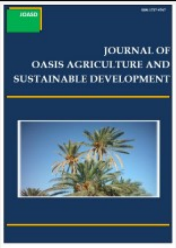

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Spatiotemporal dynamics of wild boar-induced crop damage in Southern Tunisian agroecosystems and the role of oasis characteristics

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Abstract

Wild boars (*Sus scrofa* Linnaeus, 1758) are increasingly affecting agroecosystems in arid regions, but their impact in oasis environments is not well known. This study investigates the crop damage caused by wild boars in the oasis systems of southern Tunisia, focusing on two different regions: Gabès (coastal) and Kébili (continental). We studied how location, season, vegetation, and farming practices influence damage in 17 oases, using chi-squared tests, log-linear models, and a Generalized Linear Mixed Model (GLMM). Wild boars were found in 57% of the sites, and crop damage occurred in 58% of the sites. Contrary to expectations, Damage patterns did not change significantly between seasons or regions. However, statistical models revealed strong associations between crop damage and specific human-related factors, including fertilization practices, distances to roads, and irrigation. In Kébili, damage decreased with distance from roads, increased with complex vegetation structure, was lower in fertilized fields, and taller palms reduced wild boar activity during summer by altering microclimates. These findings show that land-use has a major impact on wild boar interactions in oasis agroecosystems and point to the need for management plans that fit local conditions.

1. INTRODUCTION

Although wild boars are habitat generalists, they tend to prefer wetlands, streams, hardwoods, and dense vegetation, especially those offering shade and water, due to their limited ability to regulate body temperature (Mcllroy, 1989; Cooper & Sieckenius, 2016; Gray et al., 2020). The availability of such habitats strongly influences their home range size and movement patterns (Clontz et al., 2022). In recent decades, oasis agroecosystems have become increasingly attractive to wild boars, largely due to changes in land use and climate (Hajji & Zachos 2011; Ghandri et al., 2024). These systems now often provide water, shelter, and diverse food resources, mimicking natural habitats and drawing boars closer to human-managed landscapes (Hajji & Zachos 2011; Amici et al. 2012).

The oasis agroecosystems of southern Tunisia (Gabès, Kébili, Tozeur, and Gafsa) represent unique agricultural landscapes characterized by their layered vegetation structure combining date palms, fruit trees, vegetable crops and forage species (Elghoul et al., 2024). These oases are vital for local livelihoods, providing food security, employment and economic stability through high-value crops like Deglet Nour dates (Sghaier, 2010; Agnoletti et al., 2023) and diversified production of pomegranates, figs and vegetables (Santoro et al., 2020). Forage crops such as alfalfa additionally support small-scale livestock farming (Carpentier et al., 2017; Agnoletti et al., 2023). In these agroecosystems, farmers generally use organic fertilizers, including livestock manure (sheep, goats, and cattle) and poultry manure, which increase the abundance of soil fauna and change their community composition by altering nutrient availability (Raub et al., 2014; Miller et al., 2017). These invertebrates play an essential role in decomposing organic matter into mineral components beneficial for crop nutrition. Oasis management also includes irrigation, which is essential for growing cereals, alfalfa, vegetables, and date palms, the main crops in oasis agroecosystems. Taken together, these factors explain the attractiveness of oases for wild boars. In particular, wild boars rely on their keen sense of smell to locate food (Ditchkoff & Mayer, 2009), as much of their diet consists of underground food sources such as invertebrate larvae, small fossorial vertebrates, tubers, rhizomes, corms, and bulbs (Schley & Roper, 2003; Ditchkoff & Mayer, 2009; Canright et al., 2023).

These agroecosystems are increasingly exposed to both abiotic and biotic pressures. While abiotic stressors, such as extreme aridity (less than 100 mm of annual rainfall), soil salinization, and groundwater diminution, are well documented (Sghaier, 2010; World Bank, 2018; Besser et al., 2021), biotic disturbances remain comparatively understudied. However, recent studies show that wildlife, particularly wild boars (*Sus scrofa*), are increasingly affecting oasis agroecosystems, causing significant ecological and economic impacts having increasing ecological and economic impacts in oasis areas (Alary et al., 2022; Mrabet et al., 2024). Their rooting behavior not only disturbs soils but also damages irrigation systems and plant roots, particularly in date palms, vegetables, and cereals (Hammouda et al., 2021). In doing so, they compete with livestock for forage (Carpentier & Gana, 2017) and contribute to yield losses estimated at 20-40%, along with increased protection costs (Alary et al., 2019). Although their activity may occasionally enhance soil aeration and nutrient cycling, with some benefits to plant diversity (Barrios-Garcia et al., 2023), their overall impact remains largely detrimental (Barrios-Garcia & Ballari, 2012). Despite increasing evidence of wild boar presence in oasis agroecosystems and growing awareness of their ecological and economic impacts, the intensity and spatial variability of these damages remain insufficiently understood. Based on the agroecological diversity of Tunisian oases and the known behavior of *Sus scrofa*, we hypothesize that wild boar damage is shaped by a combination of environmental and anthropogenic factors. We expect damage levels to differ between the coastal oases of Gabès and the more continental oases of Kébili, the latter being closer to natural refuge areas and less affected by human activity. Seasonal peaks in damage are also anticipated during dry periods when irrigated crops become more attractive to wild boars. Among the key drivers, we consider oasis structure, irrigation, manure use, and proximity to roads, as well as landscape-level variables such as oasis surface, cropland and tree cover, distance to refuge areas, distance to roads, and distance to urban zones. We hypothesize that traditional, multi-layered oases with higher human presence experience less damage, while simplified, irrigated monocultures are more vulnerable. This study aims to identify the main factors influencing wild boar impact to guide targeted management strategies in these fragile agricultural systems.

2. MATERIAL AND METHODS

2.1. Study area

Our study focuses on two major oasis regions in southern Tunisia, representing the two principal oasis types: the coastal oases of Gabès and the continental (Saharan) oases of Kébili. Together, these areas represent both traditional and modern forms of oasis agriculture (Fig. 1). The Gabès oases (33°52’53’’N, 10°05’53’’E), located along the Gulf of Gabès, cover approximately 7,000–7,080 hectares and account for 13% of Tunisia's total oasis area. They are among the last remaining coastal oases in the Mediterranean basin and are ecologically and culturally unique (Abaab, 2012; Fayech & Tarhouni, 2020). These oases are predominantly traditional in structure, characterized by small-scale farms with a distinctive three-layer vertical vegetation: an upper canopy of dense date palms (>150 trees/ha), a mid-layer of fruit trees such as olives and pomegranates, and a lower layer of herbaceous plants including vegetables and fodder crops (Rhouma et al., 2021; Benmoussa et al., 2022). The region has a dry Mediterranean climate, with average yearly annual temperatures between 16 and 24°C and about 200 mm of rain, mostly falling in winter (Henia 1993; Jemai et al., 2017).

In contrast, the continental oases of Kébili (33°42’18’’N, 8°57’54’’E), situated in south-western Tunisia near Chott Jerid, span between 23,000 and 36,000 ha and constitute the largest share of the national oasis surface (67-77%)

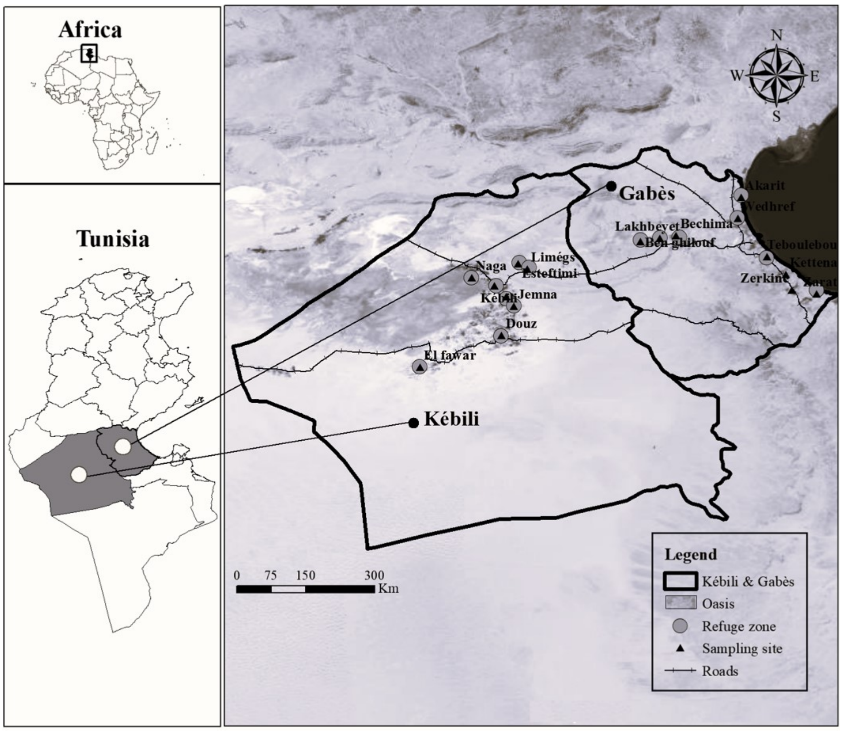

Fig. 1. Location of study area in the oases of Gabès and Kébili Governorates, including sampling sites of wild boar refuge zones.

(Sghaier, 2010; Ben Ahmed Zaag, 2017). These oases include both traditional systems, with diverse date palm varieties and fruit trees that support local livelihoods and biodiversity, and modern oases, which have expanded significantly since the 1990s. Modern oases are typically organized in large farms with lower palm tree densities (100-150 trees/ha) and simplified vegetation dominated by the Deglet Nour variety (Sghaier, 2010; Benmoussa et al., 2022). The climate of Kébili is markedly Saharan, with extreme temperatures that can reach 55°C in summer and drop to -7°C in winter (Ben Mohamed, 2003), while annual precipitation is scarce and irregular, averaging around 90 mm (Faiza et al., 2018). These environmental conditions, combined with differing agricultural practices, make Gabès and Kébili ideal case studies for examining how regional and structural variation in oasis systems influence patterns of crop damage.

2.2. Data collection

The data for this study were collected between March and October 2019 in the governorates (GOV) of Gabès and Kébili. In Gabès, we visited nine oases: Zarat, Zerkine, Kettena, Teboulbou, Akarit, Wedhref, Ben Ghilouf, Lakhbayet, and Bechima. In Kébili, we visited eight oases: Erhamet, Jemna, Douz, El Fawar, Kébili, Naga, Esteftimi, and Limégs (Fig. 1). The investigation was conducted across three seasons, spring, summer, and autumn, during which we visited all 17 randomly selected oases. At each location, we identified refuge areas or "hot spots" for wild boar, as designated by the regional services of the "Direction Generale des Forêts" (DGF). The locations of these refuge areas were georeferenced using a portable Garmin GPS (model GPSMAP 60CSx). For each refuge area, we explored three agricultural fields, varying in their distance from the refuge. The first field was the closest to the refuge area, followed by the second field at a greater distance, and the third field being the farthest. Surveys were performed by the same three-observer team (A. Ghandri, M. Jarray & A. Zaidi). Considering survey costs and sampling variability, we determined that a 100 m^2 sampling unit provides accurate and reliable information on the occurrence and abundance of wild boar in oasis agroecosystems. In each oasis, we conducted three sampling unit. Each unit was monitored during the day either in the morning or in the afternoon. Because direct observation of wild boars is difficult, observers focused their effort on identifying easily recognizable signs of presence, such as rooting, feeding traces, wallowing sites, and footprints. For each sampling unit, we assessed wild boar damage rather than mere presence. A site was classified as damaged (1) if visible signs such as rooting, trampling, or crop disturbance were observed. If no such signs were detected, the site was considered undamaged (0), regardless of whether wild boars or their presence indicators (e.g., tracks or droppings) were found. Within each sampling unit, observers also recorded field-specific variables, including the density of palm trees (DPA), the average height of date palms (HPA), and the density of fruit trees (DAF). Crops cover was characterized by the density of cereals, alfalfa, and vegetable crops, measured as the number of plants per 100 m^2. We used a composite variable called Cropland Cover (CLC) to represent overall crop density at each site. For each site and season, we added the densities of the three crop types. Then, we averaged these totals across the three seasons to obtain a single CLC value for each site. Observers also recorded irrigation (IRR) and the use of organic fertilizer (FUM) as categorical variables. Fields were categorized as "irrigated" or "non-irrigated", and as "manure applied" or "no manure applied" based on fertilizer use.

The collected data were then combined with information obtained from Google Earth imagery. This imagery was imported into QGIS software version 22.6 to measure the surface of the oasis (SUP), the surface area of the refuge zone (SZR), the distance to the refuge area (DZR), the distance to the urban area (DZU), and the distance to the nearest road (DRP). The governorate (GOV), season (SAI), and type of oasis (TYP) were treated as categorical variables. The governorate was divided into two categories: Gabès and Kébili. The season (SAI) was classified into three levels to capture seasonal variations that may affect wild animal activity and the state of the oasis agroecosystems. These three levels typically correspond to spring, summer and autumn. The type of oasis (TYP) was categorized into three levels based on the number of vegetation layers: TYP1 (oases with a single layer of palm trees), TYP2 (oases with two vegetation layers: upper layer + lower layer), and TYP3 (oases with three vegetation layers, including herb, shrub, and tree layers).

2.3. Data analyses

To assess the influence of region and season on damage occurrence, chi-squared tests of independence were performed to test associations between damage and region, and between damage and season. Hierarchical log-linear analysis was used to evaluate possible interactions between oasis type and season on damage presence.

We checked for multicollinearity among predictors (GOV, SAI, SUP, TYP, FUM, IRR, SZR, DZR, DZU, DRP, DAP, HPA, DAF, and CLC) using Pearson correlation tests. Strongly correlated predictors ($r>|0.7|$) were not included together in the model. After this preliminary screening, a Generalized Linear Mixed Model (GLMM) with a binomial error distribution and logit link function was conducted to evaluate the effects of the selected variables on damage occurrence (binary response: 1 = damage observed, 0 = no damage). The model included 153 observations and accounted for hierarchical data structure by incorporating season (SAI) and governorate (GOV) as random effects. All remaining explanatory variables were treated as fixed effects, and interactions between each of them and the random effects were also explored. The GLMM was implemented using the glmer function from the lme4 package in R (Bates et al., 2015), with fixed effect significance tested via Wald tests. Model performance was evaluated using Akaike's Information Criterion (AIC) and marginal and conditional R^2 values calculated with the MuMIn package. All statistical analysis were conducted using R software (version 4.3.2, R core Team, 2023), and a significance level of $\alpha = 0.05$ was applied.

3. RESULTS

3.1. General description of wild boar damage

Results revealed that wild boars were detected in 57% of observations across the oases of Gabès and Kébili, with signs of damage in 58% of the oases. The chi-squared tests showed no statistically significant association between damage occurrence and either region (Gabès vs. Kébili; $\chi^2 = 1.2357$, df = 1, $P = 0.2669$) or season (spring, summer, autumn, winter; $\chi^2 = 1.1812$, df = 2, $P = 0.554$) (Fig. 2). These results were further supported by the hierarchical log-linear analysis (Table 1), which revealed no significant interaction between oasis type (continental vs. coastal) and period (seasons) on the presence or absence of damage ($\chi^2 = 0.83$; df = 3; $P = 0.84$). Although some apparent differences were observed across combinations of season and oasis type, these were not statistically significant once the main effects were accounted for (Fig. 2). Together, these analyses suggest that damage occurrence is relatively consistent across both spacial and temporal scales, with no clear dependence on region or season.

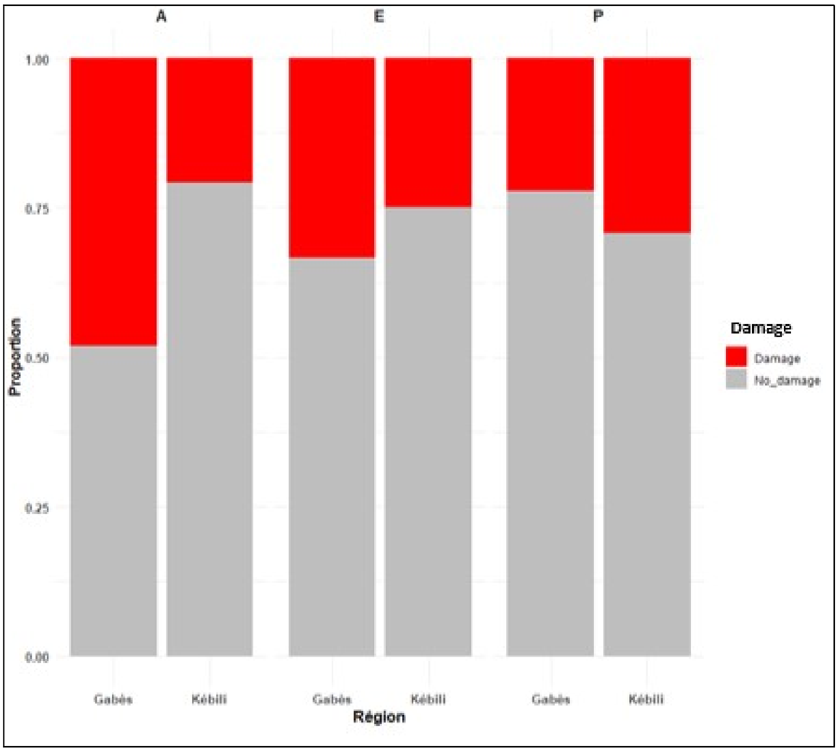

Fig. 2. Proportion of damage by region (Gabès and Kébili) and season (Spring (P), summer (E), and autumn (A).

Table 1. Hierarchical log-linear model comparisons assessing the effects of Damage (DAM), Season (SAI), and Governorate (GOV) on crop impact.

Comparison	Tested Hypothesis	Deviance	df	Δ Deviance	Δdf	*P*	Interpretation
Model 1 vs Model 2	DAM × SAI × GOV	5.895	4	5.895	4	0.207	Three-way interaction not significant.
Simple effects *vs* interactions	DAM × SAI and DAM × GOV	5.895	3	0.41	3	0.936	No significant interaction.
Without DAM ×SAI *vs* full model	DAM × SAI	2.717	4	2.717	4	0.606	Not significant.
Without DAM × GOV *vs* full model	Test of the DAM × GOV	6.86	4	6.86	4	0.143	Not significant, slight trend.
Independence model	Overall test of total independence	7.82	10	7.82	10	0.646	No significant dependence.

3.2. Multicollinearity and predictive modelling of crop damage

The collinearity matrix shows generally low correlations among the explanatory variables used in the GLM, with most values below ±0.5, indicating limited multicollinearity. However, a few notable exceptions exist, such as the strong positive correlation between GOV and DPA (r = 0.85) and moderate negative correlations between GOV and FUM (r = -0.62) and DAF (r = -0.58), suggesting potential l redundancy or confounding in models including these variables together.

The GLMM analysis, based on 153 observations (presence or absence of crop damage) and fitted with a binomial error distribution, achieved an AIC of 222.381, with a marginal R^2 of 0.576 and a conditional R^2 of 0.5257, indicating strong explanatory power and good model fit. The model identified three main predictors significantly associated with crop damage: manure application (FUM1) showed a significant positive effect (*P*= 0.0088), proximity to roads (DRP) had a strong positive effect (*P* = 0.0031), and irrigation (IRR1), displayed a moderate positive effect (*P* = 0.0459) (Table 2). Additionally, marginal effects were observed for oasis size (SUP) (*P* = 0.069) and for oasis structure (TYP2 and TYP3), which reflect variations between simplified and multi-layered

Table 2. Fixed effects estimate from the Generalized Linear Mixed Model (GLMM) of crop damage in oasis agroecosystems of southern Tunisia (AIC= 222.381, marginal R^2=0.576, conditional R^2=0.5257, significance codes: <0.0001 "***", 0.001 "**", 0.01 "*", 0.05 ".").

Predictors	Estimate	S.E.	Z	*P*	Significance
(Intercept)	-1.8111	0.9907	-1.828	0.06752	.
SUP	1.7706	0.9741	1.818	0.06910	.
DZR	-0.1016	0.4016	-0.253	0.80031	
TYP2	-2.4091	1.3040	-1.847	0.06468	.
TYP3	-3.2716	1.8532	-1.765	0.07749	.
FUM1	3.9385	1.5037	2.619	0.00881	**
IRR1	1.4061	0.7045	1.996	0.04594	*
DZU	0.0477	0.3635	0.131	0.89560	
DAF	0.7889	0.5585	1.413	0.15775	
CLC	-0.0087	0.0229	-0.382	0.70279	
HPA	-0.0588	0.5346	-0.110	0.91246	
DRP	2.9214	0.9887	2.955	0.00313	**
CLC*SAIE	0.0107	0.0326	0.327	0.74372	
CLC*SAIP	0.0100	0.0304	0.329	0.74189	
CLC*GOV2	-0.0152	0.0546	-0.279	0.78015	
DAF*SAIE	-0.7787	0.6726	-1.158	0.24693	
DAF*SAIP	0.1147	0.7145	0.161	0.87241	
DAF*GOV2	-1.6747	1.6960	-0.987	0.32341	
SUP*SAIE	-0.1287	0.5604	-0.230	0.81832	
SUP*SAIP	0.3254	0.5899	0.552	0.58121	
SUP*GOV2	-1.1462	0.9622	-1.191	0.23360	
DZR*SAIE	0.2788	0.5815	0.479	0.63167	
DZR*SAIP	-0.1307	0.5391	-0.242	0.80846	
DZR*GOV2	-0.1439	0.4752	-0.303	0.76207	
TYP2*SAIE	0.1518	1.580279	0.096	0.92344	
TYP3*SAIE	2.4935	1.9507	1.278	0.20115	
TYP2*SAIP	0.5217	1.2776	0.408	0.68301	
TYP3*SAIP	1.8011	1.8296	0.984	0.32488	
TYP2*GOV2	2.5608	1.3978	1.832	0.06695	.
TYP3*GOV2	1.6768	1.6051	1.045	0.29616	
FUM1*SAIE	-0.7381	1.3065	-0.565	0.57210	
FUM1*SAIP	-0.3606	1.2023	-0.300	0.76425	
FUM1*GOV2	-2.8282	1.6118	-1.755	0.07931	.
HPA*SAIE	-1.3266	0.7275	-1.823	0.06824	.
HPA*SAIP	0.0209	0.5858	0.036	0.97157	
HPA*GOV2	0.0723	0.6510	0.111	0.91157	
DRP*SAIE	0.0214	0.6246	0.034	0.97269	
DRP*SAIP	0.7004	0.6836	1.025	0.30557	
DRP*GOV2	-2.6789	1.0535	-2.543	0.01099	*

vegetation systems.

Although the model included random effects for season (SAI) and governorate (GOV), their variances were negligible, indicating that most of the variability was explained by the fixed effects explained most of the variability. Manure application in Gabès (FUM1), and (DRP) were significantly and positively associated with damage. Irrigation in Gabès (IRR1) showed a positive but less pronounced effect. Oasis size (SUP) and multi-layered oases (two- and three-layer structures (TYP2 and TYP3) showed marginal effects on damage occurrence. The other factors did not show any significant effect.

Some interaction effects showed that the impact of certain factors depends on the context. For example, the interaction between DRP and governance unit GOV2 (DRP*GOV2) was negative and significant ($P < 0.05$). This indicates that in areas managed in Kébili, being close to a road had less effect on damage risk. Other interactions, notably those involving two-layer structure (TYP2), manure application (FUM1), average palm height (HPA) and grouping variables (SAI and GOV) namely TYP2*GOV2, FUM1*GOV2, and HPA*SAIE, Showed marginal significance (Table 2).

4. DISCUSSION

Our study focused on crop damage caused by wild boars in the oasis agroecosystems of southern Tunisia, assessing the influence of spatiotemporal context, landscape structure, and management practices. Contrary to what we thought, we found no significant differences in damage between regions (Gabès vs. Kébili) or seasons, challenging common assumptions about the spatiotemporal variation in wildlife impacts. This lack of variation contrasts with findings from temperate regions such as Poland and Luxembourg (Schley et al., 2008; Bobek et al., 2017), where wild boar activity and crop damage tend to fluctuate seasonally in response to food availability, reproduction cycles, and climate conditions, typically increasing in spring and summer when vegetation is abundant and energy demands are higher (Barrios-García & Ballari, 2012). Similarly, in fragmented European landscapes, crop damage is frequently linked to forest proximity and crop type (Morelle & Lejeune, 2015; Bobek et al., 2017), patterns that were not evident in our study system. The lack of a significant effect of spatiotemporal context remains unclear, despite the ecological differences between the coastal oases of Gabès and the Saharan oases of Kébili, and the climatic variation across the three monitored seasons (Ben Mohamed, 2003; Jemai et al., 2017; Allouche et al., 2018). One possible explanation for this lack of spatiotemporal variation in wild damage is that oasis agroecosystems provide stable and predictable resources throughout the year and across regions, a pattern also observed by Lombardini et al., (2017) in Sardinia, Italy. This aligns with other findings from arid or Mediterranean settings where summer irrigation and perennial vegetation layers, including date palms and vegetables, ensure continuous forage availability (Rhouma et al., 2021; Benmoussa et al., 2022). Indeed, seasonal patterns in crop damage are well documented in temperate agroecosystems, often linked to crop phenology, such as seedling-stage maize in the United States (Boyce et al., 2020), or to natural food sources such as mast (Schley et al., 2008).

In contrast, our results showed a strong impact of human-made landscape features on crop damage. This is consistent with findings from Sardinia, where damage peaked near sheltered, irrigated agricultural patches, and supports the idea that in dryland systems, artificial structures and land-use practices may replace natural habitat features as key determinants of wild boar distribution (Lombardini et al., 2017). The relationship between livestock manure use and crop damage by wild boar is often positive, and there are several ecological and behavioral explanations for this. The attractiveness of fertilized plots could be explained by several ecological and behavioral factors. The use of livestock manure improves soil quality, which helps plants grow better, increases nutritional value, and leads to greater root biomass (Zhang et al., 2006; Dhaliwal et al., 2022; Liu et al., 2025). These conditions can make crops more attractive to wild boars. In addition, fertilized soils tend to be softer and easier to dig, facilitating the natural rooting behavior of wild boars, especially as they search for nutrients-rich roots rhizomes, tubers, bulbs, and inverterbrates (Schley & Roper 2003; Ditchkoff & Mayer, 2009; Canright et al., 2023). Invertebrates including microarthropods, earthworms, in particular, are often more abundant in manured soils (Kautz et al., 2006; Viketoft et al., 2021; Seleem et al., 2022; Zhu et al., 2023). In addition, the strong organic odors released by notable fresh manure may serve as olfactory cues detectable from a distance, especially given that wild boars have and advanced olfactory ability (Paudel et al., 2015).

Altogether, these factors make fertilized plots particularly attractive and more vulnerable to damage.

Results showed a positively association between the distance to the main roads and wild boar damages. This finding is consistent with previous study suggesting that boar damage tends to occur closer to roads (Tamura et al. 2024), where roads are thought to facilitate movement, foraging, and scent-marking by providing flat, open surfaces, especially in depopulated regions with otherwise restrictive vegetation or terrain (Stillfried et al., 2017a; Ghandri et al., 2024). Roads can also offer wild boars easy access to energy-rich crops (Keuling et al., 2010; Thurfjell et al., 2015). However, in our results the pattern was reversed, differing from previous studies indicating that damage tended to be larger in areas away from roads (Park & Lee, 2003; Honda & Sugita, 2007; Karami & Tavakoli, 2022; Ding et al., 2023). These studies consider the distance to roads as a proxy for the intensity of human disturbance, wild boars tend to avoid anthropogenic features such as roads, settlements, and trails. As a result, the extent of crop damage in these areas was generally reduced. Interestingly, Lombardini et al. (2017) suggested that the distance from primary roads had lower importance and an uncertain effect. In arid agroecosystems like ours, roads may serve as essential movement corridors between key resources such as water and food, particularly under water-limited conditions (Ghandri et al., 2024). This highlights the complexity of road effects in dryland settings, where the trade-offs between disturbance and accessibility vary across landscapes.

Regarding irrigation, our results indicate that the association between irrigation and wild boar damage is positive but less pronounced effect than manure application and distance to main roads on crop damage. This finding suggests that irrigation can locally enhance habitat attractiveness for wild boars. Irrigation promotes dense and diverse vegetation growth, creating resource-rich environments that support frequent boar visits and concentrated foraging activity (Karami & Tavakoli, 2022). This aligns with findings from other arid or Mediterranean landscapes where artificial water availability increases wildlife pressure on crops (Lombardini et al., 2017). Beyond its role in attracting wild boars, irrigation also contributes to ecosystem functioning by maintaining soil moisture and stabilizing plant cover. These conditions may enhance the long-term resilience of oasis agroecosystems, helping them buffer against disturbances, including those caused by wildlife (Elmqvist et al., 2003; Houssni et al., 2023). This dual effect, enhancing both resource attractiveness and ecosystem stability, highlights the need for regionally adapted management strategies that take into account both the benefits and potential trade-offs of irrigation in human-wildlife interactions.

In addition to irrigation, the availability of nearby water resources and shelter further contributes to the attractiveness of oasis habitats. The presence of water and vegetated areas around oases provides refuge from extreme temperatures and predators (Ghandri et al., 2024). Water availability plays a critical role in shaping wild boar distribution, particularly in arid environments, due to the species' limited physiological capacity to cope with heat stress (Cordeiro et al., 2018). In addition, moist soils and sediments near water sources support invertebrate populations, providing favorable foraging opportunities (Genov et al., 2017). These factors may explain the concentration of wild boar activity in irrigated or water-adjacent zones. While some studies such as Milda et al., (2023) report no clear relationship between proximity to water and damage, others, like Eshtiaghi et al. (2024) and Karami & Tavakoli (2022), found that greater distances from rivers are associated with reduced crop damage, reinforcing the importance of water as a determinant of wild boar impacts in dryland agroecosystems.

Although region and season showed no significant main effects on wild boar damage, several interaction terms revealed more nuanced patterns. Notably, the interaction between distance to roads and region showed a significant negative effect on damage in Kébili, indicating that crop damage decreased with increasing distance from roads. This suggests that, in this region, wild boars may avoid areas near roads, possibly due to higher disturbance or lower cover, unlike in other contexts where roads facilitate movement and foraging (Keuling et al., 2010; Stillfried et al., 2017a). These findings underline the importance of accounting for regional landscape features when assessing and managing wildlife damage. In addition to this significant interaction, we also found marginal interaction effects that suggest potential patterns. The positive interaction

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between three-layer vegetation structure and Kébili suggests that structurally complex oases in this region may offer more cover or food resources, thereby increasing damage levels food availability (Branco et al., 2019; Yang et al. 2024). In contrast, the negative interaction between manure use (FUM1) and kébili (GOV2) indicates that the attractiveness of fertilized fields may be less pronounced in this region, potentially due to differing agricultural practices or landscape configurations. Additionally, the negative interaction between palm height (HPA) and the summer season (SAIE) suggests that taller palms may provide shade or modify the microclimate in ways that reduce wild boar activity during hotter months.

5. CONCLUSION

This study shows that wild boar damage in oasis farming areas is caused by a mix of factors such as use of manure, irrigation, distance to roads, palm height, and some seasonal and regional conditions. Even though region and season alone did not have strong effects, their interaction with other factors did matter. This means that damage is often linked to local land use and how farms are managed. In arid areas, unlike in temperate zones where farmers use methods based on crop stages (like barriers before planting), it is more useful to focus on permanent features like water sources, field layout, and fertilizer use. Managing these factors may help reduce damage more effectively. However, our study has some limits. We did not include data on wild boar behavior or activity at different times of the day. More detailed research is needed, including things like moon phases, daily routines, and crop rotation, to better predict when and where damage will happen. Using local knowledge and better field monitoring could also help farmers take quicker action.

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