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Climate change vulnerability of Drâa-Tafilalet oases: A survey and ground-level perspective

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Abstract: This research investigates the impacts of climate change on date palm cultivation in the Drâa-Tafilalet oases of southeastern Morocco, employing a mixed-methods approach that combines on-the-ground observations and semi-structured interviews with 120 date palm farmers. Field observations across three key oases document widespread hazards and effects of climate-related stress on date palms, including disrupted flowering synchronicity, increased incidence of parthenocarpy, and heightened vulnerability to pests and diseases. A survey of these 120 farmers revealed the severity and interconnected nature of these impacts. Several farmers (30% in Boudnib, 40% in Errachidia and 40% in Zagora) observed multiple asynchronous flowering cycles per year, while parthenocarpy emerged as a significant concern, with prevalence ranging from 20% in Zagora to 40% in Boudnib. While 10–15% of farmers reported inflorescence rot, a concerning knowledge gap exists regarding effective preventative treatments, with only 3–15% of farmers employing them. Farmer surveys further revealed that wind-driven mite infestations pose a growing threat, with 50% of farmers in Zagora reporting significant issues. The research explores ways to reduce the effects of climate change through methods like creating crops resistant to climate conditions, enhancing water supply systems, combining pest and pollinator control methods, and implementing new pollination approaches. Nevertheless, it highlights the need for tailored adaptation and mitigation strategies that incorporate both scientific knowledge and local, farmer-driven insights. The study emphasises the urgency of proactive measures to address the socioeconomic consequences of climate change on these culturally and economically vital oases.

Keywords: climate change, date palm (*Phoenix dactylifera* L.), Drâa-Tafilalet (Morocco), oases ecosystems, sustainability, vulnerability

INTRODUCTION

Moroccan oases, located in the heart of the Sahara Desert, are unique ecosystems that play a crucial role in agriculture, food security, and economic development (Benqlilou and Bensaid, 2013; Chery *et al.*, 2017). These oases are characterised by a high percentage of natural oasis vegetation, including palm trees, which are vital for the survival and prosperity of the local communities. For millennia, date palms have provided sustenance, economic security, and cultural richness to generations of Moroccans, weaving themselves into the very fabric of the nation's identity. Their fruit, a staple food source, is not only a source of nourishment but also a symbol of prosperity and abundance (Chehbouni *et al.*, 2022). The palm's leaves are used for weaving baskets, mats, and even roofing materials, while its trunk provides timber for construction and fuel (El-Mously and Darwish, 2020). However, the very existence of these oases, and the livelihoods they support, are increasingly threatened by the looming specter of climate change (Sobczak, 2008). Rising temperatures, erratic rainfall patterns, and prolonged droughts are disrupting the

delicate balance of these fragile ecosystems, pushing date palm trees to their limits (Ali-Dinar, Munir and Mohammed, 2023).

Date palm trees are extremely vulnerable to heat stress and water scarcity, which can lead to decreased crop yields, economic hardship, and loss of ecosystem services. These stresses act synergistically, exacerbating the vulnerability of these trees and threatening their survival. Rising temperatures can lead to a cascade of physiological changes, including reduced photosynthesis, and accelerated respiration rate depleting the tree's energy reserves, along with causing damage to cellular structures (Ait-El-Mokhtar *et al*., 2019; Chehbouni *et al*., 2022; Benyoussef *et al*., 2024). Water scarcity, on the other hand, restricts root growth, reduces turgor pressure, and increases vulnerability to diseases and pests (Ait-El-Mokhtar *et al*., 2019; Chehbouni *et al*., 2022). The combined effects of unprecedented heat stress and water scarcity pose a grave threat to the future of Moroccan oases. These ecosystems rely heavily on groundwater resources, which are increasingly depleted due to over-use and reduced rainfall (Qadem *et al*., 2022; Boudarfa *et al*., 2023; Messaoudi *et al*., 2023; Ouharba, Mabrouki and Triqui, 2024).

The climate change implications on date palms extend far beyond the agro-ecological realm. These trees are a vital source of income for many local communities, providing employment opportunities in agriculture, processing, and trade. Dates contribute to over 65% of the income for oasis farms in the region, playing a key role in stabilising the rural population. The loss of date palm trees would have a devastating impact on local economies, exacerbating poverty and food insecurity. Furthermore, the decline in date palm populations also undermines the important cultural significance of these trees within Moroccan society (El-Juhany, 2010; Sedra, 2015). Date palms are not merely economic assets; they are deeply intertwined with the cultural and social fabric of Moroccan society. They are integral to the nation's history, traditions, and folklore. The iconic "palm groves" that dot the landscape are not only agricultural landscapes but also spaces for social gathering, recreation, and cultural expression (Sedra, 2015). The loss of these trees would represent a profound cultural loss, eroding the very identity of Moroccan oases (El-Juhany, 2010).

Addressing these pressing and recurrent concerns, particularly the impact of climate change on date palm trees, requires a multifaceted approach rooted in a deep understanding of the local context. While remote sensing technologies and models offer important information on large-scale transformations, accurately understanding the localised effects on date palm farming requires a close-up viewpoint. This research centres on the oasis in Morocco known as Drâa-Tafilalet, using it as a case study to reveal the real effects of climate change on the cultivation of date palms. Our approach involves merging observations in the field to evaluate the vulnerability of palm trees to climate change effects in three important oases, with farmer interviews to collect direct insights on this vulnerability and methods of adaptation.

This comprehensive approach enables us to address important inquiries: what is the effect of changing climates on the health, productivity, and overall function of the date palm and oasis ecosystem; what do farmers at the forefront of these changes think and how do they view the situation. This study offers valuable insights for specific strategies to adapt and mitigate based on both overall trends and local circumstances.

MATERIALS AND METHODS

RESEARCH METHODOLOGY

The present study aims to elucidate the impact of climate change on the Drâa-Tafilalet oases and their iconic date palm trees. To this end, a field observatory approach was established, with a particular focus on direct observations and engagement with local communities. This involved the implementation of a systematic ground survey and data collection process across three primary oasis locations. The study, including the survey and on-site investigation, was conducted in 2023 over a period spanning from February to November to encompass all targeted environmental disorders in three locations: Boudnib, Errachidia, and Zagora (Fig. 1). These sites were selected based on their strategic importance in representing the diverse microclimates and socio-economic contexts within the Drâa-Tafilalet region, thus allowing for a more nuanced assessment of climate change vulnerability and adaptive capacity. The main focus of this work is to capture the primary figures of inspected oases. This paper employs two complementary approaches aiming at assessing the actual climate change effects on the Moroccan oases, with a focus on date palms. Evidently, the results from the survey were represented in % as they are quantitative data, while the on-the-ground investigation (aiming to observe the reality on the ground) provided qualitative results which can not be presented in the same way as the survey, but are complementary to each other.

BACKGROUND OF THE STUDY AREA

The Drâa-Tafilalet region, located in southeastern Morocco, is one of the country's 12 regions, encompassing a vast area of 88,836 km^2 characterised by hyper-arid and arid climates (Fig. 1). This region is renowned for its historical palm groves, diverse oasis ecosystems that exhibit significant variations in size, vegetative covers, and resources. Intricately linked to desert and river components, these oases rely heavily on date palms, which serve as symbols of water security in these arid environments. Historically, these palm groves have played a critical role in supporting local economies, providing sustenance, and maintaining ecological balance. Today, the Drâa-Tafilalet contains over 5.5 mln date palm trees, which constitute approximately 80% of Morocco's total date palm trees (Ait-El-Mokhtar *et al*., 2019; Hamriri *et al*., 2024). This makes the Drâa-Tafilalet region a crucial centre for date production in Morocco, contributing 90% of the national date production, further highlighting their continued importance to both the region and the nation. Date palm cultivation is vital in the Drâa-Tafilalet oases, serving as an economic driver and contributing to the region's ecological and social dynamics (Houssni *et al*., 2023). These oases serve as an ecological barrier against desertification, and their protective effect extends to the northern shores of the Mediterranean. They also harbour a variety of natural resources including indigenous animal species (goat of Drâa, sheep of Demman, etc.) and cultivated crops (dates, olives, cereals, legumes, etc.).

CLIMATIC PATTERNS IN THE INVESTIGATED AREA

The climatological data presented in Figures 2, 3 and 4 illustrate the temperature, humidity, and precipitation variations from 2018 to the present in the primary oases of Drâa-Tafilalet:

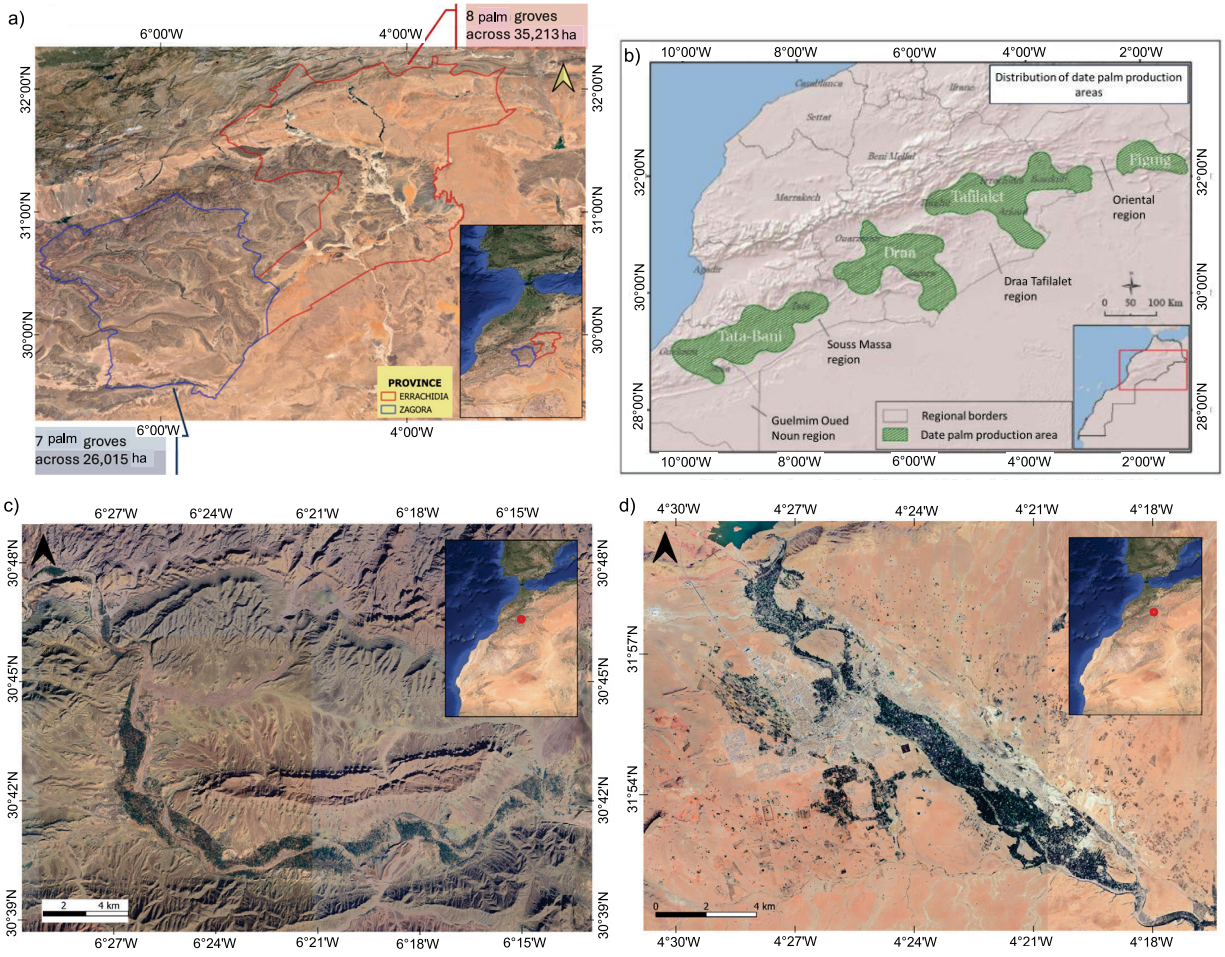
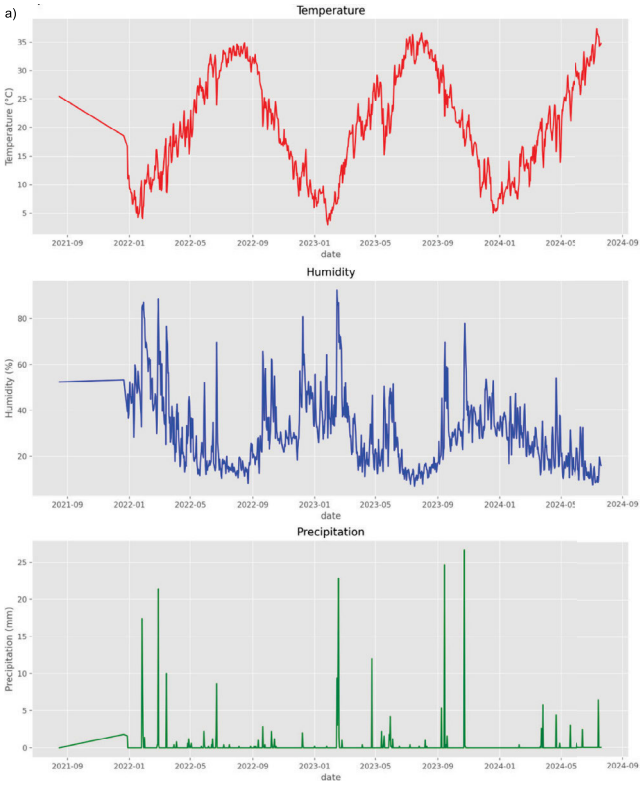


Fig. 1. Spatial distribution of palm groves and vegetation cover in the southeastern Morocco: a) location of Errachidia and Zagora provinces where the studied palm groves are located, b) geographic distribution of major date palm production areas encompassing the study area of (Draa-Tafilalet), c) example of vegetation cover within the Mezguita palm grove in the Zagora region, d) example of vegetation cover within the Errachidia palm grove; source: own elaboration

Boudnib, Errachidia, and Zagora. These data reveal a distinct pattern of aridity and high temperature variability, which is characteristic of the Moroccan oases under study. The figures demonstrate pronounced seasonality, with consistently elevated temperatures during the summer months (June to August). This is indicative of strong solar forcing and potentially low cloud cover across all three locations. Zagora exhibits the highest overall temperatures, which may be influenced by microclimatic factors related to topography or prevailing wind patterns. Precipitation patterns are characterised by sporadic events of varying intensity, which highlights the importance of convective rainfall and available underground water sources to sustain these arid ecosystems.

ON-THE-GROUND OBSERVATIONS

On-the-ground investigations were performed to examine the impact of climate change on the unique environment of the Drâa-Tafilalet oases. We visually assessed the complex interplay between rising temperatures, shifting rainfall patterns, and the local microclimate to ascertain the impact of these factors on date palm cultivation, water resources, and the overall resilience of these fragile ecosystems.



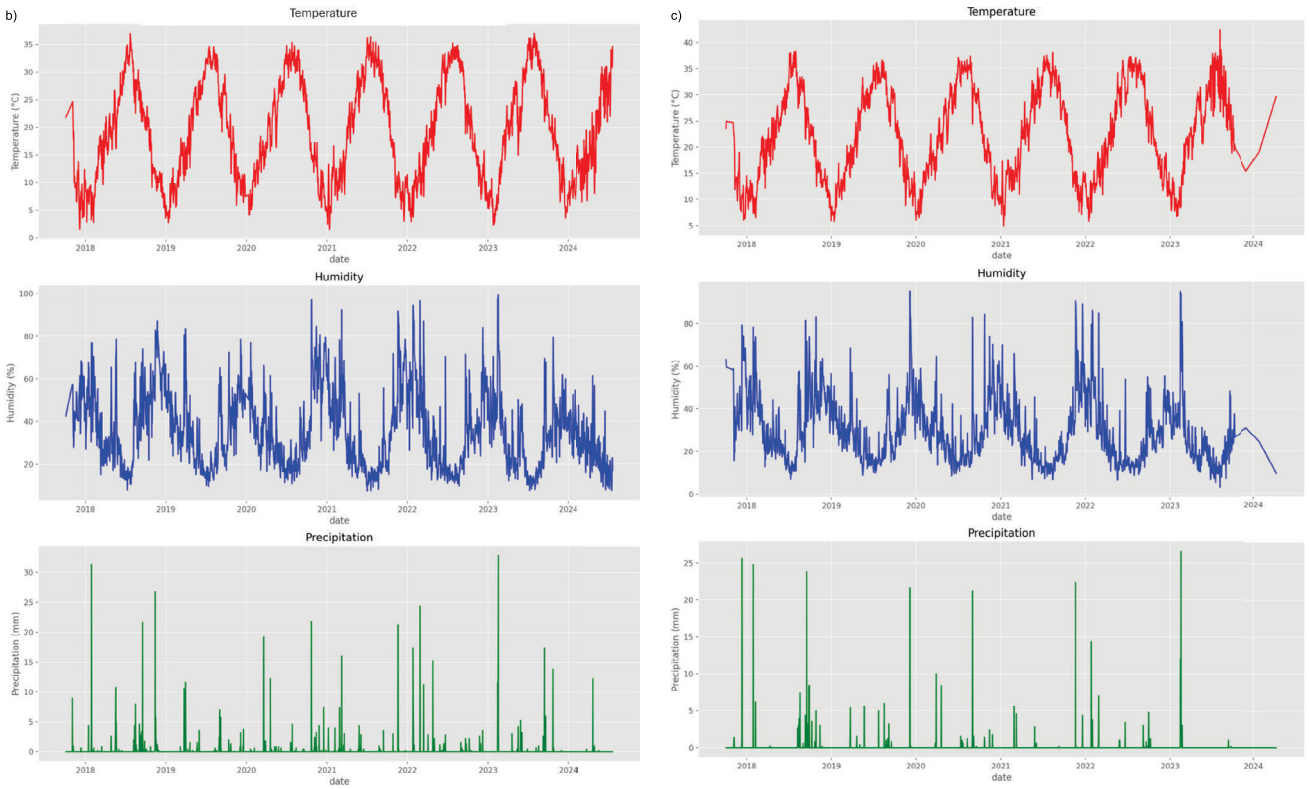


Fig. 2. Weather data from September 2021 to September 2024, including temperature, humidity, and precipitation for: a) Boudnib, b) Errachidia, c) Zagora; source: own elaboration

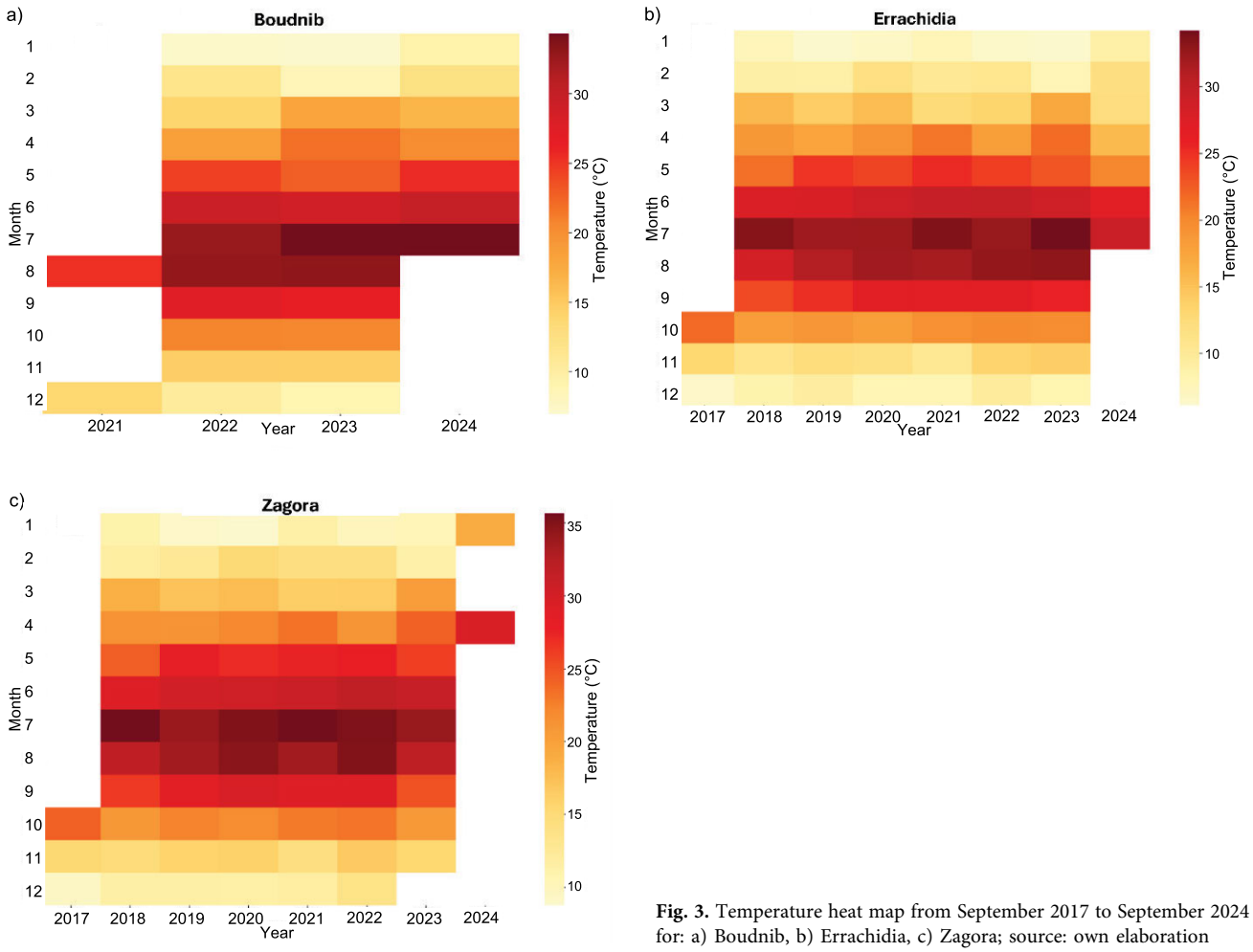


Fig. 3. Temperature heat map from September 2017 to September 2024 for: a) Boudnib, b) Errachidia, c) Zagora; source: own elaboration

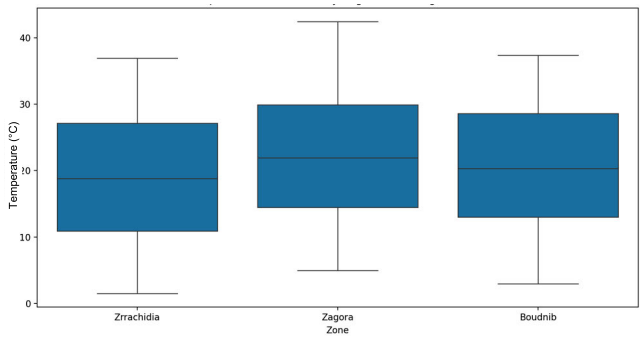


Fig. 4. The boxplot of the overall temperature comparison between the three locations of Errachidia, Zagora and Boudnib; source: own elaboration

FARMERS SURVEY

To complement the climate data analysis and field observations, we interviewed 120 date palm farmers in the three study oases using semi-structured interviews. To guarantee a variety of viewpoints and experiences within the Drâa-Tafilalet region, 40 farmers were randomly chosen from Boudnib, Errachidia, and Zagora oases each.

RESULTS AND DISCUSSION

GENERAL INFORMATION

Observed impacts of climate change on the Drâa-Tafilalet oases sustainability, will be presented in the following sections according to the prevalence and importance of each factor (temperature, rainfall, drought, wind) with a focus on the main key aspects of date palm tree vulnerability. In both approaches, the targeted questions and observations were focused, but not limited, on the main disorders that are endangering the sustainability and resilience of the Moroccan oases. During the discussion, we tried to go beyond these environmental factors by assessing their impact and relations with some inherent subfactors that may also be of importance in our context, even though not being comparable to those pointed out in this paper.

TEMPERATURE FLUCTUATIONS

Disruption of flowering synchronicity

Climate change is significantly impacting date palm cultivation in the Drâa-Tafilalet oases, primarily by disrupting natural flowering cycles due to rising and increasingly erratic temperatures. As temperatures increase, the delicate balance required for successful pollination and fruit production is severely disturbed, leading to substantial shifts in the timing and duration of flowering seasons. In the investigated area, current trends in extreme weather patterns include increasing temperatures, fewer consistently wet days, and more prolonged dry days each year. Rainfall patterns have shifted, and flowering now occurs approximately 40 days earlier (Ait-El-Mokhtar *et al.*, 2019). The warmer climate not only hinders pollination but also threatens the livelihoods of local communities that depend on date palm farming. Erratic rainfall patterns further complicate these challenges, making it difficult to maintain consistent fruit production (Tel-Zur and Keasar, 2020; Rayamajhi *et al.*, 2021; Ávila de *et al.*, 2022). Various waves of fruit-loading stages on a single tree are illustrated in Photo 1. Hence, initial opened flower blossoms occurred right at the full ripening stage of date fruits in late September. The visual juxtaposition of blossoms with ripened dates demonstrates the changes observed in the region, which is most possibly due to changing temperature patterns influencing and speeding up the typical timing for flowers/fruit load and possibly unbalanced ripening pattern. In the picture green flower clusters lately emerged, indicate late flowering. This phenomenon is conjugated to date ripening stage, affecting the overall yield.

Further research on date palm development helps to investigate the impacts of climate change on ripening patterns. A study on 'Deglet Nour' date palms in Biskra, Algeria, identified specific thermal requirements for various developmental stages, including spathe emergence and full ripening (Faci and Benziouche, 2021). Variability in cumulative temperature thresholds across palm groves highlights the sensitivity of date palms to thermal conditions throughout their life cycle. Similar impacts are evident in other species. Research conducted in the Cape Floristic Region in South Africa has revealed a significant shift towards earlier flowering due to rising temperatures. This shift, estimated at four days per degree Celsius increase, is consistent with trends observed in the northern hemisphere but is progressing at a faster pace in the southern hemisphere. The link between temperature rise and advanced flowering highlights the crucial role of temperature in influencing phenological changes (Williams, Schlichting and Holsinger, 2021).

Furthermore, studies focusing on Jacaranda trees have illustrated the intricate connection between temperature and

Photo 1. Date palm (*Phoenix dactylifera* L.) in the Drâa-Tafilalet oases, illustrating the impact of temperature pattern changes (phot.: *R. Meziani*)

flowering intensity. High solar exposure and temperatures preceding peak flowering have been identified as key factors impacting the intensity of blossoming. Interestingly, analysis of wavelength coherence has uncovered a synchronisation between rainfall, temperature, and solar exposure at specific temporal scales, indicating a time delay effect in how temperature and sunlight variations affect flowering intensity (Garcia-Rojas, Keatley and Roslan, 2022).

A survey of date palm farmers in the Drâa-Tafilalet oases further supports the evidence of disturbed flowering cycles, revealing a troubling pattern. Many farmers reported experiencing multiple blooming periods annually (Fig. 5). Typically, in this area, date palms bloom from March to April. However, the data suggests that early blooming may occur as early as February due to unusually high temperatures. Delays in blooming have also been observed in June and July. Furthermore, the appearance of new spathes in September, coinciding with the ripening phase of previous fruits, was reported by some farmers in both Errachidia and Zagora. This clearly demonstrates a dramatic shift in flowering patterns and strengthens the hypothesis that fluctuating temperatures significantly impact date palm phenology.

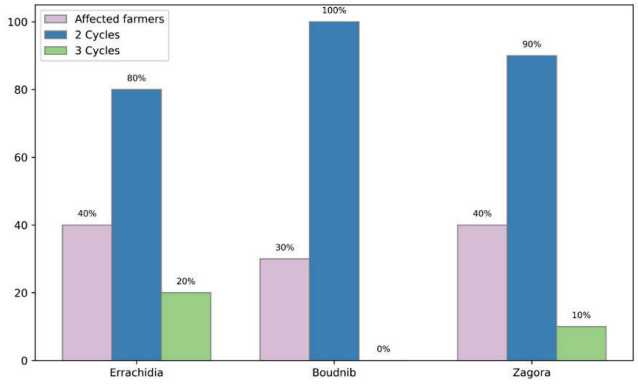


Fig. 5. Percentage of farmers affected by date palm flowering cycle disruptions and number of flowering cycles witnessed in their palm groves; source: own study

The complexity of plant responses to climate-induced temperature changes emphasises the importance of further research to understand how these fluctuations influence the phenology of date palms. By assessing the intricate relationship between temperature shifts and flowering synchrony, strategies can be devised to mitigate any negative impacts on date palm cultivation (Fitchett, Grab and Thompson, 2015; Piao *et al.*, 2019).

Reduction in fruit production

Climate change in the Drâa-Tafilalet oases has significantly affected date palm production, leading to a decline in fruit yields. Rising temperatures have disrupted the natural flowering cycles of date palms, resulting in reduced fruit output. Challenges in pollination caused by droughts contributed to lower fruit production. This not only interferes with the pollination process but also damages fruits and creates conditions conducive to pest infestations (Ait-El-Mokhtar *et al.*, 2019). Research indicates that temperature variations are key in this process. It has been noted that higher temperatures during flowering periods can lead to decreased productivity due to shorter blooming times and a reduced window for effective pollination, possibly due to dryness of the stigmas. This can impact the receptivity of the latter and fruit formation in date palms, ultimately leading to lower yields. The length of time that female inflorescences remain receptive is vital for successful pollination, underscoring the sensitivity of date palms to temperature shifts (Sedra, 2015; Wyver *et al.*, 2024).

Parthenocarpy, an asexual form of fruit development, has been frequently observed within the Drâa-Tafilalet oases date palm groves. While potentially producing a viable harvest, such instances do not typically yield fruit of sufficient quality for the market. This is further complicated by often uneven fruit loads across individual trees, creating additional challenges for agricultural productivity and potentially impacting the economic viability of date palm cultivation for local communities.

The survey of date palm farmers in the Drâa-Tafilalet oases revealed the extent of this challenge (Fig. 6). Interestingly, farmers employing proper production techniques, especially regarding fertilisation and protection of fruit bunches with Kraft paper, reported a lower incidence of parthenocarpy.

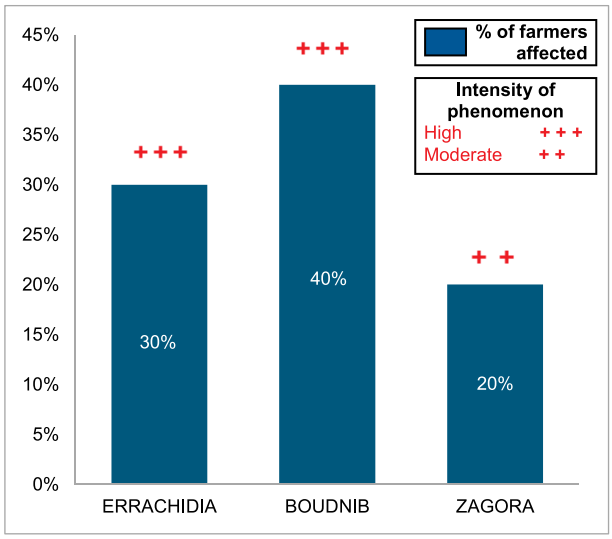


Fig. 6. Date palm growers' experiences with parthenocarpy fruit: prevalence and intensity; source: own study

A visual representation of these developing fruits, showcasing the parthenocarpy phenomena across all date ripening stages is provided in Photo 2. Small, green, immature and parthenocarpy fruits early in their development are demonstrated in Photo 2a. Slightly more developed, yet still parthenocarpy and green fruits are shown in Photo 2b. More mature, yellow-coloured parthenocarpy and seedless dates are depicted in Photo 2c. This phenomenon is potentially related to the unbalanced temperature patterns in the investigated area.

In conclusion, fluctuations in temperature driven by climate change pose a significant risk to the fruit production of date palms by limiting the timeframe for flower receptivity. The qualitative observations herein reported showed a decreased fruit size and quality due to climatic stressors, which provides strong indications of declining yields as being one of the main effect of climate stressors on date palm in the local oases. Understanding these effects is crucial for developing strategies to mitigate these impacts and safeguarding the health and productivity of date palm cultivation in the Drâa-Tafilalet oases.

Photo 2. Parthenocarpy phenomena in date across all ripening stages in the Drâa-Tafilalet palm groves: a) early immature green dates, b) advanced ripening stage of parthenocarpy dates, c) mature yellow aborted dates (phot.: *R. Meziani*)

Fires occurrence

The observed trends in these oases align with broader global patterns of climate change. Current trends in extreme weather are increasingly influenced by climate change, leading to significant alterations in temperature and precipitation patterns globally. Average global temperatures have risen markedly, with the last decade being the warmest on record. This increase has been particularly pronounced since the late 1970s, with extreme heat events becoming more frequent and intense. For instance, unusually hot summer days are now occurring three times more often than in the 1960s, and heat waves are lasting longer and becoming more severe (Robinson, 2021; Domeisen *et al.*, 2022). The scorching summer heat, which has become increasingly intense, is taking a devastating toll on date palm oases in Drâa-Tafilalet, igniting fires that threaten thousands of these trees (Photo 3). In Errachidia, for instance, between 2008 and 2010,

Photo 3. Aftermath of a date palm fire (phot.: *R. Meziani*)

fires claimed a staggering 2,485 date palms. The Aoufous commune saw even greater losses in 2019 when a fire destroyed more than 2,540 date palms and 1,500 olive trees. In the following years, in August 2021, a fire ravaged the same commune, consuming an estimated 5,500 date palms and nearly 200 olive trees across an area of 40 ha. These numbers describe a sobering situation, demonstrating the scale of destruction that a single fire can cause.

While the average fire affects roughly 0.6 ha and 75 date palms, these statistics only tell part of the story. Delayed interventions can escalate the damage exponentially. A striking example occurred in 2018, when 30 fires ravaged the province of Tata, burning a staggering 35,905 date palms, averaging over 1,197 palms per fire. A single fire in the Aguerd oasis on 9 July 2018, decimated an astonishing 19,500 date palms, scorching a vast 65 ha. These incidents underscore the critical need for rapid response and efficient fire suppression strategies to minimise the devastation. The sheer scale of these fires not only impacts the livelihoods of communities dependent on these oases, but also underscores the ecological and economic importance of these vital ecosystems. The devastation caused by these fires goes beyond the immediate loss of palm trees, impacting infrastructure, consuming resources, and adding further strain on already vulnerable communities.

RAINFALL PATTERNS

Hindrance of pollen germination and promotion of fungal diseases and fruit rot

Rainfall patterns have shifted significantly, resulting in fewer wet days and more dry days annually. While total annual precipitation has increased in some regions, areas like the southwest U.S. have experienced a decrease. The intensity of rainfall events has also increased, with a higher percentage of precipitation now falling during extreme single-day events. This variability contributes to both drought conditions and flooding, depending on the region (Konapala *et al.*, 2020; Wasko *et al.*, 2021). Observed rainfall patterns in the Drâa-Tafilalet oases are characterised by erratic and unbalanced distribution, hindering date palm pollen germination and reproductive success. Increased moisture during critical stages like pollen maturity and the pollination process, an atypical phenomenon historically, promotes fungal infections and fruit decay, directly impeding pollen germination and pollination. Higher humidity further exacerbates these issues by facilitating the spread of detrimental plant diseases, creating obstacles to pollination and seed production. This susceptibility to fungal diseases and fruit rot under wetter conditions is a growing concern for date palm farmers in the Drâa-Tafilalet region. A conducted survey revealed that a significant percentage of farmers have witnessed inflorescence rot within their groves (Fig. 7). This data underscores a critical point suggesting that farmers widely acknowledge that inflorescence rot and black scorch, alongside Bayoud disease, pose major threats under humid conditions. However, there's a clear lack of knowledge regarding appropriate treatment timings and the most effective active ingredients.

Current erratic rainfall patterns in the Drâa-Tafilalet oases increase the occurrence of unprecedented intense rainfall over short periods leading to localised flooding within the date palm grove, making Bayoud spores transportation across palm groves

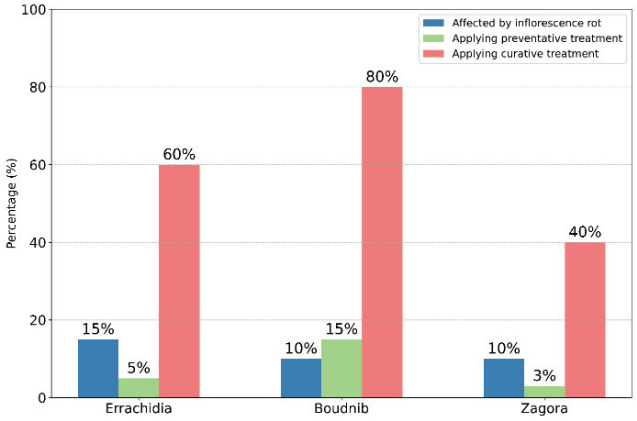


Fig. 7. Date palm inflorescence rot: prevalence (%) and treatment approaches employed by interviewed farmers across survey area; source: own study

in the area more important and frequent. Moreover, the increased rainfall creates temporary flooding that smallholders exploit to irrigate their date palms. This practice, while beneficial for immediate irrigation needs, poses a risk for the spread of this pathogen. Hence, the flooding water can carry Bayoud spores in date palm groves. The erratic rainfall not only facilitates the transportation of these spores but also increases their frequency of occurrence across palm groves.

The Bayoud disease, caused by the fungus *Fusarium oxysporum* f. sp. *albedinis*, poses a particularly significant threat to date palm trees. Originating in the late 19th century in Southern Morocco, it has devastated around 15 mln date palms in Morocco and Algeria alone. Despite containment efforts, the disease continues to spread rapidly, threatening not only the environment but also the livelihoods of communities reliant on these oases (Tantaoui *et al.*, 1996).

Bayoud disease manifests through leaf discolouration and necrosis, resulting in the deterioration and death of infected trees. It affects all commercial varieties of date palms, impacting both young shoots and mature trees. The precise mechanisms behind this disease remain unknown, highlighting the urgent need for further research (Gaceb-Terrak, 2011; Rabach *et al.*, 2022).

The profound impact of Bayoud on a date palm oasis is illustrated in Photo 4. The prevalence of desiccated, brown palm

Photo 4. Impact of Bayoud disease on a date palm oasis (phot.: *R. Meziani*)

trees visually represents the detrimental impact of the disease, particularly when exacerbated by climate change stressors such as drought and increased temperatures. The stark contrast between the few remaining green, healthy palms and the numerous dead or dying ones underscores the severity of the threat posed by Bayoud.

Flood risk

Floods are a primary environmental risk caused by climate change that impacts susceptible regions (Negese *et al.*, 2022). Research shows that the number and strength of floods have risen in various countries globally because of climate change and environmental damage (Karmaoui and Balica, 2021; Negese *et al.*, 2022). In Morocco, the Drâa-Tafilalet region faces a high risk of floods, as shown by severe events in the Souss and Upper Moulouya watersheds in recent decades (Bouaakkaz *et al.*, 2018). The flooding in the Drâa-Tafilalet oases in southern Morocco during the fall of 2024 has become an increasing concern for both the local residents and scientific experts. This area, known for its dry and semi-dry weather, has been especially susceptible to the effects of climate change, including more frequent and severe extreme weather events like flash floods (Zegait *et al.*, 2022; Hachem *et al.*, 2023). The delicate oasis ecosystems that have supported human communities in the region for centuries are in danger due to climatic changes and extreme events. It is anticipated that floods will occur more frequently in the future in this region because of the negative impacts of climate change (Zegait *et al.*, 2022). The impacts extend beyond harm to buildings and farms, presenting a significant danger to the survival of residents in the oases. To effectively deal with the flood threat in the Drâa-Tafilalet oases, it is crucial to conduct close monitoring on-site and thoroughly assess the area's hydrological features and weather patterns. The dramatic effect of the floods on the oases in Drâa-Tafilalet is illustrated in Photo 5. Floodwater filled with sediment is flooding date palm groves, which are crucial for the oasis ecosystem and economy. This picture emphasises the urgent importance of managing flood risks and putting in place protections for at-risk communities and their means of living.

Photo 5. Date palm groves in the Drâa-Tafilalet oases submerged by floodwaters following heavy rainfall in autumn 2024 (phot.: *H. Bouzelmate*)

WIND EFFECTS

Pollination disruption and fruit damage

The impact of changing climate conditions on date palms in Drâa-Tafilalet extends to pollination efficiency. Aside from temperature, the region has experienced increased wind speeds and altered wind patterns. The latter plays a significant role in influencing breeding patterns, as observed in tree swallow populations. Unfavourable wind patterns and dust storms can obstruct the success of the pollination process leading to unfertilised flowers (Zahiri *et al.*, 2023). Furthermore, the repercussions of reduced fruit production extend beyond agriculture; they pose severe economic risks to communities reliant on date palm cultivation. The cultural significance of date palms in these areas adds urgency to the situation, as traditional practices tied to palm production face threats from disrupted pollination caused by climate change.

Wind, however, exerts a multifaceted influence on date palm fruit development, extending beyond its impact on pollination and posing significant risks to the maturation process. One of the primary concerns is mechanical damage, where high winds can cause physical harm to fruit clusters by knocking them against the fronds or other structures, leading to bruising or premature dropping of fruits (Shirazi, Izadi and Khademi, 2008). This physical damage can result in a substantial loss of yield and compromise the overall quality of the dates. Furthermore, windbreaks can exacerbate water loss through increased evaporation from the soil and plant surfaces, potentially stressing the trees during critical growth periods. This stress can have a profound impact on fruit development and quality, as trees may divert energy from fruit production to cope with the environmental stress (Shirazi, Izadi and Khademi, 2008). Moreover, the combination of wind with other environmental stressors, such as high temperatures or low humidity, can compound negative effects on fruit quality, leading to issues like sunburn or uneven ripening. For instance, a study on citrus trees found that wind speeds above 15 $km \cdot h^{-1}$ can cause significant damage to fruit, resulting in a significant reduction in yield (Cataldo *et al.*, 2013). Similarly, research on kiwi trees revealed that wind-induced stress can lead to a substantial decrease in fruit quality (McAneney, Judd and Trought, 1984).

Beyond the direct effects of wind on fruit development, wind and dust also play a critical role in facilitating the spread of the date palm mite, *Oligonychus afrasiaticus*. These natural elements can carry mites over considerable distances, allowing them to invade new areas rapidly. Particularly during the fruit set and enlargement stages of the dates, when the trees are most vulnerable, these environmental conditions can lead to increased infestation rates (Larbi, Ali and M'hammed, 2021; Rafiqi *et al.*, 2022). The combination of climatic factors and the biological characteristic of the mite contributes to its ability to thrive in these settings, making it a persistent threat to date palm agriculture. Mite infestations can begin as early as the fruit set stage and continue throughout the fruit enlargement stage, coinciding with periods of heightened vulnerability for the palms (Photo 6).

This link between wind, dust, and mite proliferation is evident in the survey conducted across the Drâa-Tafilalet oases. A significant proportion of farmers in the Drâa-Tafilalet oases are grappling with mite infestations (Fig. 8). Importantly, most

Photo 6. Date palm mite damage on developing dates (phot.: *R. Meziani*)

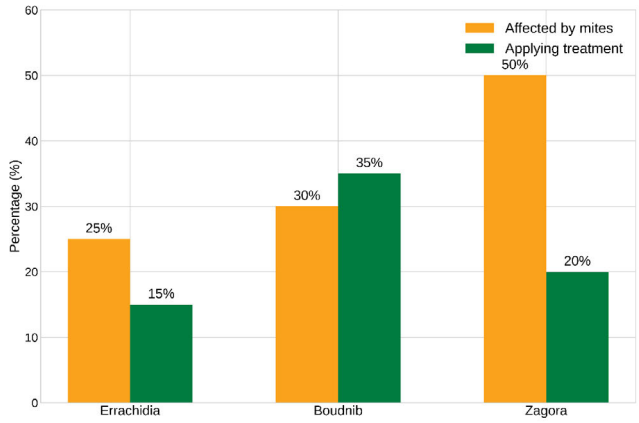


Fig. 8. Date palm mite: prevalence (%) and percentage of farmers using treatments in the survey area; source: own study

affected farms are situated in areas prone to strong winds and dust storms, highlighting the link between these environmental factors and mite proliferation.

Salinity

Changes in precipitation patterns, rising temperatures, and increased evaporation rates are leading to increasing salinity issues in the groundwater, threatening the sustainability of date palms in the Drâa-Tafilalet oases. The accumulation of soluble salts in the soil gradually degrades oases' soil quality. Soil salinisation further endangers date palm groves, as high salt concentrations can disrupt essential biological processes necessary for plant growth (Yaish and Kumar, 2015; Benslama *et al.*, 2020; Benaceur, Meziani and Jaiti, 2024). Indeed, high salinity levels disrupt osmoregulation in date palms, impairing water uptake and nutrient absorption. This biological disruption is critical as it affects photosynthesis, growth rates, and overall plant health (Yaish and Kumar, 2015). Consequently, the sustainability of date palm cultivation is at risk, which is particularly concerning given the economic and cultural significance of this crop in the region (Benslama *et al.*, 2020).

Date palms have evolved mechanisms to tolerate drought and moderate salinity; however, excessive salinity can severely reduce fruit productivity and viability of the trees. Research indicates that while some date palm varieties can withstand salinity levels up to 9 $dS \cdot m^{-1}$, prolonged exposure to high salt concentrations leads to detrimental effects on growth and development (Yaish and Kumar, 2015; Benslama *et al.*, 2020).

In certain oases, such as Rissani and Erfoud, the issue is compounded by the high salinity of irrigation water, often exceeding 12 $dS \cdot m^{-1}$ (Photo 7). While leaching is a viable solution for addressing soil salinity, date palm farmers encounter significant challenges in managing the salinity of irrigation water. Desalination units offer a potential solution, but the high cost and environmental impact of these units limit their widespread adoption. Consequently, in Moroccan date palm oases, the application of organic matter in the form of compost, manure, or humic acid, as well as certain amino acids during periods of stress, remains one of the most prevalent practices for enhancing the adaptability of date palm plants to saline stress.

Photo 7. Salinisation in a date palm oasis (phot.: *H. Bouzelmate*)

Interconnectedness of climatic factors

The interaction of various climatic elements such as temperature, rainfall, salinity, and wind play a significant role in shaping the phenology and physiology of date palms. Temperature variations can disrupt the synchronisation of flowering and influence fruit sets due to a reduced window for flower receptivity. The relationship between temperature and fruit trees is complex; they require exposure to both cool temperatures, and warm temperatures, for efficient biological activities.

Rainfall patterns also have a significant impact on date palm phenology. Excessive rainfall can hinder pollen germination during pollination and contribute to fungal diseases that cause fruit rot. Moreover, heavy rainfall can facilitate the spread of Bayoud disease, negatively affecting the health of date palms. Wind conditions can disrupt pollination efficiency and increase susceptibility to mite infestations in date palms. The negative effects of drought resulting from water scarcity limit water availability for proper growth and development, leading to decreased fruit yield and quality.

The impact of these climatic factors is not isolated but interconnected. For example, rising temperatures can lead to more frequent droughts, exacerbating the negative effects on fruit yield caused by limited water availability. Similarly, changes in rainfall patterns can influence wind behaviour, further impacting pollination efficiency. Understanding the interactions between

these climatic factors is essential for predicting their overall impact on date palm phenology.

In conclusion, understanding the interplay between temperature fluctuations, rainfall variations, wind influences, and drought effects is crucial for understanding how climate change impacts date palm phenology. By considering these interconnected climatic factors, researchers can devise more efficient strategies to mitigate the effects of climate change on date palms in the coming years.

pest management strategies can help reduce the consequences of climate change on date palm phenology. By adopting these approaches and continuously monitoring the effects of climate change on date palms, growers can ensure the ongoing health and productivity of this vital crop.

The illustration of the interplay between climate change impacts, mitigation strategies, and desired outcomes in date palm cultivation is provided in Figure 9.

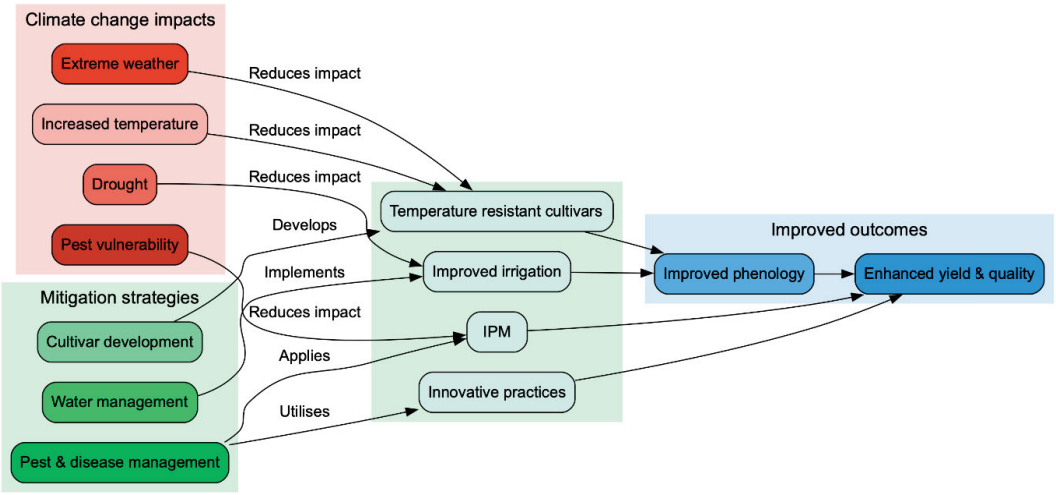


Fig. 9. Relationship between climate change impacts, mitigation strategies, and improved outcomes in date palm cultivation; IPM = integrated pest management; source: own study

Mitigation strategies

To alleviate the effects of climate change on date palms, various strategies can be implemented. One approach is to develop cultivars that are better adapted to changing climate conditions. By focusing on selecting cultivars based on their ability to respond positively to temperature fluctuations, growers can mitigate some of the negative impacts of climate change on date palm phenology.

Furthermore, adjusting irrigation practices is crucial for reducing the impact of drought on date palms. By carefully monitoring water usage, accurately calculating irrigation amounts, and ensuring proper fertilisation during fruit ripening stages, growers can help date palms withstand periods of water scarcity. Customising irrigation schedules to meet the specific needs of each cultivar can help maintain optimal fruit yield and quality even during drought conditions.

In addition, innovative date palm pollination techniques can significantly improve the vulnerability of this crucial process to climate-related events. Implementing integrated pest management strategies to address bioagressor invasions can further protect date palms from increased vulnerability due to climate change. By employing advanced machine learning models to predict these bioagressor infestations, growers can proactively monitor and predict potential threats and take proactive measures before significant damage occurs. Monitoring bioagressors and executing timely interventions, such as targeted spraying or biological control methods, allows growers to minimise date palm main bioagressors' impact.

In summary, a combination of selecting drought-resilient cultivars, improving irrigation practices, and adopting effective

Study limitation

This research offers important information on how climate change affects date palm farming in the Drâa-Tafilalet oases, but also recognises some constraints. Limiting the focus to just three main oasis locations restricts the ability to apply the findings to the whole region or other oases worldwide. The time frame, based on up-to-date climate information, might not account for the long-term historical changes and how ecosystems have adapted over time, even though it shows present patterns. More extensive research across larger areas and longer time frames, along with detailed examination of particular mitigation methods and how effective they are, is essential for improving our knowledge of climate change vulnerabilities and creating lasting solutions for these delicate ecosystems.

CONCLUSIONS

The effects of climate change on the date palm oasis are a challenging fact, impacting the multifaceted importance of this unique ecosystem. This study was aiming to investigate this concern in the Drâa-Tafilalet oases through a mixed-methods approach that combines on-the-ground observations, surveys and satellite data. Findings highlighted unprecedented effects of climate change on date palm tree resilience and sustainability. Increasing temperatures, unpredictable precipitation patterns, and extended drought periods disrupt the intricate ecological balance of the oasis ecosystem. A survey of 120 date palm farmers across three oases revealed the severity and interconnected nature of climate change impacts. Several farmers (30% in Boudnib,

40% in Errachidia and 40% in Zagora) observed multiple asynchronous flowering cycles per year, while parthenocarpy emerged as a significant concern, with prevalence ranging from 20% in Zagora to 40% in Boudnib. While 10–15% of farmers reported inflorescence rot, a concerning knowledge gap exists regarding effective preventative treatments, with only 3–15% of farmers employing them. Farmer surveys further revealed that wind-driven mite infestations pose a growing threat, with 50% of farmers in Zagora reporting significant issues. This reinforces that climate change is not just impacting date palms directly, but also exacerbating existing challenges, such as pest pressures. These findings underscore the urgent need for locally tailored adaptation strategies that address both ecological and socioeconomic challenges. It also emphasises the crucial importance of incorporating local knowledge and community engagement in the development and implementation of these strategies. The on-the-ground observations when combined with surveys and satellite data, ultimately seem crucial for understanding the current and future situation of palm oases in Morocco.

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CONFLICT OF INTERESTS

The authors declare that they have no conflicts of interest.

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