedback loop represented by "+") and counteracting (negative feedback loop represented by "-") loops, as shown in Chart 1. SMITUV utilizes an implicit backward finite difference method to solve Richards' equation for water infiltration and root water storage, transforming it into a discretised form [22]:

$$\frac{\partial\theta}{\partial t} = \frac{1}{\Delta z_i}\left[K_{i-\frac{1}{2}}\left(\frac{h_{i-1} + h_i}{\frac{\Delta z_{i-1} + \Delta z_i}{2}} + 1\right) - K_{i+\frac{1}{2}}\left(\frac{h_i + h_{i+1}}{\frac{\Delta z_i + \Delta z_{i+1}}{2}} + 1\right)\right] - S_i$$

Where Θ is the water content, h is the water pressure head, Δz_i is the soil compartment thickness, and S_i is the sink term representing root water uptake that flows out from each soil layer.

Similarly, SMITUV utilizes an explicit central finite difference method to solve the advection–diffusion equation for solute flow as a flux in the soil layer transforming it to a discretised form [22]:

$$\frac{\partial c}{\partial t} = \frac{1}{\theta_i \Delta z_i}\left[q_{i-1/2}c_{i-1/2} + \frac{\theta_{i-1/2}D_{i-1/2}(c_{i-1}-c_i)}{1/2(\Delta z_{i-1}+\Delta z_i)} - q_{i+1/2}c_{i+1/2} - \frac{\theta_{i+1/2}D_{i+1/2}(c_i-c_{i+1})}{1/2(\Delta z_i+\Delta z_{i+1})}\right]$$

where, c is the total solute concentration per unit volume of soil (g/cm^3); q is Darcy's volumetric flux (cm/day); and D is the diffusion constant (cm^2/day).

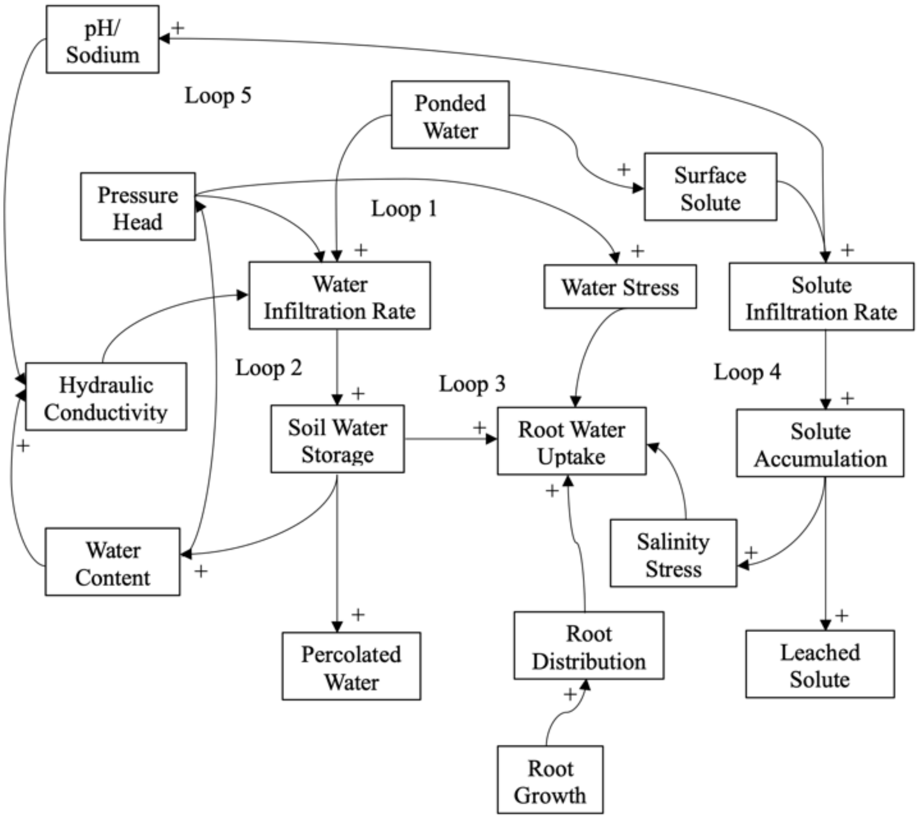

Chart -1: Causal loop diagram for salt-water dynamics by SMITUV: Loop 1 - water infiltration to the first soil layer; Loop 2 - increased hydraulic conductivity due to stored water; Loop 3 - crop root water extraction leading to water stress; Loop 4 - salt infiltration increasing soil salt content; Loop 5 - elevated sodicity and pH reducing hydraulic conductivity.

3. Methodology

The research methodology begins with systematic data collection from the project site. Subsequently, the SMITUV model is employed for simulations, and outcomes are analysed to identify patterns. The study focuses on a 10-year dataset in an arid region, examining the impact of salinity on water intake, soil salt accumulation, and yield reduction for Pecan and Cotton crops. Prolonged salinity is characterized by insufficient external water sources such as rain and river water, leading to increased reliance on groundwater irrigation, resulting in elevated salt levels within the plants and subsequent yield reduction. This investigation aims to elucidate the effects of a decade-long drought on crop yields, providing crucial insights for farmers in the region. The research methodology steps are visually represented in the Chart 2.

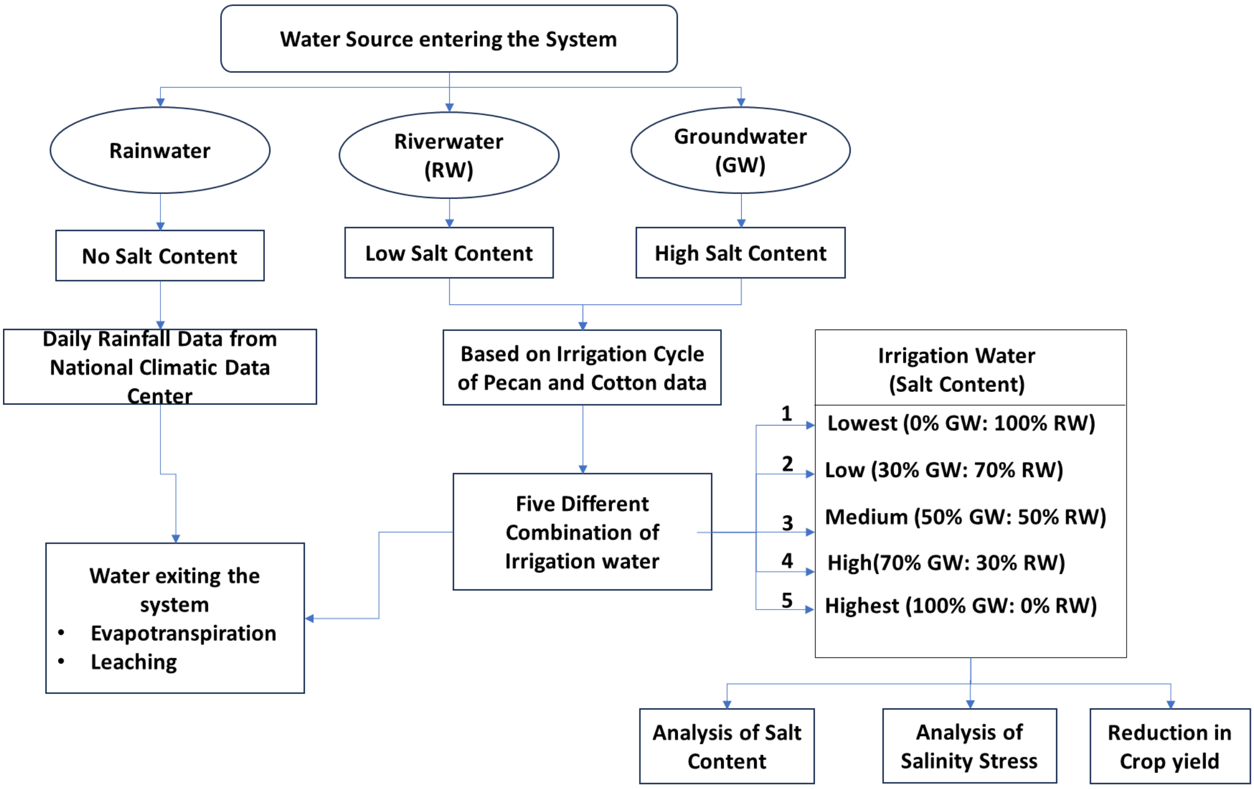

Chart -2: The flowchart depicts the incorporated data, assumptions, simulation scenarios, and the results analyzed to draw conclusions.

3.1.Study Area

Texas A&M AgriLife Centre with a farm of about sixteen hectares area, positioned at coordinates 31°30’32.30” N, 106°13’25.49” W was selected as the study area. This geographical context represents the distinctive attributes of arid regions, characterized by the scarcity of rainfall, with an average annual precipitation of approximately 15 cm, coupled with pronounced potential evapotranspiration reaching 194 cm. The diurnal temperature variations, encompassing peaks of 35.8°C and troughs of -3.4°C, underscore the region's climatic rigors. A substantial influx of solar energy, quantified at about 19.78 MJ m^{-2} d^{-1}, is met with a graceful wind velocity averaging 1.21 ms^{-1} [40]. Within this context, these farms serve as controlled environments for deciphering the intricate ramifications of salinity-induced effects on cotton and pecan crops within the challenging backdrop of arid landscapes.

Water in the region is a highly managed system with competing demands. Over the past decades, the Rio Grande has been the primary water source for the expanding municipalities and changing agriculture in the region [41]. With the recent severe drought and growing demand, the river alone no longer meets regional water needs, leading to increased groundwater use and dropping water tables [42]. The primary sources of groundwater are the Mesilla and Hueco Bolsons. The Hueco Bolson and large portions of the Mesilla Bolson are water deposits with little or no recharge, with drawdown representing withdrawals against current and future reserves [43]. Both sources, based on the location, have significant dissolved salts. At some locations, the well water contains four times as much salt compared to the average Rio Grande river, and irrigation using this well water increases the leaching requirement by 30% [44]. Pecan and Cotton are the region's major crops, and many studies have focused on these crops’ irrigation efficiencies [40], [44], [45].

3.2. Soil Hydraulic Properties

For the 16-hectare study site, the pertinent soil hydraulic properties (θr, θs, and Ks) were sourced from [46] These properties pertain to Tigua (Tg - 72%), Glendale (Gs - 12%), and Harkey (Hs - 16%) silty clay loam soils, as depicted in Figure 1. The air entry pressure (α) and pore size distribution (n) values for the Soil Water Retention Curve were derived from studies conducted by Schaap and Genutchen [47] who classified and evaluated soils across the United States based on hydraulic properties. Their research revealed that our study site's soil is categorized as silty clay loam, with α measured at 0.0178 cm^{-1} and n at 1.30. Table 1 presents the soil hydraulic properties pertinent to the simulation.

Fig -1: Soil map of the study area located at coordinates 31°30’32.30” N, 106°13’25.49” W, extracted from the Web Soil Survey website, depicting various soil classifications in the region. The study area corresponds to the Texas A&M AgriLife Extension farm in El Paso, Texas.

Table -1: The soil hydraulic properties, including soil depth (from topsoil), residual water content, saturated water content, saturated hydraulic conductivity, soil pH, and maximum water holding capacity, were extracted from the Web Soil Survey for the study area.

Soil depth (from Topsoil) (z) cm	**Residual Water Content (θ_r) cm^3 cm^3**	**Saturated Water Content (θ_s) cm^{3}cm^{-3}**	**Saturated Hydraulic Conductivity (Ksat) cm day^{-1}**	**Soil pH**	**Maximum Water Holding Capacity (cm) ($z \times \theta_s$)**
30	0.00	0.34	6.11	8.15	10.2
30	0.01	0.39	15.80	8.15	11.7
40	0.02	0.39	40.44	8.15	15.6

3.3. Daily Rainfall

Analysing historical rainfall data further reinforces the suitability of this chosen duration for simulation. The rainfall records were sourced from National Climatic Data Centre (NCDC), thoroughly collected and analysed. The information collected from this dataset, illustrated in Chart 3, reflects the evident scarcity of rainfall during the selected period. To effectively capture the degrees of this dynamic, the simulation duration spans 3,653 days. Furthermore, the SMITUV model was set to calculate each variable at intervals of 0.125 a day to ensure a high level of detail. This precise approach emphasizes the precision and rigor inherent in our analysis, enabling the understanding of intricate relationships between drought duration, salt accumulation, and associated consequences for crop behaviour.

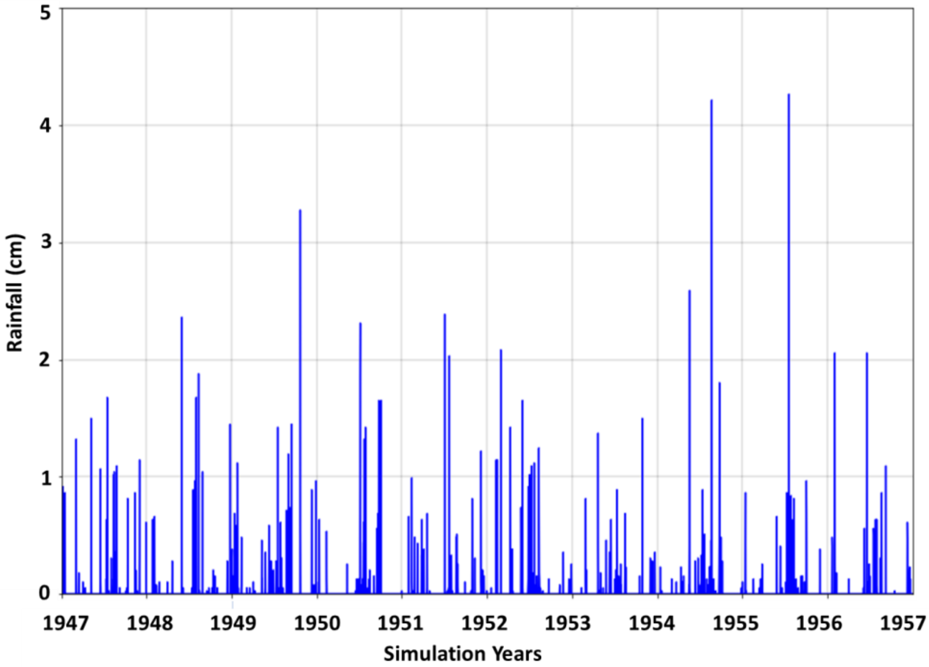

Chart -3: Ten years of daily rainfall data in centimeters, spanning from 1947 to 1956, obtained from the National Climatic Data Center (NCDC). The data illustrates sparse rainfall throughout the decade, indicating a period of drought in the region.

3.3. Annual Irrigation Cycle

The frequency and distribution of irrigation events for each crop in a year assumes that both Cotton and pecan crops adhere to a uniform irrigation frequency throughout the period from 1947 to 1956. Pecans receive irrigation twice a month from May to October, while Cotton is irrigated once a month from May to September, except in August when irrigation occurs twice. Both crops are flood-irrigated up to a depth of 12.7 cm each time. This irrigation strategy facilitates a systematic examination of how the type and frequency of irrigation influence salt accumulation within the soil layers.

3.4. Source of Irrigation Water

Rainwater is naturally used for irrigation during the simulation when rainfall occurs. The model accounts for the corresponding rain volume, assuming it carries no salt compared to river and groundwater sources. For the rest of the water needs, a mix of river water and groundwater is presumed. Both sources have higher salt content than rainwater, with groundwater leading to greater salt accumulation than river water. Salinity levels in irrigation water depend on its origin, varying between groundwater wells, rivers, and rainwater. Wells have higher salinity than rivers or rain. These differences in salt concentration from various sources significantly affect salt accumulation in the soil layers.

3.5. Surface Solute Concentration

Similar to the significance of rainfall, the initial surface solute concentration is pivotal in determining salt quantities entering the system at each time step, influencing the model's behaviour over time. To enable this, daily salt loads from rain, river, and groundwater were inputted for 10 years, yielding a dataset of 3653 data points. However, a practical approach is taken due to the lack of daily salt data, assuming that the observed surface solute concentration on a chosen day persists throughout the simulation. Additionally, a yearly increase of 4.48 mg/l of salt in groundwater is assumed based on regional observations and insights from Texas A&M AgriLife researchers.

The specific surface solute concentration observed at the research site is in Table 2. Under the assumption that this surface solute concentration remains uniform throughout the simulation period, we employ a weighted average formula to compute the resultant salt concentration for each day. By incorporating this consistent approach, the model attains a degree of authenticity that mirrors the gradual buildup of salts within the irrigation water, thereby accurately representing the complex interplay between salt content, irrigation water, and their cumulative effects.

Table -2: Observed salt concentration in irrigation Water (mg/l) in the study region was assumed to be uniform for the model simulation of 10 years, with an annual increase of 4.48 mg/l.

Salt / Water Type	Total Dissolved Salts (mg/l)	Sodium (mg/l)	Calcium (mg/l)	Magnesium (mg/l)
Rainwater (SR)	32	10.95	19.2	1.77
River Water (SRW)	512	106.94	101.38	16.52
Ground Water (SGW)	4627.2	1941	252	59.52

3.6. Monthly Potential Transpiration

The quantity of water exiting the system is as vital as the amount entering it. To account for this, the concept of daily potential evapotranspiration was simulated as the water leaving the system. Monthly average evapotranspiration data spanning the past 52 years were sourced from the Texas ET Network Chart 4. Since our model operates daily, we divided these monthly averages by the corresponding number of days each month, enabling us to approximate daily evapotranspiration rates.

Furthermore, to accurately estimate water loss from each crop, it is imperative to determine the potential evapotranspiration specific to the plants. This entails calculating the consumptive value Kc for pecan, derived from the insights of [44], and for Cotton, as obtained from [50]. These calculated Kc values serve as crucial parameters for calculating potential evapotranspiration, enabling a comprehensive assessment of water loss patterns from each crop. This comprehensive approach ensures that both the influx and efflux of water are diligently considered, facilitating a robust and holistic understanding of the intricate water dynamics within the system.

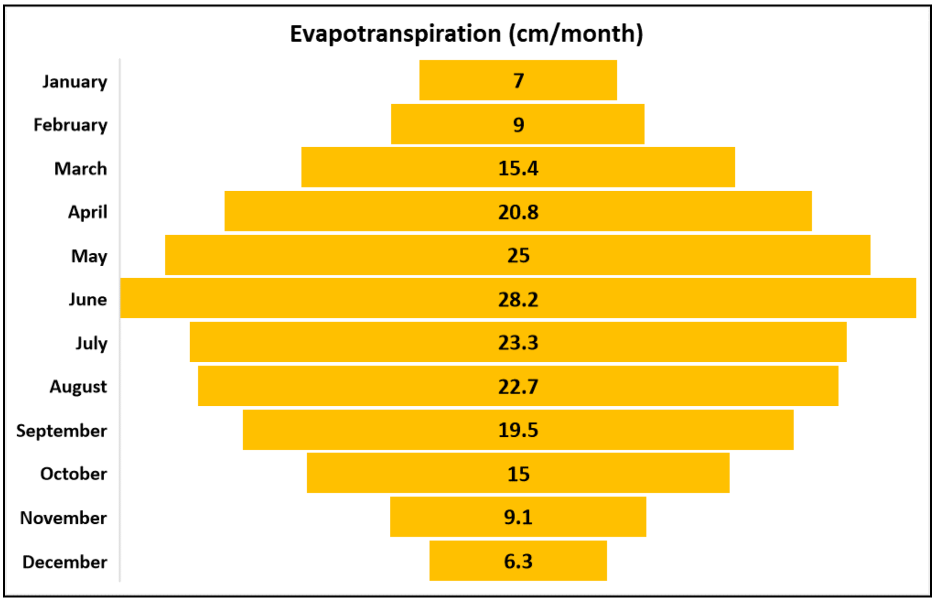

Chart -4: Average monthly evapotranspiration data spanning the last 52 years, gathered from the Texas ET Network website. The data was condensed to derive monthly averages, closely reflecting the average conditions of the study region.

3.7. Crop Salt Tolerance

Cotton has a high salt tolerance at 5 mg/cm3. This signifies that Cotton remains resilient to the impacts of salinity stress until it surpasses this threshold [51]. Conversely, Pecan exhibits lower salt tolerance at 2 mg/cm^3. This implies that Pecan is less capable of withstanding the effects of elevated salt content within the soil. This disparity underscores the distinct reactions of these crops to salt in their respective growing environments.

3.8. Crops Water Extraction Potential

Both crops display a characteristic point at which they attain 50% of their water extraction potential. In the case of Pecan, this threshold is met at a capillary pressure gradient of -150 cm, indicating its high capacity to extract water from the soil. On the other hand, Cotton demonstrates similar capabilities but does so at a less severe capillary pressure gradient of -50 cm.

3.9. Root Distribution

The model relies on the root length and the normalized distribution of roots within the soil matrix. Pecan and Cotton crops' distinctive root growth patterns were modelled to represent the real-world growth pattern. For Pecan, the fully developed roots span 300 cm on either side, with an aggregate length of 80 cm (Chart 5) [21], [22]. Importantly, these root dimensions remain constant throughout the simulation, reflecting the mature state of Pecan's root system at the study's outset. The calculation of percentage root distribution for Pecan is derived from root dimensions provided in the work by [52]. Cotton, an annual crop, exhibits a different growth trajectory. Root growth for Cotton is based on locally observed patterns, specifically the root growth of irrigated Cotton in the region (Chart 6). This growth is simulated over 180 days, reflecting the crop's typical growing period. The root distribution of cotton was extracted from the study by [53].

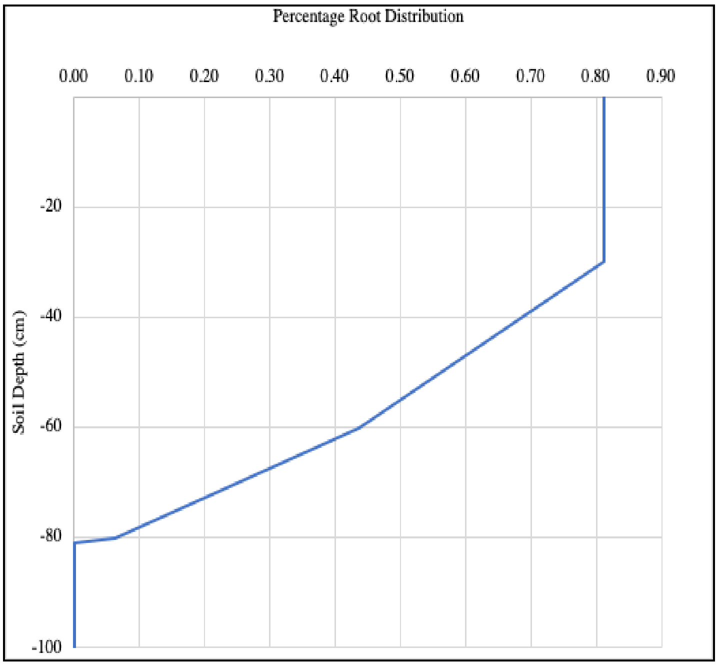

Chart -5: Root distribution of Pecan plotted against soil depth (cm) on the Y-axis and percentage distribution on the X-axis. The root growth initiates at 0 and extends downwards, represented by negative numbers indicating soil depth.

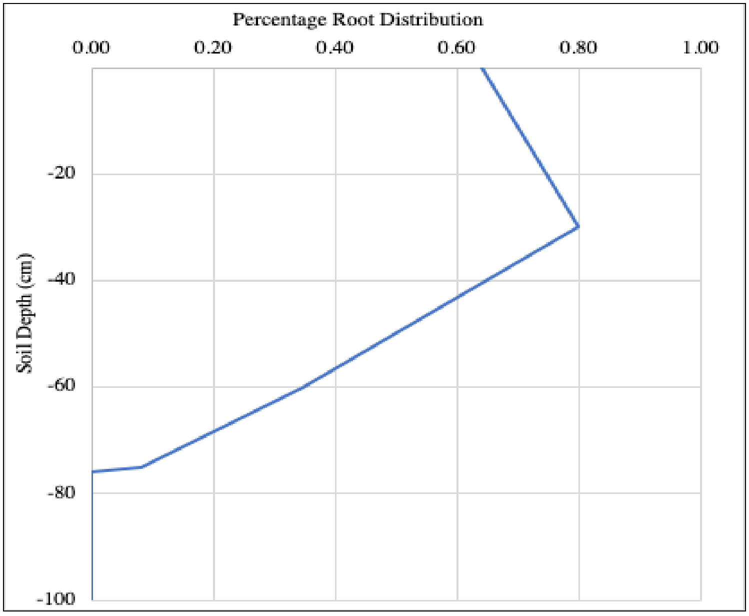

Chart -6: Root distribution of Cotton plotted against soil depth (cm) on the Y-axis and percentage distribution on the X-axis. The root growth initiates at 0 and extends downwards, represented by negative numbers indicating soil depth.

4. Model Setup

The research aims to harness the SMITUV model's potential to quantitatively unravel this intricate salt accumulation within the soil matrix. The model's predictive capabilities are utilized to unveil shifts in root water uptake patterns within two key crops, Cotton and Pecan. As these components interact, the model's outputs will provide an understanding of the complex dynamics between irrigation practices, salt and crop response, a vital fusion for devising resilient strategies in mounting aridity challenges.

4.1. Soil Stratification

Numerical models like HYDRUS adopt the finite element method to predict salt accumulation by segmenting the soil depth into discrete 1 cm nodes. This facilitates the presence of solute potential gradients within layers, thereby enhancing solute transport rates across the profile. Similarly, SMITUV follows suit, necessitating the division of soil into layers to establish gradients governing water infiltration, solute transport, and root water uptake. Accordingly, we selected a subsurface soil column with a depth of 100 cm and a unit area of one cm^2 for simulation purposes. The entire soil depth is stratified into three layers, each measuring 30 cm, 30 cm, and 40 cm in depth. The anticipation is that SMITUV will simulate salt transport and forecast salt accumulation within each layer. Subsequently, this will enable the prediction of corresponding root water uptake, facilitating a comparative analysis of root water uptake effects under varying irrigation conditions.

4.2. Simulation Period

The region experienced a series of historical droughts spanning from 1950 to 1956 [54]. These drought episodes are vital, providing valuable insights into the interplay between precipitation scarcity and salt accumulation. Identify these as a period of drought-like conditions, the simulation window of the SMITUV model was set to capture a span of 10 years, commencing from 1947 and extending through 1956. This period was particularly chosen to correspond with historical records pinpointing these years as periods characterized by the lowest recorded rainfall levels in the region.

4.3. Simulation Scenarios

To comprehend salt-related dynamics, five distinct combinations of irrigation water and groundwater as input parameters for the simulation process. Rainwater remains constant, sourced from data collected via the NCDC website. The river water and groundwater combinations are systematically ordered based on their salt content, establishing a hierarchy from the highest to the lowest concentration. This classification assists in comprehending the varying impacts of salinity levels on the patterns of salt accumulation within the soil layers.

The five simulations in the model were set up using the input data. As explained earlier, these simulations represent various combinations of water sources used for irrigation, each corresponding to different salinity levels in the water. Ten simulations were arranged, with five dedicated to Pecan and five to Cotton (Table 3).

Table -3: The ten model simulation scenarios were established, incorporating five different combinations of irrigation water comprising rain, river, and groundwater for both Pecan and Cotton crops.

Water Type	Salt Content	Simulation Runs		River water (%)	Groundwater (%)
		Pecan	Cotton		
Water 1	Highest	P1	C1	0	100
Water 2	High	P2	C2	30	70
Water 3	Medium	P3	C3	50	50
Water 4	Low	P4	C4	70	30
Water 5	Lowest	P5	C5	100	0

5. Results

The model demonstrated seamless simulation over the 10 years with minimal complexity. The graphical presentation of the model's outcomes simplifies comparisons, and these results can be effortlessly exported to Excel or processed in Python for in-depth analysis. SMITUV's user-friendly interface also streamlines data input of variables like rainfall, groundwater, river water, solute concentrations, root growth, and evapotranspiration and is conveniently facilitated through Excel files, which proves especially advantageous for managing extensive datasets.

5.1. Salt accumulation and Root Water Uptake

Simulation results were plotted for solute concentration in the root zone (Chart 7 for Pecan and Chart 8 for Cotton) and root water uptake (Chart 9 for Pecan and Chart 10 for Cotton) for different concentrations of saline water.

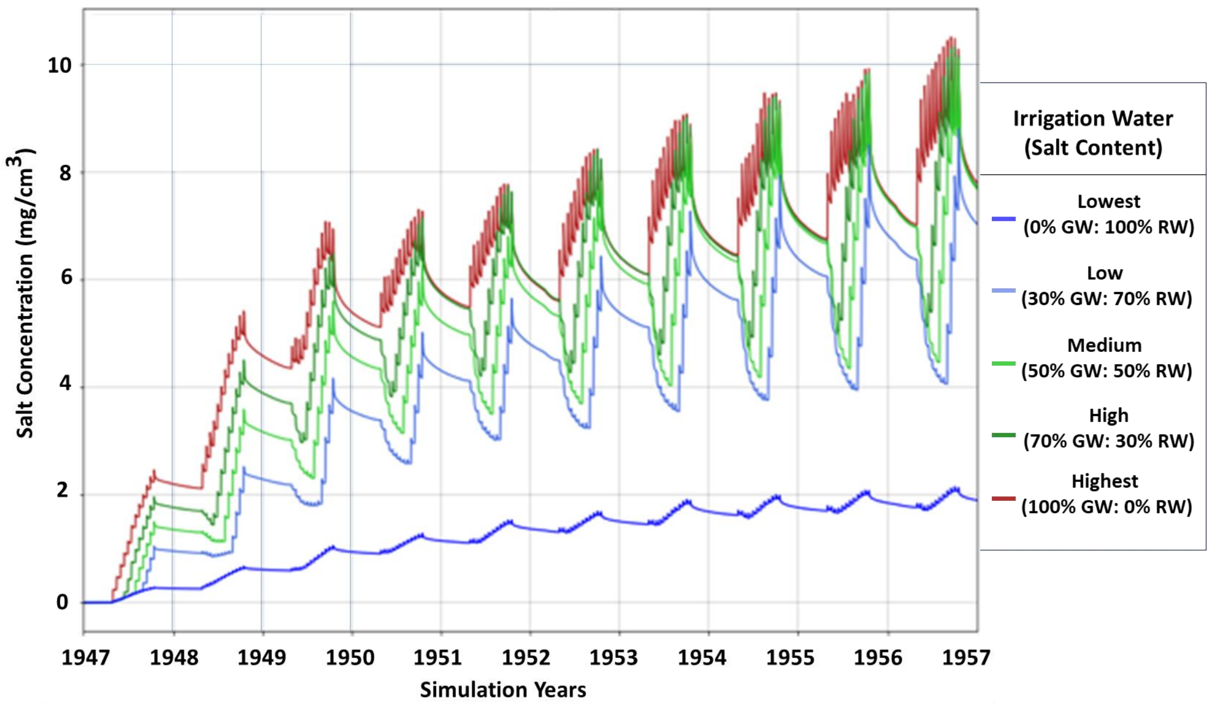

Chart -7: Salt accumulation in the root zone of Pecan from 1947 to 1957, illustrating salt concentration corresponding to various levels of salt content in the irrigation water derived from combinations of rain, river, and groundwater.

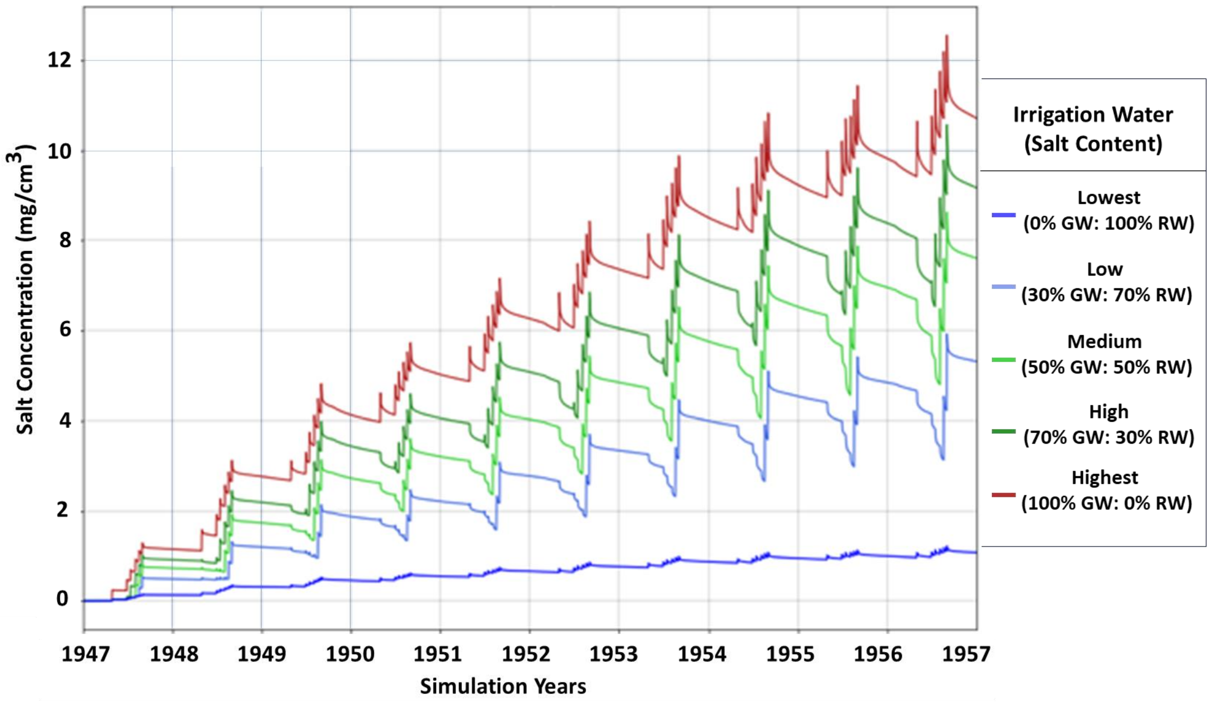

Chart -8: Salt accumulation in the root zone of Cotton from 1947 to 1957, illustrating salt concentration corresponding to various levels of salt content in the irrigation water derived from combinations of rain, river, and groundwater.

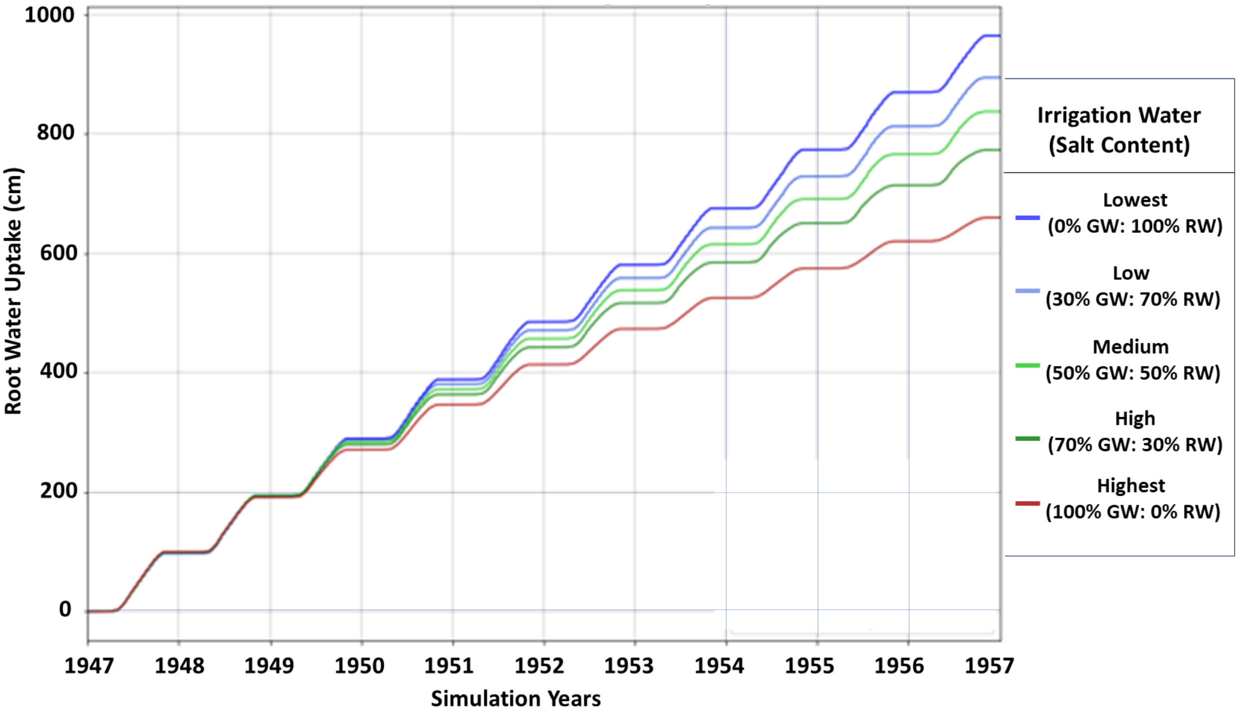

Chart -9: The water accumulation in the root zone of Pecan from 1947 to 1957 presented varying salt concentrations. The data reflects different levels of salt content in the irrigation water derived from combinations of rain, river, and groundwater.

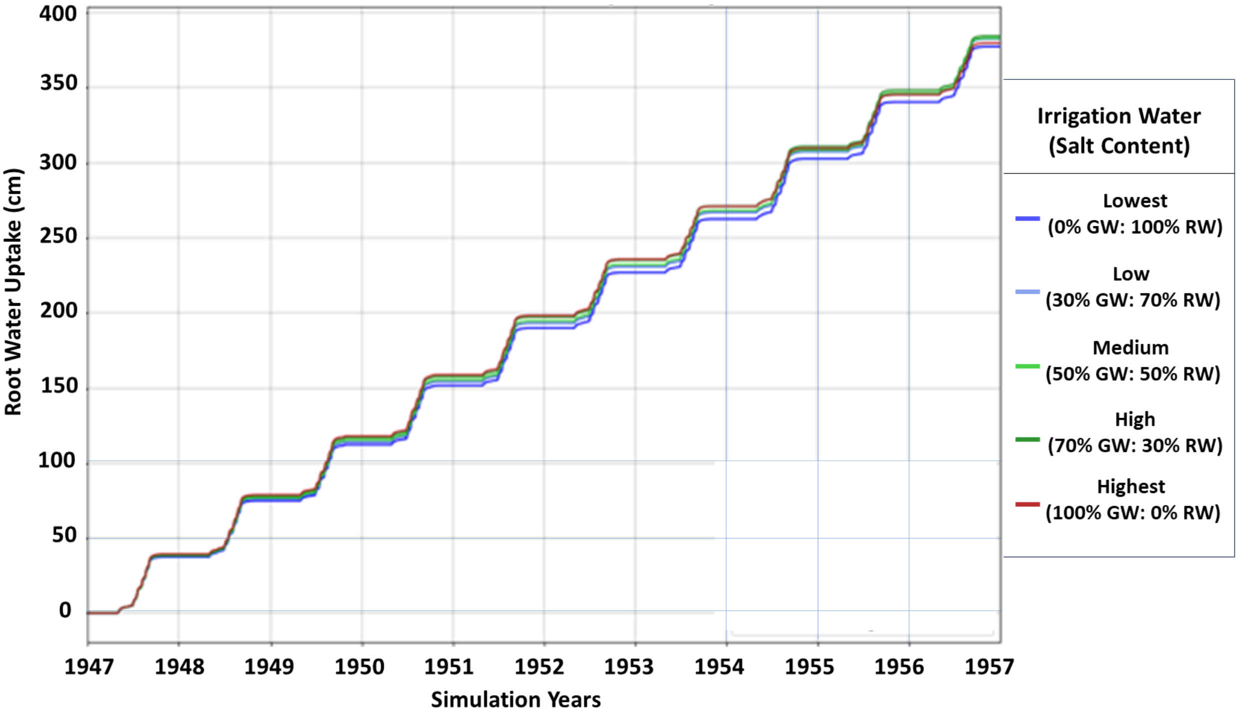

Chart -10: The water accumulation in the root zone of Cotton from 1947 to 1957, presented for varying salt concentrations. The data reflects different levels of salt content in the irrigation water derived from combinations of rain, river, and groundwater.

The analysis of the collected data explains distinct trends in salt accumulation within the root zones of crops, outlined by varying irrigation water salt content. The manifestation of salt accumulation is notably pronounced in cases were irrigation water harbors higher salt concentrations. Pecan, for instance, exhibits salt accumulation ranging from 2.27 to 8.03 mg/cm^3 for the highest salt content water, and Cotton highlights a corresponding range of 1.24 to 9.92 mg/cm^3. These findings align with previous research demonstrating the intricate connection between irrigation water salinity and soil salt accumulation [55].

Conversely, irrigation with water of lower salt content distinctly mitigates salt accumulation. Pecan and Cotton both manifest significantly lower salt concentrations, ranging from 0.28 to 1.84 mg/cm^3 and 0.14 to 1.00 mg/cm3, respectively, for the lowest salt content water. Similar conclusions were drawn by [56], who explored the correlation between irrigation water composition and salt accumulation in arid regions.

5.2. Reduction in Crop Yield

A commonly employed relationship frequently utilized to quantify the ratio of crop yield reduction due to changes in root water uptake for pecan and Cotton is given by [57].

$$\frac{Y}{Y_p} = \frac{T_a}{T_p}$$

Y is the yield under stress conditions, Y_p signifies the yield achieved under optimal and favourable circumstances, T_a corresponds to the actual root water uptake under stressful conditions (highest salt content: 100% GW: 0% RW), and T_p indicates the actual root water uptake under the most conducive conditions (Lowest salt content: 0% GW: 100% RW). This formula holds substantial significance within the agricultural research realm, serving as a valuable analytical tool for assessing how variations in root water uptake, influenced by factors like soil and water salinity, impact overall crop productivity [57]. The estimated percentage reduction in crop yield is shown in Chart 11.

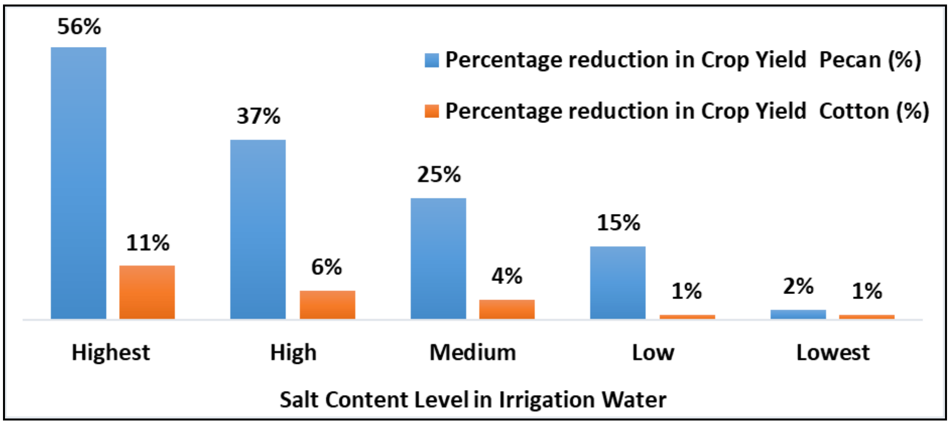

Chart -11: Percentage reduction in Cotton and Pecan crop yields due to increased salt accumulation in the root zone, impacting the crops' water extraction capability. Reduction is expressed as the ratio of crop yield at the highest salt content to the lowest salt content in irrigated water.

The impact of salt content on crop yield becomes evident when considering the data. Pecan crops, irrigated with water characterized by the highest salt content, display a substantial reduction in their yield, amounting to 56% compared to the initial two years of simulation. The response of Cotton crops to varying salt content demonstrates a different pattern. Cotton, characterized by its inherent high salt tolerance, manifests a milder crop yield reduction of 11% in the same comparative period.

6. Discussion

The examination of crop behaviour in response to salt accumulation reveals interesting dynamics. In the early simulation stage (1947-1949), pecan demonstrates a modest reduction in root water uptake due to salt accumulation, attributed to the concentration below the critical threshold of 2 mg/cm^3. This phenomenon is similar to the findings by [51], who established the link between salt content and crop response. In contrast, the subsequent years (1951-1956) marked a substantial decline in pecan's root water uptake, reflecting the escalated salt concentrations that surpassed the threshold value. These observations are similar to the works of [58], [59], shedding light on the implications of soil salinity for crop water uptake.

Cotton, characterized by its high salt tolerance with a threshold value of 5 mg/cm^3, portrays a distinctive pattern. In the initial simulation period (1947-1951), Cotton exhibited minimal reduction in root water uptake despite root zone salt concentration reaching 4 mg/cm3. This is because the salt concentration has yet to reach the threshold values for Cotton. Subsequently, the simulation years (1951-1956) reveal a decline in root water uptake with an accumulated salt content exceeding 9.7 mg/cm^3, surpassing the threshold.

In principle, this study affirms the dynamics between irrigation water salinity, soil salt accumulation, and crop behaviour and contributes to the growing knowledge in arid region agriculture. The comprehensive examination of these dynamics adds value to the ongoing discourse on crop yield sustainability and salinity management. The observations stress the critical influence of irrigation water sources on crop health in arid regions. Research by [60] emphasizes that crops irrigated with river water, characterized by lower salt content, experience significantly reduced solute accumulation in their root zones. Aligning with this, [61], [62], [63] contend that minimizing solute buildup in the root zone is pivotal to curbing salinity-related stress and promoting optimal crop growth.

Within the framework of this study, the span from 1947 to 1949 encompasses the most favourable conditions due to a lower salt accumulation during this period. In contrast, the years from 1955 to 1957 represent stress conditions characterized by a cumulative salt buildup. Applying this formula makes it possible to quantitatively evaluate the percentage reduction in crop yield during the latter two years compared to the initial two years. This analytical approach offers crucial insights into the repercussions of shifting root water uptake on the overall productivity of pecan and Cotton crops, enhancing our understanding of their responses to varying degrees of salinity-induced stress.

The pronounced reduction in pecan crop yield underscores the significant consequences of elevated salt accumulation in the root zone over the simulated 10-year period. This finding resonates with prior research investigating salinity's detrimental effects on crop production. A study by [2] explains the underlying physiological mechanisms through which high salt concentrations impair plant growth and yield, including reduced water uptake and disrupted ion balance. The observation aligns with studies such as that of [64], emphasizing the inverse relationship between salinity levels and crop productivity.

Cotton, characterized by its inherent high salt tolerance, manifests a milder crop yield reduction of 11% in the same comparative period. This result resonates with the findings of [2], who highlight the adaptability of certain plant species to saline environments. The research by [65] provides additional insight into the mechanisms underlying the salt tolerance of certain crops, revealing the role of ion exclusion and tissue tolerance. The notable difference in the extent of crop yield reduction between pecan and Cotton corroborates the concept of crop-specific salt tolerance thresholds. It underscores the dynamics between salt stress and plant species. This observation highlights the significance of selecting salt-tolerant crops in arid agricultural regions, a notion echoed by numerous studies exploring salinity's implications on crop performance [66], [67].

Salt-tolerant crops exhibit adaptive mechanisms that enable them to thrive in saline environments, while salt-sensitive crops experience severe reductions in yield under similar conditions. This intrinsic variability in salt tolerance underscores the importance of selecting suitable crop varieties for cultivation in regions prone to salinity challenges. Effective salinity management strategies mitigate these impacts and ensure sustainable agricultural practices. Researchers have explored a variety of agronomic practices, soil amendments, and precision irrigation to manage soil salinity and minimize its detrimental effects on crops. Utilizing salt-tolerant crop varieties such as Cotton effectively enhances yields and quality under saline conditions.

6.1. Importance of Desalination in Agriculture

The findings of this study highlight the importance of incorporating desalinated water into irrigation practices. It addresses the issue of soil salinity and aligns with water resource management goals. Irrigation with desalinated water can effectively mitigate the adverse effects of salinity on crops, particularly in regions where conventional water sources contain high salt concentrations [21]. Such an approach requires careful consideration of economic feasibility, environmental sustainability, and water availability. As global water scarcity intensifies, adopting innovative strategies like desalination for agricultural water use can contribute to a more resilient and productive agricultural sector in arid regions, safeguarding food security and sustainable development.

The desalination processes significantly lower salt content in irrigation water, reducing solute accumulation in the root zone and facilitating a more favourable crop growth environment [68]. Additionally, the work of [69] highlights the potential of desalinated water in combating soil salinization, thereby reducing the risk of salinity-induced crop yield reduction. Hence, the judicious use of desalinated water for irrigation holds substantial promise as a strategic approach to alleviate salinity-related stress and enhance agricultural productivity in arid regions.

The insights gathered from the 10-year simulation scenarios, focusing on the impact of high salt concentration in irrigation, hold critical implications for agricultural sustainability and resilience in arid regions. The observed substantial reduction in root water uptake by pecan, resulting in a significant 56% crop yield reduction, highlights the vulnerability of certain crops to salinity stress under prolonged drought conditions. This outcome reinforces the urgent need for strategic planning and adaptive measures to ensure food security and economic stability in regions susceptible to water scarcity and salinity-related challenges. Conversely, the modest 11% reduction in Cotton's crop yield amidst high salt concentration irrigation underscores its intrinsic resilience to salinity stress. This resilience aligns with previous research findings indicating Cotton's high salt tolerance, making it a promising candidate for cultivation in arid environments prone to salt-affected soil conditions.

The broader implication of these simulation results extends beyond individual crop performance, encompassing larger agricultural management strategies in the face of climate change-induced challenges. As the world tackles increasingly unpredictable climate patterns, arid regions are poised to experience more frequent and prolonged droughts, escalating the urgency of addressing water scarcity and soil salinization. The simulation outcomes are a valuable tool for policymakers, agronomists, and agricultural stakeholders to make informed decisions regarding crop selection and irrigation practices. Furthermore, these findings highlight the importance of implementing effective desalination technologies to bridge the gap between groundwater resources and the salinity levels conducive to healthy crop growth. Such technologies not only mitigate salt buildup in the root zone but also contribute to safeguarding the livelihoods of farming communities and ensuring food production stability in the face of changing climate dynamics.

The simulation results obtained through the SMITUV model exceed numerical outputs; they capture the importance of informed decision-making in pursuing sustainable agriculture in arid regions. These findings empower stakeholders to devise innovative strategies that mitigate risks and unlock the potential for resilient and thriving agricultural systems by simulating the dynamics between salt accumulation, irrigation practices, and crop resilience. As global climate change reshapes our agricultural landscape, models like SMITUV emerge as essential tools in navigating the complexities of resource management and securing a more sustainable future for agriculture in arid regions and beyond.

7. CONCLUSIONS

The simulation of crop behavior under varying salt accumulation levels provides significant insights into the interplay between salinity and agricultural productivity in arid regions. The study reveals that crops like pecans, with lower salt tolerance, experience substantial reductions in root water uptake and yield when exposed to high salt concentrations over time. Specifically, pecan showed a 56% yield reduction, underscoring its vulnerability to salinity stress. In contrast, cotton, known for its higher salt tolerance, exhibited a more modest 11% yield reduction, highlighting its resilience and suitability for cultivation in saline environments.

These findings emphasize the critical role of crop selection in regions prone to soil salinity. Salt-tolerant crops like cotton offer a strategic advantage in maintaining agricultural productivity under challenging conditions. Moreover, the research underscores the importance of innovative water management practices, such as the use of desalinated water for irrigation, to mitigate the adverse effects of salinity on crop health.

As climate change intensifies and droughts become more frequent, the insights gained from this study are invaluable for guiding agricultural practices and policy decisions. Effective salinity management and the adoption of resilient crop varieties are essential strategies to ensure sustainable agriculture in arid regions. The SMITUV model used in this study proves to be a powerful tool in simulating the complex dynamics of salinity, irrigation, and crop performance, offering a pathway toward securing food production and economic stability in the face of global climate challenges.

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