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Opuntia ficus-indica under climatic pressure: evapotranspiration dynamics and adaptive resilience in semi-arid Tunisia

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Introduction: Land degradation and increasing aridity threaten the sustainability of Mediterranean dryland agro-ecosystems, where water scarcity and climate variability are expected to intensify. This study examines the potential of *Opuntia ficus-indica* (OFI) as a climate-resilient crop in Central Tunisia, analyzing its response to historical and projected hydroclimatic changes and assessing its resilience and water requirements under future climate scenarios.
Methods: Observed climate records (19822005) and projections from six bias-corrected CORDEX Regional Climate Models were used to analyze air temperature (T_{air}) and precipitation variability in the semi-arid regions of Kasserine and Thala. To assess implications for crop water demand, historical and projected crop evapotranspiration (ET_c) fluxes of OFI were also analyzed.
Results and discussion: Historical hydroclimatic trends reveal significant precipitation declines (up to 55%) accompanied by increasing T_{air}, indicating ongoing aridification. Future projections (2052–2100) suggest further intensification, with precipitation decreasing by 45–60% and mean annual T_{air} rising by 0.3–0.7 °C under RCP4.5 and RCP8.5 scenarios. A marked seasonal pattern was observed in ET_c, with minimum winter values (0.41–0.50 mm d^{-1}) and summer peaks reaching 4.49 mm day^{-1} in Kasserine and 4.18 mm d^{-1} in Thala regions. Future projections indicate moderate increases in ET_c of 1–14% under RCP4.5 and up to 18% under RCP8.5 compared with historical conditions. This will lead to summer peaks of 4.69 mm d^{-1} (RCP4.5) and 4.89 mm d^{-1} (RCP8.5) in Kasserine, and 4.47 and 4.74 mm d^{-1} under RCP4.5 and RCP8.5, respectively, in Thala. Under these scenarios, OFI is expected to maintain its ecological tolerance due to its high water-use efficiency, highlighting its potential for climate-resilient agriculture and land restoration in Mediterranean semi-arid environments.

KEYWORDS
climate change, OFI, potential evapotranspiration, RCP scenarios, semi-arid regions

1 Introduction

Climate change is the foremost environmental challenge of the 21st century, threatening global food security through altered precipitation, rising temperatures, and intensified extreme events (Kamruzzaman et al., 2023). Increasingly frequent and severe droughts, heatwaves, and irregular rainfall are widely attributed to anthropogenic climate forcing (Hermassi et al., 2025; Islam et al., 2021).

In arid and semi-arid regions, where water scarcity and fragile ecosystems already constrain agricultural productivity, the impacts of climate change are projected to be disproportionately severe and potentially catastrophic (Demory et al., 2020; Madani et al., 2024). These environments are highly sensitive to shifts in precipitation, air temperature (T_{air}), and evapotranspiration (ET), with even small perturbations capable of triggering large-scale declines in soil moisture, groundwater recharge, and crop yields (Waha et al., 2017; IPCC, 2021). The combination of recurrent droughts, rising atmospheric water demand, and increasing interannual climate variability amplifies the vulnerability of both natural ecosystems and human livelihoods, thereby intensifying risks of land degradation, food insecurity, and ecosystem collapse (Ashraf et al., 2021; Ghazi et al., 2023).

One of the most critical hydrological responses to these changes is the alteration of ET, which integrates atmospheric demand for water through the combined processes of evaporation and plant transpiration (Ahbari et al., 2020). A variety of empirical and semi-empirical methods have been developed to estimate ET from commonly available climatic data, providing practical alternatives to physically based approaches, such as Penman–Monteith FAO-56 approach (Allen et al., 1998), which require extensive datasets often unavailable in semi-arid regions (Miralha et al., 2021). Among the most widely used methods, are the temperature- and radiation-based formulations of Hargreaves and Samani (1982), the temperature-driven method of Thornthwaite (1948), the Blaney and Criddle (1950) approach, incorporating T_{air} and day length, and the Oudin et al. (2005) formulation, based on energy balance simplifications. These methods rely primarily on accessible variables, such as T_{air}, solar radiation, and photoperiod, which facilitates their application in data-scarce environments (Miralha et al., 2021). However, their performance and accuracy are strongly conditioned by geographical and climatic contexts, often leading to variable levels of reliability across regions (Tabari et al., 2014; Miralha et al., 2021). In this sense, a study evaluated and recalibrated the Hargreaves–Samani (H–S) method, which requires only T_{air} data and empirical coefficients, under different climatic conditions, reflecting a strong global interest in simplified approaches for estimating reference evapotranspiration (ET_0) (Aschonitis et al., 2017). This interest is largely driven by the limited availability of complete agrometeorological datasets, particularly in data-scarce regions. Additionally, estimating the ET_0 in semi-arid contexts is indispensable for building climate adaptation strategies and ensuring sustainable management of water resources in the face of uncertain future climatic trajectories (Paredes et al., 2020). Note that rising T_{air}, enhanced radiative forcing, and prolonged dry periods directly intensify ET_0, thereby, accelerating soil moisture depletion and amplifying water stress on natural ecosystems and agricultural systems (Aschale et al., 2023). These alterations in hydroclimatic dynamics contribute to exacerbate water scarcity and soil degradation and destabilize agricultural production systems, particularly in semi-arid regions, where resilience thresholds are already exceeded (Roy et al., 2022; Abul-Soad and Al-Khayri, 2023).

Under this context, OFI stands out as a model of drought-resilient agriculture due to its Crassulacean Acid Metabolism (CAM) photosynthetic pathway, which confers exceptional water-use efficiency (Magalhães et al., 2021; Jarray et al., 2026). Originating from the arid regions of Mexico, OFI is inherently structured to tolerate extreme aridity and water-scarce conditions, requiring advanced predictive metrics to accurately monitor the nutritional, physiological, and morphological traits of its commercial cladodes under shifting agroecosystems (Hernández-Vidal et al., 2021). In its native territory, it stands as an emblematic species heavily intertwined with Mexican culture, prominently featured in the national cuisine and symbolized on the country's (Lugo-Palacios et al., 2025). Though relatively resilient, OFI remains vulnerable to prolonged drought and high temperatures, emphasizing the need for conserving local genotypes and soil moisture (Moniruzzaman et al., 2020). Weather variability plays a key role in shaping plant adaptation through morphological, physiological, and molecular mechanisms. In OFI, these adaptive responses include CAM photosynthesis, high water-use efficiency, nocturnal CO_2 uptake, and water storage in cladodes, which enhance tolerance to drought and heat stress. Nevertheless, the effectiveness of these mechanisms under increasingly severe climatic conditions remains uncertain, highlighting the importance of evaluating the response of OFI to future changes in temperature and precipitation regimes (Jorge et al., 2023).

The role of OFI is particularly relevant also for ecological purposes in arid and water-limited environments (Mendez et al., 2020; Martins et al., 2023). Beyond its role as a hardy survival crop, OFI has garnered significant scientific interest due to its diverse structural properties and commercial applications, extending into the pharmaceutical and cosmetic industries. This includes optimization mapping for macro-nutrient compositions and physiological structural variations to maximize secondary metabolite extraction (Blanco-Macías et al., 2022).

Specifically, in Tunisia, OFI has long been cultivated as both a traditional food crop and a strategic component of dryland farming systems, ensuring rural livelihoods and buffering against climate variability (Dubeux et al., 2021; Bakewell-Stone, 2023). Despite the increasing interest in drought-resilient crops, climate-change impacts on the ET dynamics of OFI remain poorly quantified. Moreover, understanding future changes in key climatic drivers, such as T_{air}, precipitation and crop evapotranspiration (ET_c), is essential for predicting the long-term survival and productivity of OFI, underling its strategic role in supporting sustainable agriculture, enhancing food security, and restoring degraded lands in arid and semi-arid regions (Mesta and Kentel, 2022).

Thus, the main objective of this study was to assess how climate change may influence the water requirements and resilience of OFI in the semi-arid regions of Kasserine and Thala in Central Tunisia. To this purpose, multiple scenarios projections were derived from six regional climate models (RCMs) (Van Vooren et al., 2019) of the CORDEX program, bias-corrected and combined in a multi-model ensemble (MME) to reduce uncertainties (Dimri, 2021; Miralha et al., 2021). Specifically, scenarios RCP4.5 and RCP8.5 (representing radiative forcing pathways of 4.5 and 8.5 W m^{-2} by 2100; 2052-2100) provide insights into how rising T_{air} and shifting precipitation patterns will reshape *ET* processes and consequently, OFI water requirements (Ahbari et al., 2020). By linking ET_c estimation with climate projections and crop-specific analysis, this study proposes methodological knowledge advances in semi-arid hydrology and addresses a pressing practical question: what role can OFI cultivation play in supporting climate change adaptation and sustainable water resource management in Tunisia's vulnerable agricultural landscapes? In this way, the study emphasizes both the ecological value of OFI and its potential as a cornerstone of sustainable agricultural systems in Mediterranean drylands. Finally, this study focuses on four specific objectives: (i) to analyze historical hydroclimatic trends (T_{air} and precipitation) in the semi-arid regions of Kasserine and Thala during the period 1982–2005, (ii) to evaluate future climate projections for the period 2052–2100 under the RCP4.5 and RCP8.5 scenarios, (iii) to assess the historical and projected ET_c of OFI, and (iv) to evaluate the implications of projected hydroclimatic changes on the water requirements and climate resilience of OFI in Mediterranean semi-arid agroecosystems.

2 Materials and methods

2.1 Study area

The study areas are located in Thala and Kasserine, with Thala delegation being part of the Kasserine Governorate in the central-western region of Tunisia (Figure 1). The Kasserine Governorate covers an area of approximately 8260 km². This zone is characterized by an elevated topography exceeding 700 m a.s.l. and falls within a semi-arid climatic zone. The region faces severe environmental constraints, including low and irregular precipitation as well as recurrent drought episodes, which together impose significant limitations on agricultural productivity and land sustainability. Historical climate data from 1982 to 2005, corresponding to the baseline period available from the CORDEX regional climate simulations, were used as a reference for model evaluation and future climate projections. During the period 1982–2005, the study area was characterized by semi-arid conditions, with a mean annual precipitation of 383 mm and a mean temperature of 16 °C. For the period 2005–2025, Kasserine recorded a mean annual precipitation of 305 mm and a mean temperature of 17 °C, while Thala recorded a mean annual precipitation of 420 mm and a mean temperature of 15.5 °C. Observations from 2005–2025 indicate a continuation of similar climatic tendencies, with no marked discontinuity in temperature or precipitation trends, supporting the use of 1982–2005 as a representative reference period. The annual reference evapotranspiration (ET_0), estimated using the modified Hargreaves–Samani method with the correction coefficients provided by Aschonitis et al. (2017),

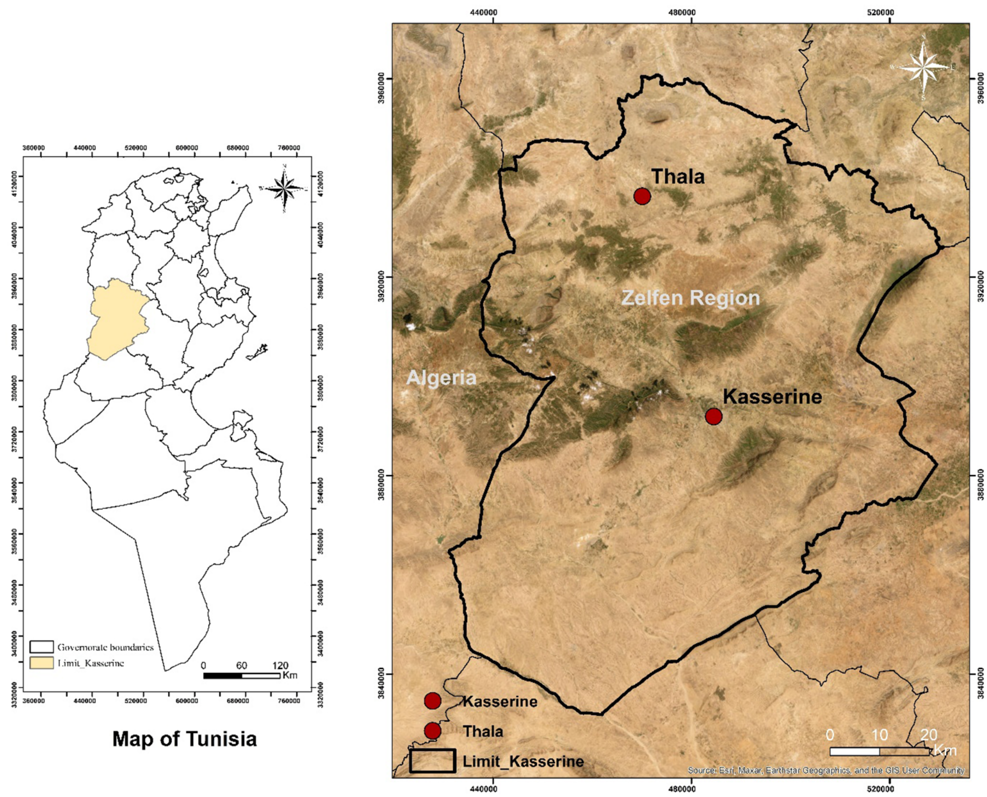

FIGURE 1
Location map of studied stations.

reached approximately 688 mm year^{-1}, highlighting a pronounced water deficit. Precipitation was lowest during July and August and highest during December and January, while maximum temperatures peaked in July and August and minimum temperatures occurred in January and February.

Despite these climatic constraints, the area supports a combination of traditional and adaptive land uses. Among the most distinctive cultivated species is the OFI, which has progressively adapted to the local conditions, exhibiting remarkable resilience to water scarcity and degraded soils (Iqbal et al., 2020). To assess the resilience of OFI to future climatic changes, two meteorological stations, Kasserine and Thala, were selected. Their geographic coordinates were recorded in decimal degrees using the WGS 84 datum. The Kasserine station is located at 8.83° E and 35.17° N, with an elevation of 656 m a.s.l., whereas the Thala station is situated at 8.67° E and 35.57° N, at an elevation of 1017 m a.s.l.

2.2 Climate modeling

The Coordinated Regional Climate Downscaling Experiment (CORDEX) is an international initiative designed to generate high-resolution regional climate projections through dynamic and statistical downscaling. By refining global climate model outputs, CORDEX provides more accurate and spatially detailed information, thereby enhancing the assessment of climate change impacts at regional and local scales worldwide (Martinez-Salvador et al., 2021).

To assess future climatic conditions in the study area, a MME approach was applied, based on six regional climate models from the Africa-CORDEX initiative. The multi-model ensemble (MME) approach averages the outputs of six regional climate models, reducing individual model uncertainties and strengthening the robustness of climate projections. Its effectiveness has been confirmed in similar contexts (Zeroual et al., 2019; Bichet et al., 2020). In fact, six models with 50 km resolution (CCMA-CanESM2, CSIRO-RCA4, NOAA-RCA4, ICHEC-REMO2009, MIROC-RCA4, MPI-REMO2009) were selected for their performance in the Mediterranean and North Africa. Bias correction of precipitation and temperature was performed using the Distribution Mapping (DM) method to align simulations with historical observations. This step is essential for reliable climate impact assessments (Tan et al., 2020). The DM technique was selected for its demonstrated effectiveness in Mediterranean and semi-arid regions. The BIAS evaluates the systematic error between the data simulated by RCMs and the observed data. It allows estimating the models' ability to reproduce observations over the reference period (1982–2005). This metric has been widely applied in previous studies (Gulakhmadov et al., 2021).

Climate simulations were conducted for both the historical period 1982–2005 and the future period 2052–2100, under two representative greenhouse gas concentration scenarios: an intermediate mitigation scenario (RCP4.5) and a high-emission, 'worst-case' scenario (RCP8.5). In fact, the period 1982–2005 was selected because it represents the historical period covered by the CORDEX-Africa simulations used in this study and for which corresponding observed climate data were available. Using the same period for observed and simulated data ensures a consistent comparison between the two datasets. Future changes were then assessed using the corresponding projection period. The analysis of model outputs will thus enable a better understanding of future climate trends, particularly regarding the evolution of T_{air}, precipitation and *ET* in the semi-arid regions of Kasserine and Thala.

Historical and projected climate data were processed using descriptive statistical methods. The analysis included the calculation of mean values, as well as comparisons between observed data and the MME derived from six CORDEX-Africa climate models after bias correction. The bias correction procedure was applied prior to the statistical analysis to reduce systematic errors and improve the consistency between simulated and observed data.

2.3 Assessment of crop evapotranspiration

It is important to note that this study does not rely on *in-situ* experimental measurements of OFI evapotranspiration. No field, greenhouse, or pot experiments were conducted, and no individual plants were monitored for physiological or water balance measurements. Instead, ET_c is estimated using a modelling approach, combining ET_0 derived from long-term meteorological data and crop coefficient (K_c) values obtained from published literature. Therefore, ET_c in this study represents a modeled estimate of crop water requirements rather than direct plant-scale evapotranspiration observations.

In this study, ET_c was calculated using the ET_0 and the corresponding K_c, according to the following formulation (Equation 1):

$$ET_c = K_c \times ET_0 \tag{1}$$

Where ET_c is the crop evapotranspiration (mm d^{-1}), ET_0 is the reference evapotranspiration (mm d^{-1}), and K_c is the crop coefficient.

In this study, the ET_0 was estimated using the Hargreaves–Samani formula (H–S) (Hargreaves and Samani, 1982; 1985) combined with the global grid of locally adapted correction coefficients provided by Aschonitis et al. (2017). The correction coefficients were calibrated using as benchmark the ASCE standardized method for short reference crop (former FAO-56 method) (Allen et al., 2005), as follows (Equation 2):

$$ET_0 = C_{hs2} \times (T_{mean} + 17.8) \times \frac{R_a}{\lambda} \times (TD)^{0.5} \tag{2}$$

Where ETo is the potential/reference evapotranspiration (mm d^{-1}), Tmean is the mean daily temperature (°C), TD is the difference between maximum and minimum daily temperature (°C), Ra is the extraterrestrial radiation (MJ m^{-2} d^{-1}), λ is the latent heat of vaporization (considered equal to ~2.45 MJ kg^{-1}) and chs2 is the local correction coefficient. In fact, these correction coefficients calculated using a Partial Weighted Average (PWA) approach. First, monthly coefficients are derived by calibrating the Hargreaves–Samani equation against the ASCE-standardized Penman–Monteith reference evapotranspiration. Instead of taking a simple arithmetic mean, the annual coefficient is computed as a weighted average of these monthly values, where the weighting factor is the monthly ETo itself. This ensures that months with higher evaporative demand contribute more to the final annual coefficient. Additionally, a threshold filter is applied to exclude months with very low ET_0 values, preventing them from skewing the coefficient. This method yields a single, optimized annual coefficient that minimizes errors when used for estimating evapotranspiration across diverse climatic zones (Aschonitis et al., 2017).

In Equation 2, if T_{mean} <−17.8 °C, the value of Tmean is set to 0, which is necessary for a global application (Weiß and Menzel, 2008). Note that the original formula uses 0.0023 as a value of chs2. In this study, the correction coefficients C_{hs2} in Equation 2 were 0.00246 and 0.00237, respectively, for the two meteorological stations.

The data used for calibrating the K_c model were based on mean monthly K_c values (Table 1) that were derived from published ranges of K_c values or daily measured/estimated values at different phenological stages for OFI (Consoli et al., 2013; Allen et al., 1998; Divincula et al., 2019; Araújo Júnior et al., 2025; Pereira et al., 2017). For building the model, the mean monthly values were linked to the 15th day of each month (Table 1). In Tunisia, no long-term local measurements of OFI crop coefficients, lysimeter-based evapotranspiration, soil water balance, or leaf area index are currently available for the Kasserine and Thala regions. Consequently, the K_c model was developed using values reported in the scientific literature. While this approach introduces uncertainty regarding the representation of local physiological responses, the selected studies were conducted under arid and semi-arid conditions comparable to those of the study area, providing the most suitable basis for estimating OFI evapotranspiration in the absence of site-specific calibration data.

To solve this problem, it was assumed that the K_c curve follows a bell-shaped form with minimum values during winter due to the phenological stage of dormancy considering the minimum values observed in the published datasets.

For building the K_c model, a Fourier series model was adopted to describe the variation of daily K_c as a function of the day of the year (DOY). The general periodic function is reported in Equation 3:

$$f(t) = a_0 + \sum_{n=1}^{\infty}[a_n \cos(n\omega t) + b_n \sin(n\omega t)] \text{ where } \omega = 2\pi/T \quad (3)$$

where T is the period equal to 365 and t is the day of the year (DOY).

Based on fitting analysis trials, a 2-harmonic seasonal model (second-order Fourier model) was selected with the following formula (Equation 4):

$$K_c(DOY) = a_0 + a_1 \cos\left(\frac{2\pi DOY}{365}\right) + b_1 \sin\left(\frac{2\pi DOY}{365}\right) + a_2 \cos\left(\frac{4\pi DOY}{365}\right) + b_2 \sin\left(\frac{4\pi DOY}{365}\right) \quad (4)$$

The fitting was performed with multiple regression using StatGraphics Centurion 10 after converting Equation 4 to the following form (Equation 5):

$$K_c(DOY) = a_0 + a_1X_1 + b_1X_2 + a_2X_3 + b_2X_4 \quad (5)$$

where X_1=cos(ωDOY), X_2=sin(ωDOY), X_3=cos(2ωDOY), X_4=sin(2ωDOY).

The results of the fitting procedure are provided in Figure 2 and Table 1.

3 Results

3.1 Historical climatic data (1982–2005)

In the Kasserine region (Figure 3A), the analysis of precipitation data for the period 1982–2005 reveals a rainfall regime marked by increasing aridity and heightened water vulnerability. The most severe deficits occurred in 1990 (−55%), 1988 (−42%), and 2003 (−41%). By contrast, the few surpluses, such as in 1984 (+3%), were insufficient to offset the prolonged dry periods.

In the Thala region (Figure 3B), historical data show significant interannual variability in precipitation, with a predominance of negative anomalies indicating persistent rainfall deficits relative to

TABLE 1 Mean monthly crop coefficient (K_c) values of *Opuntia ficus-indica* derived using various sources (Consoli et al., 2013; Allen et al., 1998; Divincula et al., 2019; Araújo Júnior et al., 2025; Pereira et al., 2017).

Month	Phenological stage	Final mean monthly adopted K_c	Day of the year
January	Winter Dormancy	0.32	15
February		0.32	46
March	Early Spring Growth/Bud Break	0.38	74
April	Active Vegetative Growth/Flowering	0.42	105
May	Flowering/Early Fruit Set	0.48	135
June	Fruit Development	0.56	166
July	Peak Fruit Swelling/Maturation	0.60	196
August	Harvest/Late Fruit Maturation	0.60	227
September	Post-Harvest/Autumn Vegetative Flush	0.52	258
October	Hardening for Winter	0.42	288
November	Entering Dormancy	0.38	319
December	Winter Dormancy	0.32	349

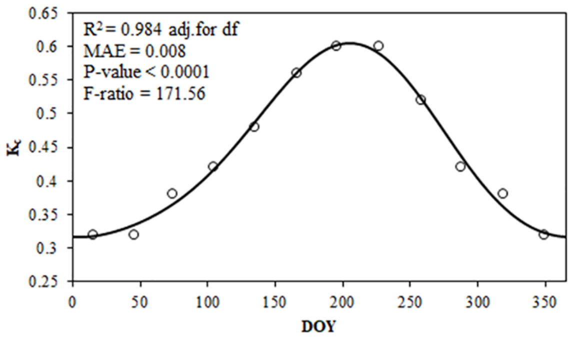

FIGURE 2
Fitting of the crop coefficient (K_c) model (Equation 5) versus the data of Table 1.

the mean. The most notable deficits were observed in 2003 (−55%), 2000 (−47%), 1998 (−21%), and 2005 (−19%). An additional positive anomaly was recorded in 1988 (+4%), which contrasts with the generally dry conditions and highlights the occurrence of occasional wet years within an overall aridification trend. The persistence of negative anomalies over more than two decades suggests a progressive shift toward a drier climatic regime.

In comparison with the Kasserine region (Figure 3A), both locations exhibit a similar tendency toward recurrent drought conditions, particularly in the early 2000s (e.g., 2003), indicating the regional-scale nature of extreme dry events. However, Kasserine shows slightly less interannual variability in terms of positive anomalies, whereas Thala presents more pronounced fluctuations, including isolated wet years such as 1988 (+4%), which were not sufficient to offset the long-term precipitation deficit.

Regarding the T_{air}, in the Kasserine region (Figure 4A), historical T_{air} data exhibit interannual variability, with values generally close to zero, fluctuating between slight reductions and moderate increases. Maximum T_{air} (T_{max}) values were below average in 1983 (−0.04 °C ± 0.02 °C) and 1994 (−0.05 °C ± 0.005 °C), indicating colder-than-average years, while positive anomalies were recorded in 1990 (0.04 °C± 0.016 °C) and 2004 (0.05 °C ± 0.001 °C). Minimum T_{air} (T_{min}) followed a similar trend, with a slight reduction in 1987 (−0.05 °C± 0.026 °C) and increase in 1996 (0.14 °C± 0.001 °C) and 2005 (0.11 °C± 0.005 °C). The relatively low standard deviation values indicate limited temperature variability during the historical period.

In the Thala region (Figure 4B), historical temperature records exhibit only minor fluctuations. Variations in T_{max} and T_{min} are small and often close to zero. Years such as 1987 and 1994 were colder than average, with T_{max} reduction reaching −0.05 °C ± 0.003 °C and −0.06 °C ± 0.003 °C, respectively. In contrast, years such as 1996 and 2005 experienced slight increase, with T_{min}

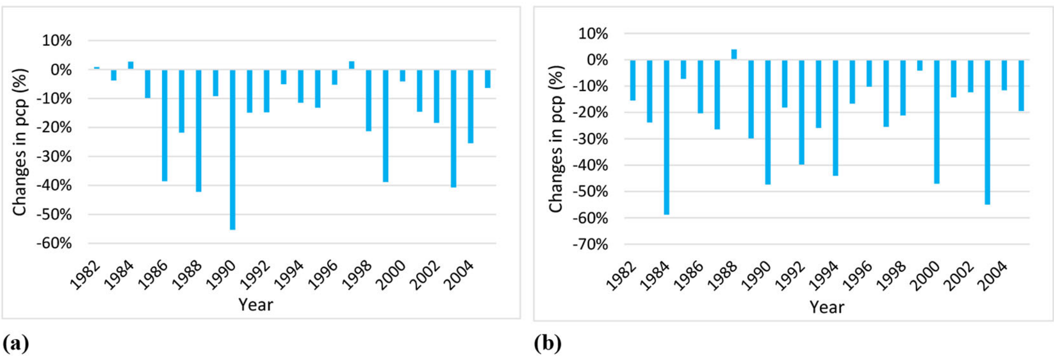

FIGURE 3
Changes in precipitation during the historical period (1982–2005) in Kasserine **(A)** and Thala **(B)**.

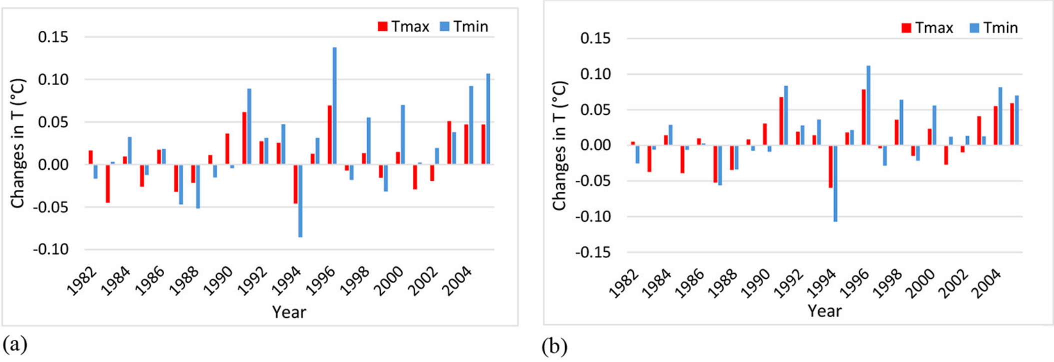

FIGURE 4
Changes in temperature during the historical period (1982–2005) in Kasserine **(A)** and Thala **(B)**.

reaching +0.11 °C ± 0.003 °C in 1996. Overall, the relatively low standard deviation values indicate limited interannual temperature variability during the historical period.

3.2 Projected changes (2052–2100) in climatic variables under RCP scenarios

In the Kasserine region (Figure 5A), precipitation projections under the RCP4.5 and RCP8.5 scenarios indicate a marked intensification of rainfall deficits, suggesting a potential shift in the regional climate regime. Under the RCP4.5 scenario, moderate greenhouse gas mitigation is projected to intensify precipitation deficits, with extreme reductions of (–49%) in 2092 and (–47%) in 2064, though minor surpluses may occur, for example (+14%) in 2080. The RCP8.5 scenario forecasts severe and frequent deficits, with extremes up to (–61%) in 2099 and (–53%) in 2082, suggesting a transition toward an almost permanent arid state and a high risk of irreversible water stress in the region.

In the Thala region (Figure 5B), future projections under both the RCP4.5 and RCP8.5 scenarios also indicate a pronounced deterioration in precipitation patterns. Projected precipitation values indicate a trend toward persistent deficits in the region. Under the RCP4.5 scenario, these deficits are expected to intensify gradually, with the largest reductions occurring in 2060 (–52%), 2067 (–51%), 2098 (–50%), and 2079 (–47%), while minor surpluses, such as +6% in 2093, remain exceptional. In contrast, the RCP8.5 scenario forecasts more frequent and severe deficits, with extreme reductions of –63% in 2099, –61% in 2079, –59% in 2058, –57% in 2091, and –56% in 2063, indicating a continuous and potentially irreversible decline in the region's water resources.

At the Kasserine level (Figure 6A), future projections under both climate scenarios indicate an intensification of warming, with the magnitude and frequency of temperature increases more pronounced than those observed historically. The RCP4.5 scenario projects a significant rise in T_{air}, with both T_{max} and T_{min} remaining above the reference period average throughout the projection period. T_{max} increases from 0.06 °C (2073 and 2097) to 0.15 °C (2087). T_{min} rises are even more pronounced, varying from 0.13 °C (2099) to 0.28 °C (2085). The faster rise in T_{min} compared to Tmax highlights enhanced warming during cooler periods. The RCP8.5 scenario predicts an alarming acceleration of warming. T_{max} peaks at 0.7 °C in 2096 and 0.66 °C in 2097, while T_{min} reaches 0.73 °C in 2098 and 0.72 °C in 2099. These results indicate a shift toward a much warmer climate, with more frequent and intense heatwaves.

For the Thala region (Figure 6B), future projections under RCP4.5 and RCP8.5 scenarios indicate a radical change in thermal regime, with a systematic and significant increase in temperatures. Under the RCP4.5 scenario, temperatures are projected to rise

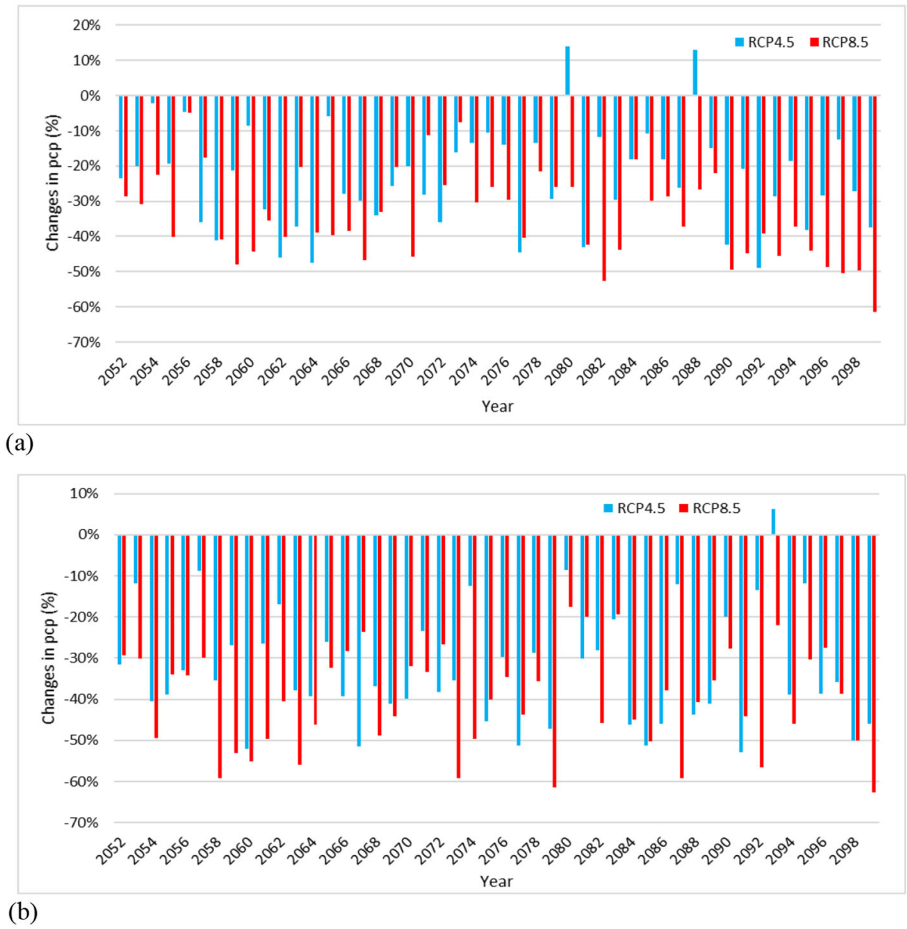

FIGURE 5
Projection of precipitation during the projection period (2052–2100) under RCP4.5 and RCP8.5 at Kasserine **(A)** and Thala **(B)**.

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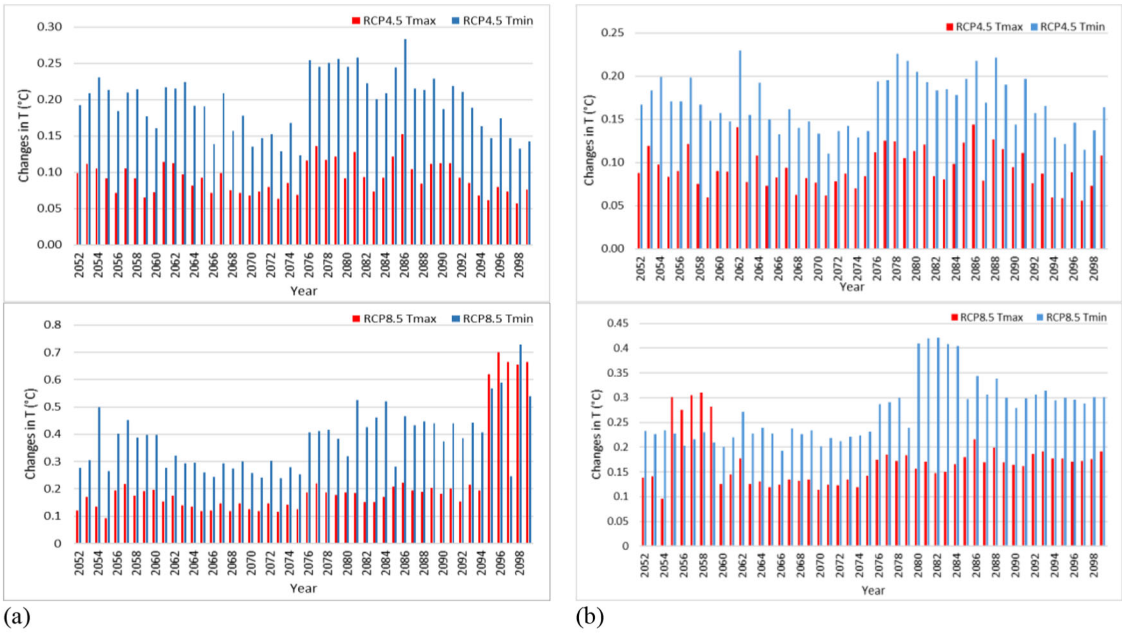

FIGURE 6
Temperature (T_{min}, T_{max}) projections during the projection period (2052–2100) under RCP4.5 and RCP8.5 at Kasserine **(A)** and Thala **(B)**.

steadily and consistently, with all T_{max} and T_{min} values exceeding historical averages, indicating that each year will be warmer than the reference period, with T_{max} increases ranging from +0.06 °C to +0.14 °C and T_{min} increases varying between +0.11 °C and +0.25 °C. In the RCP8.5 scenario, warming accelerates further, with T_{max} reaching up to +0.19 °C in 2098 and T_{min} peaking at +0.44 °C in 2083.

3.3 Crop evapotranspiration of *Opuntia ficus-indica* under historical and future climate conditions

3.3.1 Historical crop evapotranspiration (1982–2005)

The historical analysis of the mean daily ET_c for OFI between 1982 and 2005 reveals a highly seasonal, bell-shaped water demand that is intricately synchronized with the plant's phenological cycle in both Kasserine and Thala (Figure 7).

During the "Winter Dormancy" phase, water consumption reaches its absolute minimum, dropping to approximately 0.50 and 0.43 mm d^{-1} in Kasserine and Thala, respectively. As temperatures rise and the plant transitions into the "Early Spring Growth" and "Budding and Flowering" stages, its physiological water demand accelerates rapidly. For instance, the ET_c in Kasserine more than doubles from 1.21 mm d^{-1} in March to 3.05 mm d^{-1} by May, mirroring the active expansion of new cladodes and the metabolic cost of floral development. The evaporative trajectory peaks during the intense summer months (June to August). July represents the absolute zenith of water consumption, where the ET_c reaches 4.49 and 4.18 mm d^{-1} in Kasserine and in Thala, respectively. Crucially, throughout the entire annual cycle, Kasserine consistently indicates higher ET_c values than Thala. This persistent evaporative gap, where Kasserine demands roughly 0.10 to 0.30 mm d^{-1} more than Thala depending on the month, highlights a more intense localized atmospheric demand in the Kasserine region.

Zooming out from the monthly dynamics to the inter-annual scale (1982–2005), the cumulative annual ET_c further solidifies this regional disparity while demonstrating the plant's long-term environmental resilience. The historical time series reveals that Kasserine's annual water requirement fluctuated within a defined, higher band of approximately 700 mm to 800 mm, whereas Thala maintained a consistently lower envelope ranging from 640 mm to 730 mm (Figure 7). Despite the inherent year-to-year climatic variability typical of semi-arid environments, the overall trajectory of the annual ET_c exhibits remarkable stability.

3.3.2 Projected ET_c under future climate scenarios (2052–2100)

The projection of ET_c for OFI under future RCPs (RCP4.5 and RCP8.5) (Figure 8) reveals a possibility of an intensification of the hydrological cycle in the semi-arid regions of Kasserine and Thala. Building upon the historical baseline (1982–2005), the monthly ET_c values for the 2052–2100 period exhibit a persistent seasonal bell-shaped curve, yet with substantially elevated peak demands and a shifted evaporative amplitude. In Kasserine, the maximum daily ET_c on July is projected to reach 4.69 mm d^{-1} under RCP4.5 and climb to 4.89 mm d^{-1} under the extreme RCP8.5 scenario. Thala follows a similar upward trajectory, with July peaks reaching 4.47 and 4.74 mm d^{-1} for the respective scenarios. Under the high-emission RCP8.5 scenario, the annual ET_c in Kasserine is projected to breach the 850 mm threshold frequently after 2080, with a modeled peak of 917.38 mm in 2085. Thala, despite its historically cooler profile, shows an even more volatile response under RCP8.5, with annual demand soaring to a maximum of 931mm in 2084. In

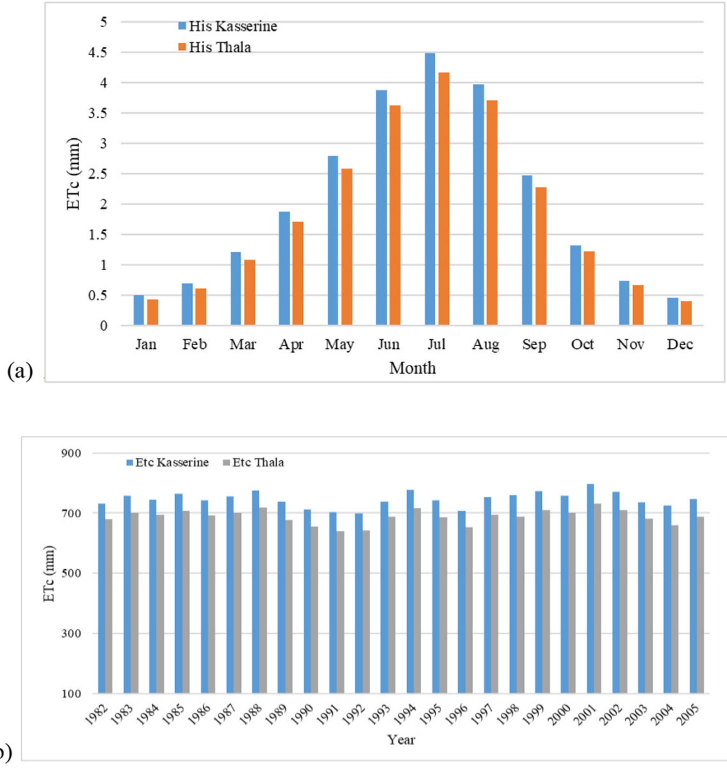

FIGURE 7
Monthly **(A)** and annual **(B)** changes in ET_c during the historical period (1982–2005) in Kasserine and Thala.

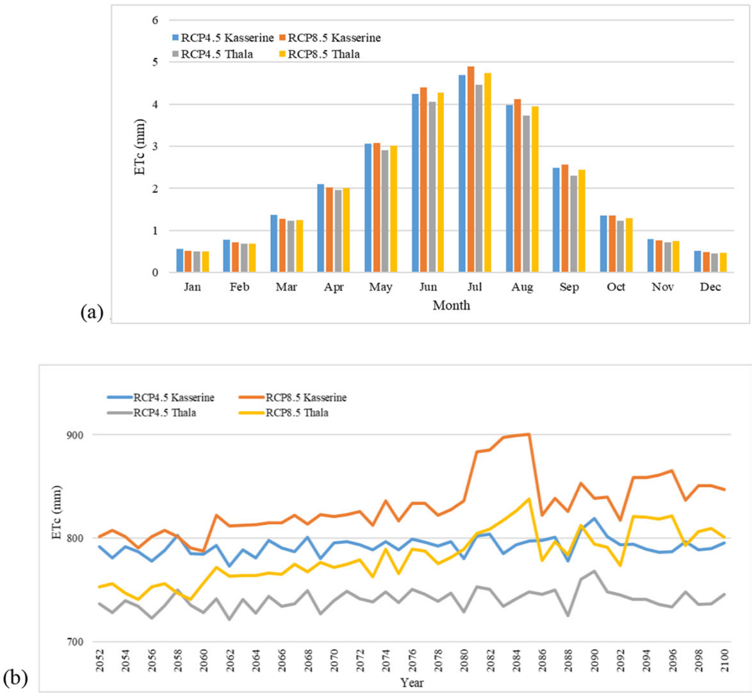

FIGURE 8
Monthly **(A)** and annual **(B)** variation of ETc during the projection period (2052–2100) under RCP4.5 and RCP8.5 at Kasserine and Thala.

contrast, the RCP4.5 scenario indicates more moderate conditions, with annual ET_c values in Kasserine ranging between 773 and 819 mm, while Thala remains between 721 and 768 mm, suggesting that mitigation pathways may help limit increases in crop water demand.

4 Discussion

Understanding the interactions between T_{air}, precipitation, and ET is fundamental for assessing the resilience of semi-arid ecosystems under climate change. In Central Tunisia, where water availability represents the primary constraint to agricultural and ecological stability, variations in these climatic variables exert profound control over vegetation dynamics, soil moisture balance, and hydrological fluxes. This discussion integrates historical climatic data (1982–2005) with future projections (2052–2100) under RCP4.5 and RCP8.5 scenarios to analyze how shifts in air temperature and precipitation patterns regulate ET and, consequently, the potential eco-physiological response of OFI under changing climatic conditions. These changes will affect ET_c and overall water-use dynamics. By evaluating these interlinked processes, this study aims to elucidate the climatic thresholds that define the persistence and productivity of OFI as a resilient species and a key component of sustainable land-use strategies in arid and semi-arid regions.

4.1 Historical and projected climate trends

Historical climatic records (1982–2005) for Kasserine and Thala show a clear trend toward progressive aridification, marked by recurrent rainfall deficits and moderate T_{air} increases. These observations are consistent with broader regional studies of the Tunisian climate (Haj-Amor et al., 2020) and underscore the vulnerability of these areas to water scarcity and drought, which pose significant stress on conventional crops. Although T_{air} fluctuations were relatively modest historically, the gradual warming of the late 20th century establishes a baseline for evaluating future climate impacts (Latrech et al., 2023). The historical temperature records for both regions highlight relatively stable conditions, providing a critical baseline for assessing the resilience of key species under anticipated climate change scenarios (Jarray et al., 2025).

Future climate projections under RCP4.5 and RCP8.5 scenarios suggest a marked intensification of arid and warm conditions in both study regions. Overall, results indicate a consistent tendency toward reduced precipitation and increased air temperatures, reflecting a transition toward more water-limited environments. In Kasserine, precipitation deficits are projected to reach up to (−61%) by the end of the century under RCP8.5, while in Thala, extreme reductions may reach (−63%). Both regions are also expected to experience a systematic warming, with Tmax and Tmin values consistently exceeding historical averages under all scenarios. Under RCP8.5, Kasserine is projected to experience Tmax increases up to +0.7 °C and Tmin up to +0.73 °C, whereas Thala shows increases of up to +0.19 °C for Tmax and +0.44 °C for Tmin. These combined climatic changes indicate a shift toward warmer and drier conditions, with increased frequency of heat stress events, thereby intensifying water stress and reinforcing the need for adaptive management strategies in semi-arid agroecosystems.

The observed interannual variability in precipitation and temperature over the study area can be explained by the combined influence of regional and large-scale climatic drivers. In central-western Tunisia, climate variability is strongly modulated by Mediterranean atmospheric circulation patterns, including fluctuations in the North Atlantic Oscillation, variability in storm track activity, and the occurrence of persistent atmospheric blocking events that influence rainfall distribution. In addition, the progressive increase in global mean temperature enhances atmospheric evaporative demand and intensifies temperature extremes, particularly in semi-arid inland regions such as Kasserine and Thala. The interaction between these large-scale circulation mechanisms and local topographic effects contributes to the observed variability in climatic conditions, which directly affects evapotranspiration processes and water availability.

For projections covering the period 2070–2100, Enyew et al. (2014) report a maximum increase in mean monthly T_{air} of 8.9 °C. Additionally, a substantial long-term decline in precipitation is anticipated, a trend that has been corroborated by multiple studies (Carvalho et al., 2022; Pereira et al., 2021; Carvalho et al., 2021). This combination of reduced precipitation and T_{air} elevation signals intensified atmospheric water demand and increased aridity. These findings are consistent with Jarray et al. (2025), who reported similar trends in the Wadi Rmel watershed, demonstrating decreasing precipitation and a significant rise in maximum temperatures in the long term, ranging from 1.5 to 5.2 °C under RCP8.5 scenarios. Moreover, these results are consistent with the conclusions of the latest IPCC AR6 report (2021), which reports a robust warming signal over North Africa accompanied by a general decline in precipitation across semi-arid regions, thereby confirming the observed long-term climatic trends in the study area.

The relatively moderate projected temperature increases observed in our study (0.3–0.7 °C) compared to typical Mediterranean projections can be attributed to several factors. In fact, the study area (Kasserine and Thala) is characterized by specific local climatic conditions, including elevation and continental influences, which may moderate the magnitude of projected warming compared to coastal Mediterranean regions. Aridity in this context refers to the persistent water deficit that characterizes the region, whereas aridification denotes the gradual intensification of dry conditions resulting from recurrent droughts, declining precipitation, and increasing temperatures. These trends highlight the vulnerability of the study area to water scarcity and underscore the importance of evaluating the adaptive capacity and resilience of OFI under future climate scenarios.

It is important to acknowledge that future climate projections are inherently associated with uncertainties arising from greenhouse gas emission scenarios, model parameterization, boundary conditions, and natural climate variability. Although the multi-model ensemble approach adopted in this study reduces the influence of individual model biases and generally provides more robust estimates than single-model projections, uncertainty tends to increase toward the end of the century. Therefore, the projected decreases in precipitation and increases in temperature should be interpreted as plausible future trajectories rather than deterministic outcomes. Recent studies have highlighted that increasing aridity does not necessarily result in proportional ecosystem degradation, as dryland environments may exhibit substantial adaptive capacity and resilience through ecological, hydrological, and physiological feedback mechanisms. In the case of OFI, its drought-adaptive traits, high water-use efficiency, and water-storage cladodes, may partially buffer the impacts of increasing evaporative demand. Consequently, while the projected climatic trends indicate heightened water stress, the magnitude of ecological and agricultural responses remains uncertain and will depend on the interaction between climate forcing, local environmental conditions, and species-specific adaptation mechanisms.

Although the use of a multi-model ensemble of six bias-corrected CORDEX-Africa simulations helps reduce uncertainties associated with individual models, some limitations remain. These include uncertainties related to the representation of regional climate processes, model spatial resolution, and the relatively short historical reference period (1982–2005) used for model evaluation. Nevertheless, the selected models demonstrated satisfactory performance in reproducing the observed climate variability over the study area, supporting the robustness of the projected changes while recognizing the inherent uncertainties associated with climate projections.

4.2 Seasonal dynamics of OFI evapotranspiration under semi-arid conditions

Although both regions show very similar *ET* dynamics, Kasserine consistently exhibits slightly higher ET_c values than Thala throughout the year. The difference ranges between 0.1 and 0.3 mm d^{-1} depending on the month, which results in a higher cumulative annual ET_c in Kasserine. Even relatively small differences in temperature or solar radiation can influence ET_0, and, consequently, crop water requirements. The sensitivity of *ET* to climatic variables has been has been widely demonstrated in global analyses of crop coefficients, indicating that regional climatic gradients can significantly influence *ET* rates even under comparable vegetation conditions (Aschonitis et al., 2017). In this context, the observed evaporative gap between Kasserine and Thala can be interpreted as the result of subtle regional differences in energy balance and atmospheric demand rather than fundamental differences in crop physiology.

The historical *ET* values obtained for OFI demonstrate a pronounced seasonal variability, with minimum ET_c values during winter (0.41–0.50 mm d^{-1}) and maximum values during summer reaching 4.49 mm d^{-1} in Kasserine and 4.18 mm d^{-1} in Thala. This seasonal bell-shaped pattern is consistent with the physiological functioning of cactus species growing in semi-arid environments, where *ET* is strongly regulated by both climatic forcing and plant phenology. These findings are consistent with the seminal research of Consoli et al. (2013), which utilized a micro-meteorological surface energy balance approach to quantify the water requirements of OFI in a Mediterranean conditions (Consoli et al., 2013).

Comparable *ET* magnitudes have been reported in studies on cactus crops cultivated in semi-arid regions. For instance, irrigation experiments conducted on cactus clones (OFI used as forage cactus) indicated that *ET* increases significantly during the active growth stages and peaks during the warmest months of the year (Pereira et al., 2017). Similarly, K_c studies on prickly pear cultivation reported maximum *ET* rates during summer, reflecting the strong influence of temperature and radiation on plant water demand (Divincula et al., 2019). In the present study area, only OFI (prickly pear) is cultivated; therefore, all comparisons are interpreted within the same species, with differences mainly related to management practices and growing conditions rather than species variability.

Despite these seasonal peaks, the annual ET_c values estimated in this study (approximately 700–800 mm for Kasserine and 640–730 mm for Thala) remain relatively moderate compared with many conventional crops cultivated in semi-arid environments. This confirms the well-known drought tolerance and high water-use efficiency of cactus species, which rely on CAM photosynthesis to reduce daytime transpiration losses (Araújo Júnior et al., 2025). Field observations of OFI energy balance also indicate that *ET* is strongly constrained by stomatal regulation, maintaining relatively low water consumption even under high evaporative demand (Jardim et al., 2023). For this study, the observed interannual consistency indicates a relatively stable mean annual K_c over the 23-year period, suggesting that OFI maintains strong physiological regulation of transpiration over time, thereby partially buffering the effects of interannual climatic variability. Ultimately, this historical baseline demonstrates the plant's dynamic yet controlled transpiration range, providing a robust foundational metric to evaluate exactly how these baseline totals will shift under future climate warming scenarios.

Future climate projections indicate an expected intensification of ET_c for OFI across both regions, particularly under the high-emission RCP8.5 scenario, with the most pronounced increases occurring during the summer months when atmospheric evaporative demand already reaches its seasonal maximum. On July, which represents the peak evapotranspiration period, ET_c in Kasserine increases from 4.49 mm d^{-1} during the historical period (1982–2005) to 4.69 mm d^{-1} under RCP4.5 and 4.89 mm d^{-1} under RCP8.5, while in Thala values rise from 4.18 mm d^{-1} historically to 4.47 mm d^{-1} under RCP4.5 and 4.74 mm d^{-1} under RCP8.5. These results correspond to an increase of approximately 4–9% under the moderate scenario and up to 9–14% under the high-emission scenario, highlighting the strong sensitivity of evapotranspiration to climatic warming during peak growth periods. At the annual scale, the projections confirm this upward trend, although the magnitude of change varies between scenarios. Under RCP4.5, annual ET_c remains relatively close to historical values, fluctuating between 773–819 mm in Kasserine and 721–768 mm in Thala, suggesting that moderate warming would maintain crop water requirements within a range comparable to present conditions. Conversely, under RCP8.5, annual ET_c frequently exceeds 900 mm in both regions toward the end of the century, indicating possibility of intensification of the regional hydrological demand. These projected increases are primarily associated with rising temperatures and enhanced atmospheric evaporative demand, as higher temperatures amplify vapor pressure deficit and consequently accelerate evapotranspiration processes (Aschonitis et al., 2017). This trend is consistent with the findings of Latrech et al. (2024), who also reported a possible increases in evapotranspiration under high-emission scenarios.

Similar responses have been observed in cactus cultivation systems, where evapotranspiration increases under warmer conditions despite the plant's inherently high water-use efficiency (Pereira et al., 2017; Divincula et al., 2019). Nevertheless, field observations of cactus energy balance indicate that CAM physiology continues to regulate water losses efficiently even under high thermal stress, allowing cactus species to maintain relatively moderate evapotranspiration compared with many conventional crops (Jardim et al., 2023).

These findings emphasize that while OFI remains a premier candidate for climate-resilient agriculture, its projected annual ET_c increase of 5% to 11% under extreme trajectories necessitates advanced hydro-agricultural planning to sustain current productivity levels. Despite these growing hydrological constraints, OFI demonstrates remarkable physiological resilience to high evapotranspiration through its CAM and superior Water-Use Efficiency, which allow for sustained photosynthesis and biomass production even under severe water stress. By utilizing nocturnal CO_2 fixation and minimizing transpiration losses, this species can survive in arid Mediterranean environments where most conventional crops fail, thereby alleviating pressure on limited water resources. Ultimately, the relatively moderate and stable increase in ET_c projected across future scenarios highlights a robust adaptive capacity, confirming that OFI remains both ecologically and economically viable as a sustainable solution for agricultural production in an increasingly warming world.

4.3 Climatic suitability and resilience of OFI

The resilience of OFI under severe climatic conditions has established it as a strategic crop in arid and semi-arid regions such as central Tunisia. Its adaptability is primarily governed by rainfall and temperature regimes, which influence its overall performance, spatial distribution, and long-term sustainability. Understanding the bioclimatic thresholds of OFI growth is essential to explain its historical expansion and to guide future optimization strategies under climate change. In fact, regional climate models provide a robust foundation for examining precipitation and temperature patterns and for evaluating the resilience of OFI under changing climatic conditions.

Between 1982 and 2005, the average annual precipitation was 272 mm in Kasserine and 384 mm in Thala, while the mean annual temperature (Tmean) was 22.5 °C across both regions. During this period, average of T_{max} and T_{min} were 16 °C and 10 °C, respectively. All these values were obtained from Directorate General of Water Resources (DGRE) of Tunisia. Both precipitation and temperature exhibited sinusoidal trends, reflecting the strong seasonality characteristic of Mediterranean semi-arid climates.

In parallel, OFI plantations expanded progressively in Tunisia, with recent remote sensing analyses revealing an increase from 6759 ha in 2000 to 30494 ha in 2024 in Zelfen region, central Tunisia, corresponding to an expansion exceeding 350% over the study period (Jarray et al., 2026). This remarkable increase demonstrates the species' adaptability to low and irregular rainfall, recurrent droughts, and thermal variability. Its widespread adoption also reflects its strategic socio-economic role as a multifunctional crop. These baseline climatic and land-use dynamics provide a critical reference for assessing the adaptive potential of OFI under future climate change scenarios.

It should be noted that the projected climatic changes and associated ET_c responses are subject to uncertainties inherent to climate models and emission scenarios. Therefore, the reported trends should be interpreted as plausible future trajectories rather than deterministic outcomes. In addition, elevated atmospheric CO_2 concentrations may partially enhance water-use efficiency in OFI, a CAM species, through reduced stomatal conductance and transpiration losses. However, the extent to which this effect may compensate for increasing temperatures and declining precipitation remains uncertain. Given that OFI cultivation in the study area is predominantly rainfed and does not rely on irrigation or fertilization, the projected increase in evaporative demand highlights the importance of the species' inherent drought tolerance for maintaining productivity under future climatic conditions.

OFI exhibits key morphological and physiological adaptive mechanisms that support its survival under water-limited environments, succulent cladodes that store water, reduced transpiring surface area, and efficient stomatal regulation, which collectively enhance water-use efficiency under high evaporative demand. Moreover, weather variability strongly influences both plant and soil systems by altering soil moisture dynamics, infiltration rates, and the duration of plant-available water. Increased temperature and irregular precipitation accelerate soil drying, reduce water retention, and intensify plant water stress, thereby directly affecting evapotranspiration processes and overall crop water requirements.

Louhaichi et al. (2013) indicated that OFI requires between 250 and 1000 mm of annual rainfall for sustained growth. Growth becomes critical below 250 mm or above 1000 mm (Inglese and Scalenghe, 2009). On the other hand, FAO (2013) detailed that an average annual rainfall between 200 to 600 mm is appropriate for OFI growth.

These thresholds highlight the species' broad ecological plasticity, while also indicating its vulnerability to both extreme aridity and excessive moisture conditions. In the case of Central Tunisia, with observed mean rainfall of 272 mm in Kasserine and 384 mm in Thala during 1982–2005, OFI expansion reflects its ability to acclimate to sub-optimal yet highly variable semi-arid conditions, thereby reinforcing its role as an adaptive crop in vulnerable landscapes.

Future projections under the RCP4.5 scenario indicate that precipitation deficits will persist and intensify in both regions, with extreme annual reductions reaching approximately (−49%) in Kasserine and (−52%) in Thala during critical years. Under the RCP8.5 scenario, precipitation deficits intensify dramatically, with extreme reductions up to (−61%) in Kasserine and (−63%) in Thala. Despite these declines, the projected rainfall amounts remain within the ecological tolerance and optimal ranges reported in the literature for OFI (200–1000 mm annually). This suggests that, based on precipitation alone, OFI can withstand and adapt to these future conditions, maintaining its overall performance and continuing to fulfill its ecological and socio-economic functions.

In addition to rainfall, temperature is a critical determinant of the agroecological suitability of OFI cultivation, as it directly influences physiological activity, growth dynamics, and overall plant development. The literature reports that OFI exhibits a broad thermal tolerance, remaining viable across temperatures ranging from approximately 5 °C to 40 °C. Optimal vegetative development and biomass accumulation are typically observed within the temperature range of 18–23 °C (Le Houérou, 2000). Moreover, OFI exhibits high tolerance to arid tropical climates, maintaining physiological activity at temperatures exceeding 40 °C, with fruit maturation occurring during peak heat periods (Domenico, 2021). Its drought resilience is attributed to its cladodes, which act as water storage organs, enabling survival under prolonged water deficits through the use of internal water reserves (DeFelice, 2004).

When the annual mean temperature falls below 15 °C, growth is progressively constrained and conditions become unsuitable when the mean drops below 10 °C (Inglese and Scalenghe, 2009). Despite its high resilience, OFI cannot develop under average minimum temperatures below (−5 °C) (Louhaichi et al., 2013; Acharya et al., 2019). Moreover, the range from (−14 °C) to (−8 °C) is considered highly lethal, beyond which the species cannot survive (Le Houérou, 1989; Acharya et al., 2019). The optimal growth of this plant occurs within a temperature range of 10–15 °C during winter, which supports basic metabolic activity, and 30–35 °C in summer, which promotes vigorous growth and fruit development (Domenico, 2021). Temperatures outside this optimal range may reduce metabolic activity and growth rates, thereby lowering productivity, which underscores the species' strong adaptation to warm, semi-arid environments.

For temperature, historical data (1982–2005) indicate mean annual conditions of 22.5 °C in both Kasserine and Thala, with average T_{max} around 16 °C and T_{min} near 10 °C. Under the RCP4.5 scenario, temperatures are projected to rise steadily, with T_{max} increases ranging between +0.06 °C and +0.15 °C and T_{min} between +0.11 °C and +0.28 °C, indicating a gradual but systematic warming trend. The RCP8.5 scenario, however, predicts a more alarming acceleration, with T_{max} rising up to +0.19 °C and T_{min} reaching as high as +0.44 °C. When compared to ecological thresholds reported in the literature, where OFI growth is optimal between 18 °C and 23 °C, but remains viable within 5–40 °C, it is evident that future temperature conditions, even under the pessimistic scenario, will remain within the species' tolerance range.

Indeed, these changes, although indicative of a hotter and drier climate, will keep regional temperatures well within the ecological thresholds for OFI development. Moreover, the slightly higher increases in T_{min} compared to T_{max} are consistent with enhanced night-time warming. These projections confirm that, despite significant climatic shifts, OFI is expected to retain its adaptive capacity, supporting its continued role as a strategic crop for food, forage, and ecosystem services in Central Tunisia.

The H–S method, highly sensitive to temperature, relies on the diurnal range of T_{max} and T_{min}, with higher mean temperatures driving increased ET_0. Although ET_c is projected to increase under future climate conditions, the magnitude of this increase remains relatively moderate compared with that of many traditional crops. Despite projected temperature increases and associated ET_c values exceeding 900 mm yr-1, these levels remain within the optimal growth range for OFI. Even under the extreme RCP8.5 scenario, the projected increase in annual ET_c remains within 10–18% of the historical baseline, suggesting that OFI maintains a relatively stable water demand despite climatic warming. Experimental studies on cactus energy balance confirm that this mechanism provides high water-use efficiency and enables cactus species to maintain productivity under severe drought conditions (Jardim et al., 2023). Previous research on prickly pear cultivation also indicates that cactus crops can maintain stable growth and biomass production under limited water availability, making them particularly suitable for dryland agriculture (Divincula et al., 2019; Pereira et al., 2017). Therefore, despite the projected increase in evapotranspiration due to climate change, OFI remains a highly promising crop for sustainable agricultural systems in semi-arid regions. Its capacity to combine low water requirements with high drought tolerance makes it a key component of climate adaptation strategies in Mediterranean dryland regions.

These findings demonstrate that OFI is likely to preserve a high level of adaptive capacity under future climate conditions, thereby sustaining its key ecological and socio-economic roles, including forage supply, food production, and land restoration. The resilience observed in Central Tunisia further suggests that other semi-arid and arid regions across the Mediterranean and beyond could benefit from the wider adoption of OFI cultivation. Its ability to tolerate low and highly variable rainfall, elevated temperatures, and degraded soils makes it a highly valuable crop for enhancing food security, supporting rural livelihoods, and contributing to the mitigation of land degradation and desertification processes. Finally, these results provide strong evidence supporting the promotion of OFI as a strategic crop for climate adaptation in comparable Mediterranean environments.

5 Conclusions

Understanding the interactions between climatic variability, hydrological processes, and vegetation response is essential for anticipating the impacts of climate change on semi-arid ecosystems. This study integrated multi-decadal climatic data with future projections (2052–2100) to assess the evolution of T_{air}, precipitation and ET_c in Central Tunisia and, thus, to evaluate the adaptive resilience of OFI as a drought-tolerant species.

The results provide valuable insights into how ongoing and projected climatic changes could reshape the hydroclimatic balance and vegetation dynamics in vulnerable Mediterranean drylands. The analysis highlights a progressive transition toward warmer and drier conditions, consistent with the regional aridification trend observed across North Africa. Historical records (1982–2005) already indicated a marked decline in precipitation and moderate warming, suggesting the onset of a persistent hydroclimatic imbalance. Future projections under RCP4.5 and RCP8.5 confirm this intensification, characterized by a systematic rise in temperature and a continued reduction in rainfall.

The findings reveal a clear and progressive transition toward warmer and drier conditions across both Kasserine and Thala. Historically, the two regions have already exhibited pronounced rainfall deficits and moderate warming, signaling an early stage of aridification. Precipitation is expected to decline sharply, with reductions ranging from 45–50% under RCP4.5 to more than 60% under RCP8.5 by 2099, indicating a transition toward an almost permanent arid state. Under the RCP4.5 scenario, mean annual temperatures are projected to rise by 0.1–0.3 °C, while under RCP8.5, more severe warming is anticipated, with increases reaching 0.7 °C for T_{max} and up to 0.75 °C for T_{min} by the late 21st century. The amplification of thermal extremes, combined with increasingly irregular precipitation, is expected to elevate atmospheric evaporative demand substantially.

Moreover, this study assessed the historical and future dynamics of ET_c of OFI in the semi-arid regions of Kasserine and Thala using historical climate data and future climate projections under the RCP4.5 and RCP8.5 scenarios. The results reveal a pronounced seasonal evapotranspiration pattern characterized by minimal water demand during winter dormancy and a progressive increase from spring to summer, with maximum ET_c values occurring in July. Historically, peak ET_c reached approximately 4.49 mm day^{-1} in Kasserine and 4.18 mm day^{-1} in Thala, while annual ET_c ranged between 700–800 mm in Kasserine and 640–730 mm in Thala, highlighting the moderate water requirements of the crop under semi-arid conditions.

Future projections indicate a consistent increase in evapotranspiration across both climate scenarios, primarily driven by rising temperatures and increased atmospheric evaporative demand. Under the moderate RCP4.5 scenario, the increase remains relatively limited, with annual ET_c remaining close to the historical range. In contrast, the RCP8.5 scenario suggests a possible increase of evapotranspiration, with annual values occasionally exceeding 900 mm toward the end of the century. The largest increases are projected during the summer months, when evapotranspiration demand is already at its peak, resulting in increases of approximately 1–14% under RCP4.5 and up to 18% under RCP8.5 compared with historical conditions. Despite these projected increases, OFI demonstrates remarkable resilience to climatic stress due to its CAM photosynthetic pathway and high water-use efficiency, which allow the species to regulate transpiration and maintain productivity under water-limited environments. The relatively moderate magnitude of the projected increase in ET_c suggests that OFI will remain well adapted to semi-arid Mediterranean environments even under future warming scenarios.

These findings establish OFI as a key asset for climate-resilient agriculture in dryland regions. Its unique adaptive traits effectively mitigate water stress associated with increasing evaporative demand, thereby providing a stable foundation for sustainable production under changing climatic conditions. The implications for agricultural planning are significant: in vulnerable semi-arid regions like Tunisia, OFI functions as a frontline adaptation strategy that combats land degradation, preserves soil health, and sustains rural livelihoods. Ultimately, this study underscores the urgency of integrating drought-resilient crops like OFI into adaptive agricultural policies and hydro-agricultural management to secure Mediterranean ecosystems. These results recommend promoting OFI within climate-smart agricultural strategies in semi-arid regions, particularly under rainfed systems where water resources are limited. Future research should incorporate field-based physiological measurements, soil moisture dynamics, and yield responses to improve the understanding of plant–soil–climate interactions and reduce uncertainties associated with ET_c estimations. In addition, strengthening local monitoring networks and validating model outputs under real field conditions are essential to enhance the robustness of projections and to support more effective water resource management and climate adaptation planning.

Data availability statement

The datasets presented in this article are not readily available because the data cannot be shared because they are in priority of INRGREF. Requests to access the datasets should be directed to taoufik.hermassi@ingref.ucar.tn.

Author contributions

TH: Supervision, Investigation, Writing – review & editing, Funding acquisition, Conceptualization, Writing – original draft, Visualization, Formal Analysis, Validation, Data curation, Methodology, Resources, Project administration. AM: Software, Writing – original draft, Resources, Data curation, Methodology. FJ: Writing – original draft, Software, Methodology, Investigation. MK: Writing – review & editing. SC: Writing – review & editing, Validation. DV: Validation, Writing – review & editing. PI: Validation, Writing – review & editing. VA: Investigation, Validation, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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