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Evaluating management strategies with crop modeling for salinity stress mitigation in quinoa: A case study from Laayoune, Morocco

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ABSTRACT

Quinoa, known for its high nutritional value and resilience to saline and drought conditions, is a dietary staple in arid regions like Morocco, where agriculture relies heavily on irrigation with variable salinity levels. A previous study in Laayoune, southern Morocco, pointed out that overirrigation during the germination and seedling stages results in salt accumulation in the topsoil and exacerbates salinity stress. In the current study, we assessed management scenarios (mulch, irrigation strategies) limiting soil evaporation and mitigating salinity stress in the Laayoune region. Simulations indicate that reducing irrigation frequency and employing mulch, decreases soil evaporation and soil salt concentration, improving yield. Quinoa is most sensitive to salinity stress during germination and seedling stages, whereas its sensitivity to drought is highest during flowering and seed filling. Mitigating stress mainly in those periods with the proposed management practices, allows to reduce irrigation water use and enable the use of higher-salinity irrigation water without significantly affecting yield. These findings offer practical insights for cultivating crops using saline irrigation water in arid regions, and provides a basis for field-scale testing.

1. Introduction

The latest Global Map of Salt-affected Soils (GSASmap v1.0.0) developed by FAO (2021) indicates that approximately 10.7 % of the global land area is affected by salinity, with more than two-thirds located in arid and semi-arid regions (FAO, 2024). Soil salinization in arid regions is a critical environmental challenge due to their inherently dry and hot climate, a problem that is further aggravated with climate change. Agriculture in these regions relies heavily on irrigation, often with saline groundwater or treated wastewater. Without adapted irrigation, drainage management and solute leaching, these practices accelerate soil salinization (FAO, 2024).

Salt-affected soils can be classified as saline, sodic, or saline-sodic soils (FAO, 2024). Saline soils contain high concentration of soluble salts, mainly sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), among others. Sodic soils are characterized by a high proportion of Na^+ ions adsorbed to the soil exchange complex, relative to other cations (Paz et al., 2023). Saline-sodic soils have characteristics of both saline and sodic soils. Most commonly, salinity is through its osmotic effects, arising from the high salt concentrations, reducing root water uptake, which directly affects the growth of roots and new leaves (Munns and Tester, 2008). Salt-affected soils also often experience nutrient deficiencies as salts interfere with the availability and uptake of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Bidalia et al., 2019). Over time, the accumulation of salts inside the plant can reach toxic levels, severely impairing plant growth and reducing crop productivity (Munns and Tester, 2008).

The cultivation of salt-tolerant crops, combined with effective management practices, can help sustain agriculture in salt-affected soils (Paz et al., 2023). Quinoa (*Chenopodium quinoa Willd.*), a pseudo-cereal native to South America, is widely grown in Morocco and globally due to its exceptional tolerance to drought and salinity stress (Adolf et al., 2013) and its high nutritional value (De Bock et al., 2021). In Morocco, its cultivation started in 1999/2000 as an alternative to traditional cereals such as wheat or barley, which are more susceptible to abiotic stresses (Benlhabib et al., 2014; Hirich et al., 2021). Since then, several

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quinoa varieties have been introduced, including ICBA-Q5 from the International Center for Biosaline Agriculture (ICBA) and the Danish varieties Titicaca and Puno, which have demonstrated better yields and quality under Moroccan conditions (Hirich et al., 2021; Taaime et al., 2023). Quinoa is known for its low soil nutrient requirements and high tolerance to drought and salinity stress, but production can be boosted by the use of deficit irrigation and organic amendments (Benlhabib et al., 2014; El Mouttaqi et al., 2023; Hirich et al., 2021; Taaime et al., 2023).

Management strategies such as combining fresh and saline water for irrigation, mulching, organic amendments, and crop rotation are essential to mitigate the adverse effects of soil salinization (Tedeschi et al., 2023). Alternating between irrigation with saline and fresh water during sensitive growing stages, and using drip irrigation with the adequate frequency and volume, prevents salt buildup and promotes salt leaching, while meeting the crop water requirements (Li et al., 2019; Paz et al., 2023). Mulching increases soil water availability by decreasing soil evaporation, regulates soil temperature, protects the soil surface from erosion and crust formation, suppresses weeds, and enriches the soil with organic matter when employing organic materials (Akhtar et al., 2022). As organic materials decompose, they contribute to nutrient availability and microbial activity (Akhtar et al., 2022; Tu et al., 2006), which indirectly improves soil structure. Similarly, organic amendments such as biochar and compost improve soil physical, chemical and biological properties (FAO, 2024), and have shown to increase quinoa yield and seed quality (i.e., lower saponin contents) due to higher soil water retention and nutrient availability (El Mouttaqi et al., 2023; Yang et al., 2020). Furthermore, soil amendments like gypsum can ameliorate soil properties by replacing excess Na^+ ions with Ca^{2+} (Paz et al., 2023; Shaaban et al., 2013).

Selecting appropriate management practices for agriculture in salt-affected soils is challenging due to variability in soil, water quality, and climate (Paz et al., 2023). Soil-crop models are valuable tools to support this process, as they enable the systematic assessment of numerous management scenarios under variable environmental conditions, before implementing them in the field. By simulating crop–soil–water interactions over different years, these models can help identify the most effective and site-specific practices to improve crop production and water use efficiency.

In the Laayoune region of southern Morocco, where irrigation water often contains high salt concentration, farmers often overirrigate quinoa at the beginning of the season to ensure seed emergence. In a previous study, we calibrated the SWAP-WOFOST model for quinoa (ICBA-Q5) cultivated under saline conditions in Laayoune (Estrella Delgado et al., 2025), using the field experimental data from El Mouttaqi et al. (2023). The model results indicated that overirrigation with saline water during early stages of crop development increased soil evaporation, resulting in salt accumulation in the topsoil and lower water productivity. Quinoa is most vulnerable to salinity during the germination and seedling stages (Hinojosa et al., 2018; Maleki et al., 2018), while it is more sensitive to drought stress during flowering and seed filling stages (Awa et al., 2024; Hirich et al., 2012). Building on this previously calibrated model, the present study aims to identify suitable management practices to improve quinoa productivity in the Laayoune region, and potentially other salt-affected areas. We focused on practices that can limit soil evaporation and salt accumulation, thereby optimizing water use and improving yield. Specifically, we evaluated the combined effects of four key factors: irrigation quantity, irrigation quality, irrigation frequency, and mulching, over a 30-year simulation period (1994–2023).

2. Materials and methods

This section provides a brief description of the field experiment used to calibrate the SWAP-WOFOST model parameters, and the model workflow. For more detailed information on the model calibration, the reader is referred to Estrella Delgado et al. (2025). In addition, we present an overview of the evaluated management scenarios.

2.1. Field experiment

Quinoa (*Chenopodium quinoa Willd.)*, variety ICBA-Q5, was cultivated in the experimental farm of the National Institute of Agricultural Research in Foum El Oued area, Laayoune, southern Morocco (lat = 27.186°, lon = −13.341°), from 13 April 2021–29 July 2021, under drip irrigation with three different salinity levels: EC_{water}= 4 dS m^{-1}, 12 dS m^{-1} and 20 dS m^{-1}. Before crop emergence, the soil was irrigated with low-salinity water (4 dS m^{-1}). After crop emergence (two weeks after sowing), irrigation treatments with the different salinity levels, 4 dS m^{-1}, 12 dS m^{-1} and 20 dS m^{-1}, were adopted. Irrigation was applied twice a week at a rate of 8 mm per application, totaling 240 mm over the growing season. The soil is a sandy loam consisting of 61.8 % sand, 19.6 % loam and 18.6 % clay, with high salinity (EC_e = 9.55 dS m^{-1}) and low organic carbon content (0.28 %). Further details about this experiment are available in El Mouttaqi et al. (2023).

This irrigation management strategy served as reference for comparison with the alternative management scenarios evaluated.

2.2. SWAP-WOFOST model

The SWAP-WOFOST model parameters were calibrated using the experimental conditions described in Section 2.1. The model simulations showed good agreement with the observed soil water content, soil salinity concentration, and yield. Therefore, it provides a robust basis for evaluating management scenarios in Laayoune. All the relevant crop parameters and model assumptions are presented in Estrella Delgado et al. (2025).

SWAP (Soil, Water, Atmosphere and Plant) is a 1-D field-scale model that simulates the transport of water, solutes and heat, in interaction with crop development (Kroes et al., 2017). The crop growth module WOFOST (WOrld FOod STudies) is integrated in SWAP to describe the phenological development, growth and yield production of major arable crops (de Wit et al., 2020).

2.2.1. Soil water and solute transport

SWAP computes the transport of water, solutes and heat in the soil using the Richards equation, including root water and solute uptake (Kroes et al., 2017). To simulate soil salinity dynamics, the model tracks the movement of a single representative solute, which serves as a proxy for the collective behavior of all dissolved salts in the soil solution. We assumed that this representative solute behaves as a conservative solute, meaning it does not undergo chemical reactions, adsorption, dissolution or precipitation, a valid assumption for ions typically found in saline soils (e.g. Na^+, Ca^{2+}) (Kroes et al., 2017). Therefore, we considered only convection, dispersion and root solute uptake, when simulating solute transport.

2.2.2. Soil evaporation and crop transpiration

The potential soil evaporation (E_p, mm d^{-1}) and potential crop transpiration (T_p, mm d^{-1}) represent the maximum rates at which water evaporates from the soil surface and transpires through the crop canopy, respectively, under optimal soil water conditions. SWAP allows the calculation of E_p and T_p by direct application of the Penman-Monteith equation (equations 3.17 and 3.16 of the SWAP manual) (Kroes et al., 2017), by using soil (RSOIL, s m^{-1}) and canopy surface (RSC, s m^{-1}) resistances. RSOIL is the resistance to evaporation from a wet soil surface, while RSC is the minimum resistance to water loss through crop transpiration.

When the soil surface is wet, water is not a limiting factor and actual soil evaporation (E_a, mm d^{-1}) equals E_p. As the topsoil dries out and its hydraulic conductivity decreases, E_a becomes limited by the maximum soil evaporation rate (E_{max}, mm d^{-1}), which is determined by the hydraulic properties of the topsoil layer. Since the soil surface is exposed to rain splashing or crust formation, empirical evaporation functions can be used to account for the variability of soil hydraulic properties within the topsoil layer, but their parameters should ideally be calibrated for the local soil, climate, cultivation and drainage conditions (Kroes et al., 2017). We used the empirical evaporation function of Boesten and Stroosnijder (1986) (Eq. 1) that calculates the cumulative E_a during a drying cycle of t days ($\sum_{i=1}^{i=t} E_{a,i}$, mm), based on the cumulative potential evaporation during the drying cycle ($\sum_{i=1}^{i=t} E_{p,i}$, mm) and an empirical coefficient β_2. This empirical coefficient β_2, called COFRED in the SWAP files, was assumed equal to 0.54 $cm^{1/2}$ (default). For each day (i) within the drying cycle, $E_{a,i}$ is calculated based on this empirical function and the amount of rainfall and irrigation during that day (Boesten and Stroosnijder, 1986).

$$\sum_{i=1}^{i=t} E_{a,i} = \begin{cases} \sum_{i=1}^{i=t} E_{p,i} & \sum_{i=1}^{i=t} E_{p,i} \leq \beta_2^{\,2} \\ \beta_2 \left(\sum_{i=1}^{i=t} E_{p,i} \right)^{1/2} & \sum_{i=1}^{i=t} E_{p,i} > \beta_2^{\,2} \end{cases} \tag{1}$$

The actual evaporation (E_a) is then calculated as the minimum of three values: E_p, E_{max} and the result from this empirical equation.

The potential transpiration (T_p) is distributed over the rooting depth based on the root length density, and thus equals the potential root water uptake (S_p, d^{-1}). The actual root water uptake (S_a, d^{-1}) at a certain depth (z) may be lower than S_p due to different stresses such as drought, oxygen or salinity stress. These stresses are represented by stress reduction factors that range between 0 (complete inhibition of water uptake) and 1 (no stress). In this study, only drought and salinity stress were considered, so the reduction in water uptake, at a given depth ($S_a(z)$), is calculated by Eq. 2, where α_{rd} is the drought stress factor and α_{rs} is the salinity stress factor. The actual transpiration (T_a, mm d^{-1}) is then calculated as the sum of $S_a(z)$ over the rooting zone.

$$S_a(z) = \alpha_{rd} \quad \alpha_{rs} \, S_p(z) \tag{2}$$

Drought stress results from insufficient water in the root zone to meet the crop water demand, leading to reduced root water uptake. The drought stress factor, α_{rd}, is calculated by the function of Feddes et al. (1978). Salinity stress results from an excess of dissolved solutes in the soil solution around the roots (more negative osmotic potential), leading to reduced water uptake. The salinity stress factor, α_{rs}, is calculated using the function of Maas and Hoffman (1977), which focuses solely on how salts directly affect transpiration and crop growth through osmotic effects.

2.2.3. *Crop growth and yield production*

The reduction in transpiration due to different abiotic stresses is translated into a reduction in biomass and yield within the dynamic crop growth model WOFOST. WOFOST calculates how much light and CO_2 is intercepted and potentially converted by photosynthesis into carbohydrates, which are the building blocks for biomass production. This potential photosynthesis is reduced by the relevant stress reduction factors (α_{rd} and α_{rs}), as calculated by SWAP, to obtain the actual photosynthesis. The actual photosynthesis, minus what is used for maintenance respiration, is converted into dry matter and distributed to roots, stems, leaves and storage organs, based on partitioning coefficients that vary with the development stage of the crop (de Wit et al., 2020). Crop yield corresponds to the dry matter allocated to storage organs. The dry matter distribution to leaves translates into leaf area and subsequently influences how much light can be intercepted. Due to all these complex interactions, feedback mechanisms and crop physiological responses, there is not a linear relationship between transpiration reduction and yield reduction.

2.2.4. *Representing mulch in SWAP-WOFOST*

Mulch refers to a layer of organic or inorganic material applied on the soil surface to conserve soil moisture and buffer soil temperature (Kader et al., 2017). It also protects the soil surface from erosion and crust formation, reducing surface runoff and improving soil structure. The changes in soil temperature and soil moisture directly impact microbial activity, organic matter decomposition, and soil physical and chemical properties (Akhtar et al., 2022; Kader et al., 2017). Because soil temperature and soil water content are the main drivers of crop development, the use of mulch can significantly influence plant growth, particularly during the early stages when the soil is still uncovered (Akhtar et al., 2022; Chen et al., 2007). The magnitude and direction of these effects depend on the mulch material (e.g., organic versus inorganic materials), the thickness of the mulch layer, the crop type and the climatic conditions (Akhtar et al., 2022; Chen et al., 2007; Kader et al., 2017).

Mulching is not incorporated in most soil-crop models, including SWAP. However, its effects on soil water balance, soil heat regulation and crop growth can be considered by modifying relevant parameters from the different processes involved. The model AquaCrop (Raes et al., 2023) simulates the effect of mulch only on soil evaporation by using the fraction of the soil surface covered by mulch and a soil evaporation decrease coefficient that varies between 0.5 for organic mulch to up to 1.0 for plastic mulch. In a study with maize using transparent film mulching, Zhao et al. (2020a), (2020b) modified the relevant equations in the SWAP modules related to soil water content (rainfall interception and soil evaporation), soil temperature and crop growth by means of empirical factors, providing acceptable results. To account for the mulch effect on evaporation, they adjusted E_p, E_{max}, and the empirical evaporation function (Black et al., 1969) by multiplying each by ($1 - C_{film}$), where $C_{film} = 0.6$. This corresponds to a 60 % reduction in evaporation compared with non-mulched conditions.

In the current study, we used a similar approach by adjusting the parameters RSOIL and COFRED to mimic the effect of organic mulch on soil evaporation, which will affect soil water storage and ultimately crop growth. Note that we recognize that this neglects the effect mulch has on rainfall interception and infiltration, and on crop growth and transpiration through its effect on soil nutrients and temperature. RSOIL is the resistance of a wet soil, used in the calculation of potential soil evaporation, while COFRED (β_2) is an empirical parameter used in Eq. (1) for estimating actual evaporation. To reduce potential evaporation under mulch conditions, we increased RSOIL from 460 s m^{-1} (calibrated in our previous work) to 1000 s m^{-1}, the upper limit defined in the SWAP model files (Kroes et al., 2017). To further reduce actual evaporation, we decreased COFRED from 0.54 $cm^{1/2}$ (default value) to 0.3 $cm^{1/2}$, corresponding to an approximately 45 % reduction in the empirically determined E_a. This aligns with experimentally found reductions, ranging between 20 % and 50 % depending on the organic mulch's thickness and material, and the crop development stage (McMillen, 2013; Onwuka and Uzoma, 2018; Zribi et al., 2015).

2.3. *Field management scenarios*

We tested 36 different management scenarios, varying four factors: irrigation quantity, quality and frequency, and the use of mulch

Table 1
Factors levels included in the management scenarios.

Factor	Levels
Quantity (mm)	240, 180
Quality (dS m^{-1})	4, 12, 20
Frequency (times/week)	1x, 2x, 4x*
Mulch	No mulch, organic mulch

* 1x, 2x and 4x correspond to 15, 30 and 60 irrigation events during the growing season, respectively.

(Table 1). Irrigation quantity refers to the total irrigation amount applied during the growing season (in mm), irrigation frequency indicates the times per week that the irrigation event takes place, and irrigation quality corresponds to the salinity concentration in irrigation water (EC in dS m^{-1}). For all scenarios, we assumed that irrigation is applied uniformly throughout the growing season, depending on the quantity and frequency. Therefore, for the same irrigation quantity, a higher irrigation frequency requires a lower irrigation dose per event. Among the tested combinations, the scenarios with an irrigation quantity of 240 mm, applied twice per week, without mulch, and across three salinity levels, represents the field management practices employed in the Laayoune experimental site during 2021 (see Section 2.1). This scenario serves as the reference condition for comparison with the alternative management strategies evaluated in this study.

To account for weather variability, we used historical weather data from NASA POWER (2025), from 1994 to 2023. These satellite and model-based data contain mean daily meteorological data, available globally, with a resolution of 0.5° x 0.625° latitude/longitude grid (~ 55 km x 70 km). Higher resolution data for Laayoune was not available for the entire historical period. Temperatures at this location were unrealistically high due to the influence of the dessert climate. To reduce this effect, we averaged data from two grid cells: the target location and a nearby cell closer to the sea. In this way, temperatures aligned better with the observations available during the growing season in 2021. For all scenarios and years, we assumed a fixed growing season, from April 13th to June 29th.

To optimize water use and reduce soil salinity, we tested a set of additional scenarios for the Frequency of 1 time per week. Instead of applying uniform irrigation volumes throughout the growing season, we adjusted the schedule to align with the most sensitive growth stages of quinoa. During the first month after sowing (~30 days), the irrigation volume applied at each event was reduced to one-third of the uniform irrigation, using low-salinity water (4 dS m^{-1}). Afterwards, the irrigation volume was increased by one-third of the uniform irrigation, using either 12 dS m^{-1} or 20 dS m^{-1} salinity. This irrigation schedule resulted in the same total irrigation amount as the uniform irrigation scenarios.

2.4. Analyses of the sensitivity of the model outputs to management factors and weather variability using Linear Mixed Models (LMMs)

We used linear mixed models (LMMs) to identify which factors and factor interactions most strongly influence the model outputs, while accounting for weather variability. LMMs partition the total variation in the model output (response variable) into contributions from fixed effects and random effects. Fixed effects represent factors that are consistent across simulations and for which we aim to estimate their effect on the response variable (i.e. the management factors of interest). In contrast, random effects accounts for sources of variability that differ across simulations, such as year-to-year weather variability, which introduce random fluctuations in the response variable (Pinheiro, 2002).

We performed this analysis on the response variables yield and evaporation, using Quantity, Quality, Frequency and Mulching as categorical fixed effects, Cumulative Reference Evapotranspiration over the growing season (ETo) as continuous fixed effect, and Year as a random effect (Eq. 3).

$$\mathrm{sqrt(response\ variable)} \sim \mathrm{Quality} * \mathrm{Quantity} * \mathrm{Frequency} * \mathrm{Mulch} * \mathrm{ETo} + (1|\ \mathrm{Year}) \tag{3}$$

The variable Year accounts for any unexplained variation between years, which influence the response variable. Including Year as a random effect enables testing for differences among factors within each year, therefore ensuring that the estimated effects are generalizable across different weather conditions. Incorporating ETo as a fixed effect helps account for part of the between-year variability, allowing the LMM to more effectively isolate the effects of each of the four factors on interest.

We applied a square root transformation to the simulated yield and evaporation data before fitting the linear mixed model. This approach resulted in a better model fit, with lower residual errors and ensured that the estimated marginal means by the LMM remained positive. Based on these estimated marginal means, we performed post-hoc pairwise comparisons to clearly identify the most influential factors and their interactions.

This analysis was performed in the programming language R, using the *lmerTest* (Kuznetsova et al., 2013), *emmeans* (Lenth, 2017) and *multcomp* (Hothorn et al., 2002) packages.

3. Results

Fig. 1 presents the simulated yield for each scenario combining Quantity, Quality, Frequency and Mulch, over the 30 year-period (1994 – 2023), along with the post-hoc pairwise comparisons based on a simplified linear mixed model that includes only significant terms and interactions. The addition of mulch leads to more stable and higher yields, reducing the effect of the other factors: irrigation frequency, quantity and quality (salinity). In the absence of mulch, irrigation frequency and quality strongly affect yields, as also indicated by distinct letter groupings. The effect of irrigation frequency is most pronounced under high salinity and no-mulch conditions, showing a strong interaction between frequency, quality and mulch. However, within each salinity level, applying irrigation at a frequency of 1 time/week, which delivers a higher irrigation volume per event, consistently results in higher yields, which are comparable to those obtained with mulch in most cases (grey-shaded boxplots). The only exception is observed under the most stressful combination of high salinity (20 dS m^{-1}) and low irrigation amount (180 mm).

Beyond the effects of irrigation management and mulch, weather conditions significantly influence yield, as reflected in the spread of the boxplots. Figure A.1 in Appendix demonstrates that yield is higher in years with lower reference evapotranspiration (ET_o) and specifically, lower maximum daily temperature ($T_{\max}$), such as 2018 (outlier in Fig. 1), where water requirements are lower and air temperatures are more favorable for quinoa development (see Figure A.1 in Appendix). Quinoa growth is inhibited when daily average temperatures are above 30 °C (crop parameter).

Fig. 2 shows how irrigation frequency influences water and solute dynamics, which helps to explain the yield changes presented earlier. These results focus specifically on scenarios without mulch, irrigation water salinity of 12 dS m^{-1} and irrigation frequency of 1 time/week (16 mm per application) and 2 times/week (8 mm per application), with a total irrigation quantity of 240 mm. Reducing irrigation frequency to once per week, but with twice as much irrigation per application compared to irrigating twice a week, significantly decreases soil evaporation, as the soil surface remains dry for longer periods between irrigations, creating a barrier for soil evaporation. The reduction in evaporation results in increased soil water content and higher actual transpiration, with more water available for plant growth and reduced water stress. With larger irrigation applications per event, the soil water content temporarily exceeds the water holding capacity of the soil promoting deep percolation and carrying solutes downward. As a result, soil salinity concentration decreases, as salts become more diluted in the soil solution and some move away of the root zone. With lower soil salinity concentration, quinoa takes up less solutes, alleviating salinity stress. The shaded 10th –90th percentile range widens markedly after around 30 days after planting (DAP), when canopy growth increases crop water demand and interannual weather variability has a stronger influence.

A similar effect occurs with the use of mulch (see Figure A.2 in Appendix).

Fig. 3 compares the simulated yield and cumulative soil evaporation

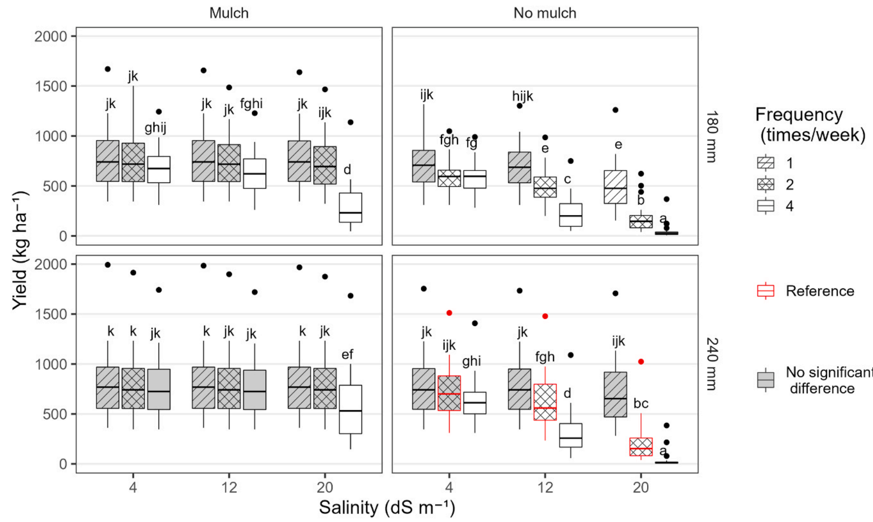

Fig. 1. Simulated yield variation over the 30 year-period (1994 – 2023) and across the four different factors: Quantity (180 and 240 mm), Quality (4, 12 and 20 dS m^{-1}), Frequency (once, twice and four times a week) and Mulch (organic mulch, no mulch). Letters above boxplots denote post-hoc pairwise comparisons based on a simplified linear mixed model. Scenarios sharing the same letter have similar yield responses, while different letters indicate scenarios where yield significantly differs, highlighting which factors and interactions have a greater influence on yield. Boxplots with red outline correspond to the irrigation management used in the field experiment in 2021, which serves as reference condition.

for the additional scenarios, involving uniform and variable irrigation, applied once a week during the growing season. On the x-axis, scenario 4 refers to uniform irrigation events of 12 mm (180 mm in total) or 16 mm (240 mm in total), with a salinity of 4 dS m^{-1}. The (4, 12) and (4, 20) scenarios correspond to variable irrigation volumes and quality: one-third of the uniform irrigation rate during the first month (~30 days) with 4 dS m^{-1} salinity, followed by irrigation events increased by one-third of the uniform irrigation rate, with 12 or 20 dS m^{-1} salinity. The results show that similar yields can be obtained under uniform low-salinity irrigation and variable irrigation that combines different irrigation volumes and higher salinity levels, independently of the presence of mulch or the total irrigation applied. Mulch substantially reduces soil evaporation, and limiting irrigation during initial stages when evaporative demand is high but crop water requirements are low, further minimizes water loss without affecting crop development.

4. Discussion

Our scenario analysis explored the effects of irrigation quantity (180 and 240 mm), frequency (once, twice, and four times per week) and quality (4, 12, and 20 dS m^{-1}), the use of mulch, and variable irrigation amount and quality throughout the growing season. The results demonstrated that tailoring irrigation practices to the local conditions of Laayoune can substantially increase and stabilize quinoa productivity, helping to reach its potential yield. The simulations suggest that less frequent irrigation with higher doses, especially when combined with mulch, sustains yields even under reduced total water volumes and low water quality. The main reasons are greater soil moisture retention in deeper layers, reduced evaporation due to less frequent wetting of the soil surface, and enhanced salt leaching. The effect of irrigation frequency was more pronounced under high salinity and no-mulch conditions, showing a strong interaction between Frequency, Quality and Mulch. These interaction effects are related to the non linear relation between yield and salinity in the model and to the effects of the different factors on evaporation.

The use of organic mulch effectively reduced soil evaporation and contributed to increased yields. While plastic mulch can reduce evaporation by up to 80 % compared to bare soil, organic mulch can achieve reductions of 20–50 % depending on its thickness and material, and the evaporation stage (McMillen, 2013; Onwuka and Uzoma, 2018; Zribi et al., 2015). Our results showed that mulch was particularly beneficial under highly saline irrigation conditions, helping to achieve yields comparable to those obtained with low and medium salinity levels. Previous studies have reported yield increases by up to 60 % with mulch, depending on the crop type, mulch type, environmental conditions and management practices (Li et al., 2025; Qin et al., 2015; Song et al., 2024). Furthermore, mulching has been shown to increase yield and soil water retention in saline soils for sunflower and common bean (Abd El-Wahed et al., 2017; Zhao et al., 2014), while reducing EC levels in soil water. Thi Nien et al. (2025) demonstrated that mulching in saline environments is also beneficial for salt tolerant crops like quinoa. In our study, mulch not only increased yields but also helped stabilize them. However, interannual weather variability still led to considerable yield variation within each scenario.

Our simplified approach to consider mulch in SWAP, by modifying key parameters to reduce potential and actual soil evaporation, proved effective in capturing its effect on soil evaporation. On average, evaporation was reduced by 15–48 % across irrigation scenarios and years, which is consistent with values reported in the literature for organic mulch (Chen et al., 2007; Onwuka and Uzoma, 2018; Zribi et al., 2015). However, the model did not account for other important mulch effects such as rainfall interception and infiltration, soil temperature regulation, and nutrient cycling, important in organic mulches. Most field studies show higher net infiltration under mulch over a growing season (Blanchy et al., 2023; Blanco-Canqui and Lal, 2007; Mulumba and Lal, 2008), as a result of reduced run-off and surface sealing, despite possible interception in light rainfall events. This implies that our approach may underestimate infiltration and, consequently, the leaching of salts. Depending on the rainfall intensity and frequency, this may have resulted in an overestimation of soil salinity levels. Soil temperature influences root and shoot growth and the duration of the growing season (de Wit et al., 2020; Garcia-Parra et al., 2020). Under the warm conditions of Laayoune, this temperature regulation would likely be beneficial for quinoa. Organic mulch materials provides organic matter to the soil after decomposing, which improves soil structure and water holding capacity. However, depending on the carbon-to-nitrogen (C:N) ratio of the mulching materials, their decomposition can reduce or increase nitrogen availability in the soil (Kader et al., 2017; Rossi et al., 2024), which influences crop development and yield. In the model, a nutrient module is not included and nutrients are considered optimal for crop

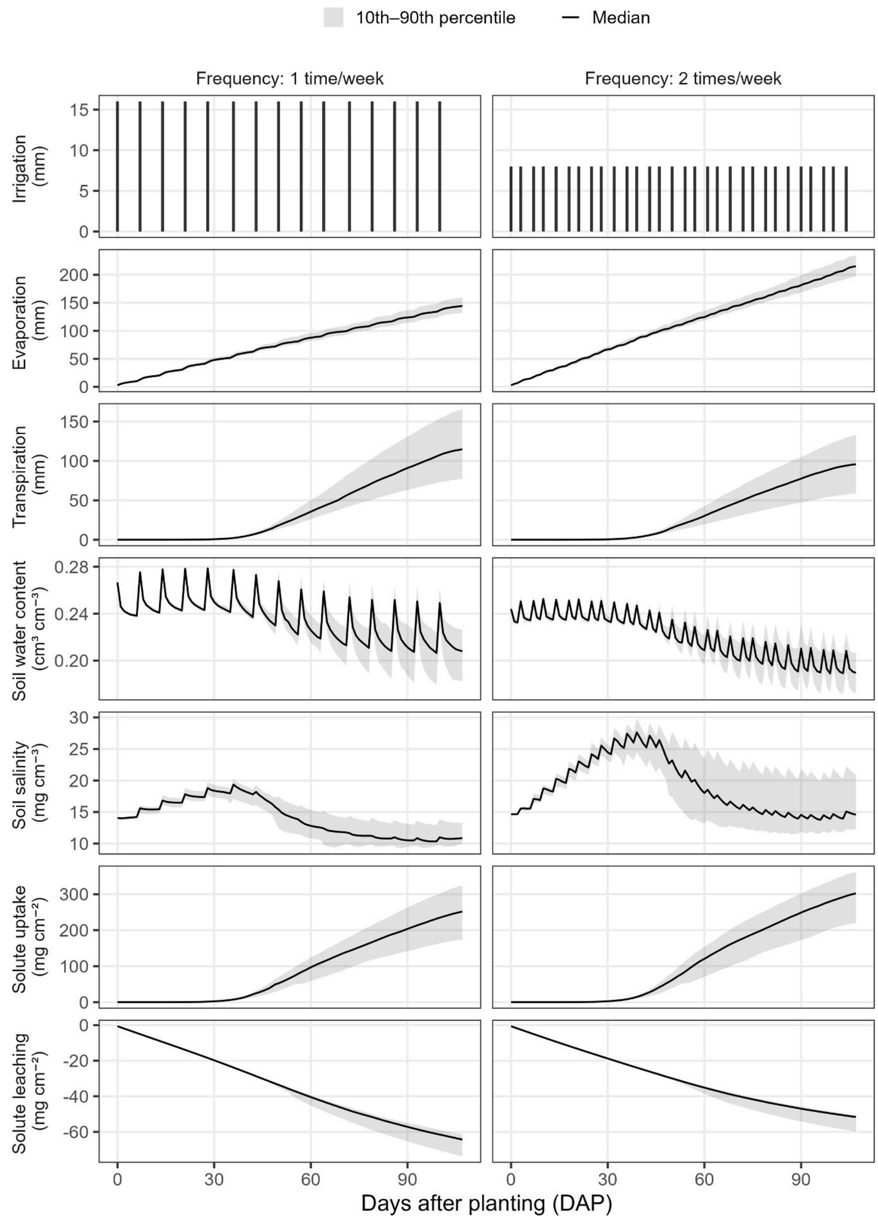

Fig. 2. Uniform irrigation applications, soil water content and soil salinity concentration at 10 cm depth, and cumulative water and solute fluxes, under irrigation frequencies of once and twice per week, for the irrigation water quality of 12 dS m^{-1} and no mulch. Irrigation is constant throughout the season with applications of 16 mm (1 time/week) and 8 mm (2 times/week), totalling 240 mm. The shaded area represents the 10th-90th percentile range over the 30 year-period (1994 – 2023), while the black line indicates the median.

growth. Despite these limitations, our simple yet practical approach effectively demonstrated the advantages of mulch and offers a basis for testing it in Laayoune field conditions, where different organic materials can be evaluated. This modeling approach can also serve as a benchmark for comparison with more complex methods that simulate mulch as an additional layer (Kodešová et al., 2014) or that incorporate a broader range of effects (Zhao et al., 2020b), provided that the necessary data for validation are available.

Irrigation scheduling that considers crop water requirements and salinity tolerance is crucial for optimizing irrigation and maximize yields in saline environments. Several studies have proposed saline irrigation strategies that limit soil salinization, reduce water use, and sustain crop productivity (El Mokh et al., 2024; Nagaz et al., 2012; Wang et al., 2007). For quinoa, a certain water availability and low salinity are critical during the emergence and seedling stages. On the other hand, water demand peaks during flowering and seed filling stages, but the crop can tolerate higher salinity (Awa et al., 2024; Maleki et al., 2018). Our simulation results indicated that applying less irrigation but with low salinity during the first month after sowing, while increasing the irrigation and the salinity later, does not significantly affect yield. Hirich et al. (2012) demonstrated that applying deficit irrigation (50 % of potential evapotranspiration) during quinoa's vegetative stage, while maintaining full irrigation during later stages, maximized yields under low-salinity conditions (0.17 dS m^{-1} in soil and 1.4 dS m^{-1} in irrigation water). In our study area, where water availability and soil and water salinity are limiting factors, deficit irrigation reduced soil evaporation and salt input to the soil. For this drought and salinity tolerant quinoa variety (ICBA-Q5), ensuring enough water during the flowering and seed-filling stages appeared more critical than the salinity level. Other quinoa varieties with a lower tolerance for salinity could be virtually represented by different values for the parameters TSCF (the Transpiration Stream Concentration Factor), SALTMAX (the threshold of salt

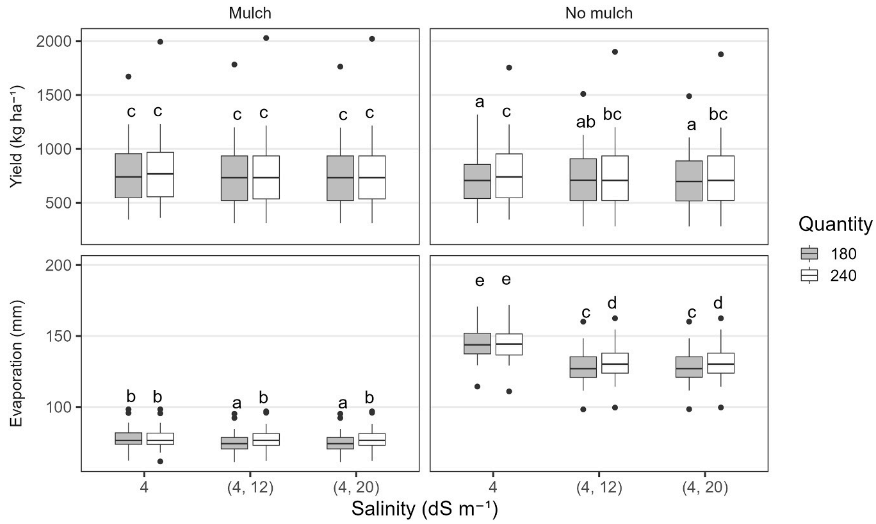

Fig. 3. Simulated yield and cumulative soil evaporation during the growing season (April 13th to June 29th) from 1994 to 2023, for the irrigation frequency of once a week, for irrigation quantity of 180 and 240 mm, with or with no mulch. On the x-axis, the "4" scenario represents uniform irrigation events applied every week, with 4 dS m^{-1}. The "(4, 12)" and "(4, 20)" scenarios correspond to variable irrigation amount and quality: one-third of the uniform irrigation rate during first month with 4 dS m^{-1} salinity, followed by irrigation events increased by one-third of the uniform irrigation rate, with 12 or 20 dS m^{-1} salinity. Letters denote post-hoc pairwise comparisons based on the linear mixed model.

concentration in soil water) and SALTSLOPE (the decline of root water uptake above the threshold of sat concentration in soil water) in SWAP (Estrella Delgado et al., 2025, Maas and Hoffman, 1977). The simulated water uptake and growth of these varieties will respond differently, especially to the medium- and high-salinity conditions. The extent to which mulching can mitigate yield losses from medium- and high-salinity irrigation water, as predicted for ICBA-Q5 (Fig. 1), will depend on the variety's salinity tolerance level. However, in the early stages of crop development soil water and salt contents are not affected by the crop variety or its tolerance, but rather by the soil. Our results are confined to a sandy loam soil, and, as soil water relations are to a large extent characterized by the soil texture, our applied irrigation and mulch management regimes may produce quantitatively different results regarding the evolution of soil moisture and salinity, and, consequently, crop growth and yield. Despite this limitation, the use of an agronomically relevant, moderately coarse-textured soil (sandy loam) provides a robust basis for interpreting the results and allows qualitative insights that are broadly transferable to similar production environments.

Process-based crop models such as SWAP-WOFOST rely on physiologically based mathematical formulations (e.g., temperature response functions, radiation use efficiency, root water uptake and transport equations). Although these processes are represented at a simplified level, the models synthesize decades of ecophysiological and agronomic knowledge into a coherent framework. As a result, they can generate qualitative predictions for environmental or management conditions that extend beyond the calibration dataset. Thus, even when the model is calibrated with limited observations, its mechanistic foundation provides insight into general patterns of crop response. However, for a precise quantification of the impacts of these practices on soil salinity, water balance, and yield, dedicated field experiments should be carried out. The current model outcomes are valuable for designing such experiments, helping to prioritize the most promising strategies such as mulching or reduced irrigation frequency. The multi-year simulations revealed that although improved irrigation management enhances quinoa productivity, potential yield in Laayoune remains constrained by climatic conditions. High reference evapotranspiration and elevated maximum temperatures limit productivity even under optimal irrigation. Some uncertainty remains due to the coarse spatial resolution (~55 × 70 km) of the weather data, which captures both desert and ocean influences, and may overestimate temperature. Nevertheless, the observed trends across scenarios were consistent among years and support the adoption of management strategies better adapted to saline conditions.

5. Conclusions

Based on a previously calibrated SWAP-WOFOST model for the quinoa variety ICBA-Q5, we evaluated several management scenarios involving irrigation strategies and mulch, to optimize water use and improve quinoa productivity in the Laayoune region, south of Morocco. We ran the scenarios for the period 1994–2023, to account for weather variability. Arid and salt-affected regions like Laayoune require resilient crops combined with efficient management practices to make agriculture sustainable and profitable. Our modeling results demonstrated that choosing a lower irrigation frequency with higher volumes, and employing mulch, significantly reduce soil evaporation and soil salinity concentration, and increase quinoa productivity even when irrigating with highly saline water (EC = 20 dS m^{-1}). By aligning irrigation with quinoa's sensitive growth stages for water and salinity, irrigation volume and quality can be reduced without significantly affecting yield. These findings offer practical insights for cultivating crops using saline irrigation water in arid regions, and provides a basis for field-scale testing in Laayoune conditions.

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Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Microsoft Copilot in order to improve the readability and clarity of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

Tom De Swaef: Writing – review & editing, Supervision, Methodology, Conceptualization. **Diana C. Estrella Delgado:** Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Ayoub El Mouttaqi:** Resources. **Jan Vanderborght:** Writing – review & editing, Methodology, Conceptualization. **Sarah Garré:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Abdelaziz Hirich:** Writing – review & editing, Resources.

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.

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Appendices

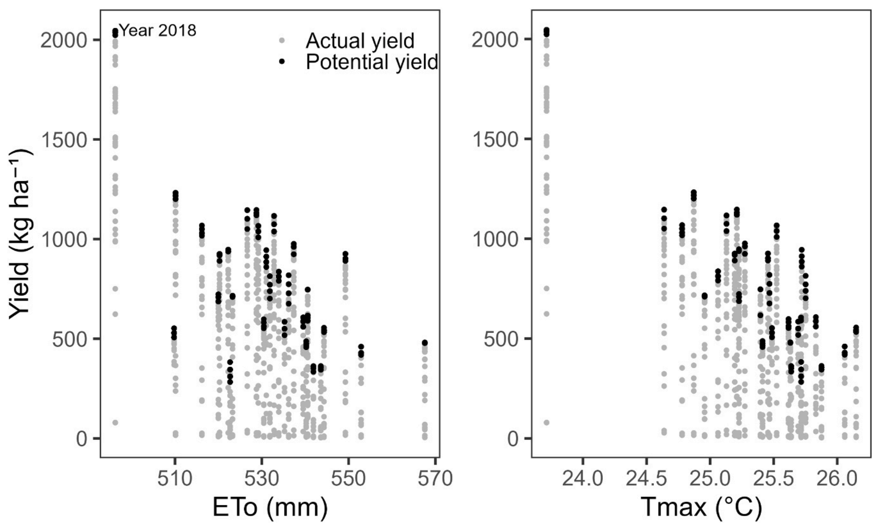

Figure A.1. Potential and actual yield versus cumulative reference evapotranspiration (ETo) and average daily maximum temperature (Tmax) during the growing season, from 1994 to 2023, for all scenarios. ETo was computed with the FAO Penman-Monteith method and reflects the evaporative demand of the atmosphere

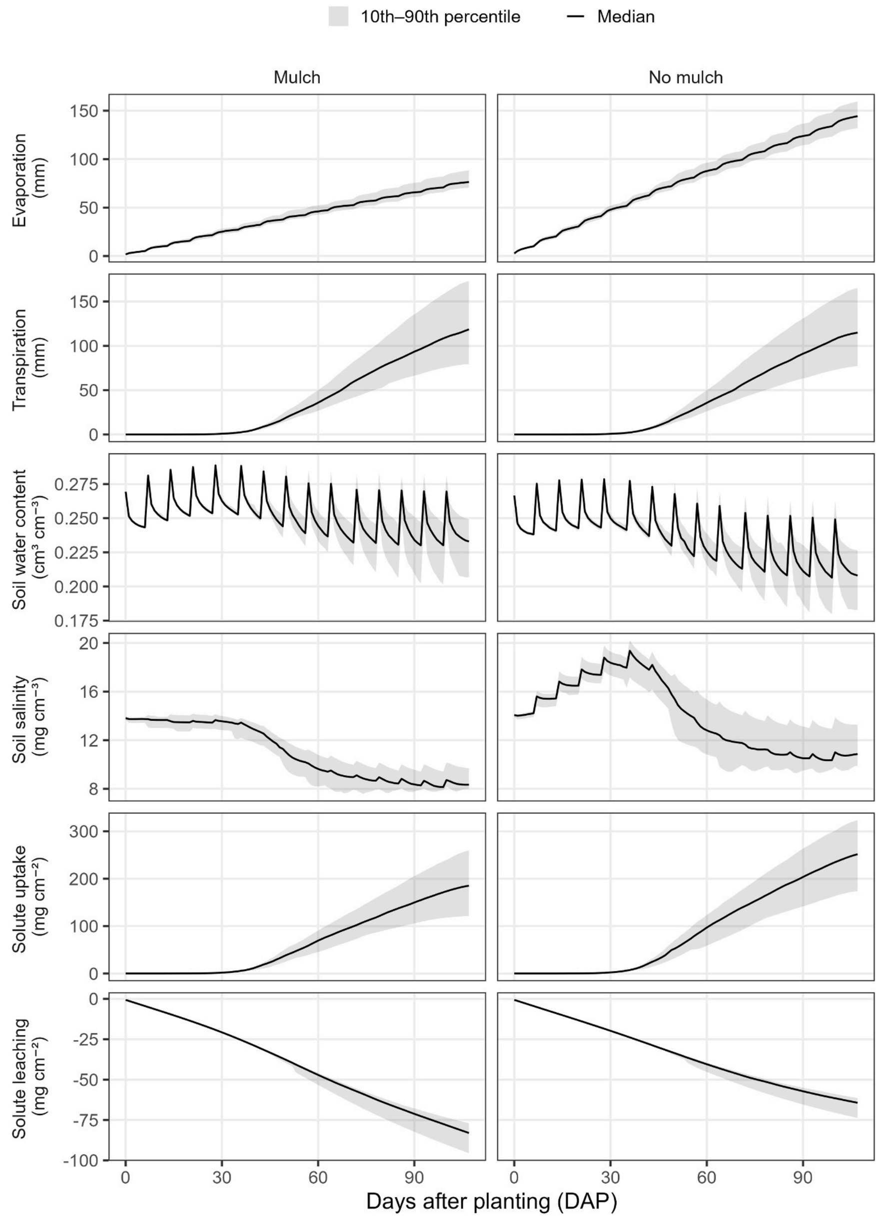

Figure A.2. Soil water content and soil salinity concentration at 10 cm depth, and cumulative water and solute fluxes, under irrigation frequency of 1 time per week with a total of 240 mm, for the irrigation water quality of 12 dS m^{-1}. The shaded area represents the 10th-90th percentile range over the 30 year-period (1994 – 2023), while the black line indicates the median

Data availability

The data used for model setup and the scripts for model execution and result analysis are openly available at https://gitlab.ilvo.be/plant-modelling/swap-dream

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