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Combined Effects of Climate and Pests on Fig (*Ficus carica* L.) Yield in a Mediterranean Region: Implications for Sustainable Agricultural Strategies

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Abstract: Fig cultivation has long been an agricultural tradition in the Mediterranean region, providing economic and social benefits to local communities. Understanding fig tree yield response to the rapid invasions of fig pests and shifts in climatic conditions is essential for developing appropriate sustainable agricultural strategies. In this context, we investigate whether rapid changes in climate and pest invasions have had a combined effect on fig (*Ficus carica* L.) tree yield. We used data collected over 10 years in Bejaïa province, Algeria, and conducted a regression analysis to investigate the relationship between fig tree yield and two key factors. Results revealed a significant warming trend (0.057 °C yr^{-1}), and a decrease in precipitation (-27.1 mm yr^{-1}), in the region. Multiple pests, including pathogenic fungi (*Diaporthe cinerascens, Fusarium* spp.) and ravaging bark beetles (*Hypocryphalus scabricollis*), have spread in the region. Fig tree yield declined by 25% during the study period and was affected by both factors. Our findings provide valuable insights that can aid farmers and practitioners in mitigating risks that arise from the combined effects of climate change and pest invasions, thereby promoting sustainable farming practices.

Keywords: climate change; pest invasions; fig orchards; *Hypocryphalus scabricollis*; *Diaporthe cinerascens*; Algeria; Bejaïa province; sustainable farming

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1. Introduction

Achieving sustainable agricultural production while serving a growing human population is a central topic in the 21st century [1–3]. To accomplish this objective, it is vital to develop strategies that optimize crop yield without expanding the total agricultural area at the cost of natural habitats and biodiversity [4]. In this regard, understanding environmental drivers that determine crop yield is essential in decreasing yield gaps (i.e., differences between actual and potential yields) in existing agricultural areas [5,6]. It is well-known that crop yield is influenced by many environmental factors, especially variations in climatic conditions and the prevalence of pests [7–9]. The individual effects of climate change and pests on crop yields have been extensively studied [10–12], but the combined effects of these factors on crop yield are still not fully understood. Given recent rapid climate change and the increasing incidence of pest invasion, comprehending the impact of these factors on the dynamics of crop yield is crucial in developing targeted policies and measures to improve crop productivity at the regional or national level [13–15].

Climate change has become a real concern for agriculture worldwide due to the rapid shifts in temperatures and precipitation, and the increased frequency of extreme weather events [16,17]. In the Mediterranean region, where the climate is characterized by seasonal and year-to-year fluctuations, air temperature is expected to increase 25% faster than the average increase worldwide in the future; summer, in particular, is expected to warm up at a rate 40% faster than the global average [18,19]. Reduced precipitation in many dry Mediterranean regions has been recorded [20–22], and future projections suggest that drought will increase in intensity and duration. Thus, changes in climatic conditions are expected to have major direct and indirect effects on crops, reducing yield and threatening food security [23].

Agricultural pest outbreaks often have substantial repercussions for agro-ecosystems and their productivity [24,25]. Crops can be damaged by an array of pathogens, including bacteria [26], viruses [27], helminths [28], and many fungi and oomycetes [29]. In addition, some groups of arthropods, especially defoliators and borers, can damage the entire plant and facilitate the transmission of plant disease [30,31]. In the Mediterranean region, studies have reported the invasion of new pests causing multiple outbreaks with severe socioeconomic impacts [32–35]. Studies have argued that recent pest outbreaks were fostered by climate change [36–38], which suggests that future scenarios of climate warming might exacerbate the number of outbreaks on crop fields [38]. Therefore, understanding how agro-ecosystems are influenced by the combined impacts of abiotic and biotic stressors is vital for maintaining food security and nutrition.

The common fig (*Ficus carica* L.) is one of the oldest cultivated trees worldwide. Native to the Middle East, it was domesticated in the Mediterranean region, where it was among the first crops to be cultivated in association with grape and olive trees, marking the beginning of horticulture in this region [39]. *F. carica* L. cultivation has expanded mostly due to its adaptability to different environmental conditions, as well as the economic importance of its fruit, which provides an excellent source of nutrients and antioxidants [40–42]. Fig trees are mostly cultivated in the Mediterranean region; more than 70% of the world's fig production occurs in this region [43]. A combination of arthropod pests and plant diseases has increasingly affected fig fruit production in recent times; this trend has altered ecological and economic sustainability threatening the livelihoods of a large number of farmers worldwide [32,33,44]. Studies on the impact of abiotic and biotic factors on fig orchards have been carried out in different Mediterranean regions; however, North Africa in general, and Algeria in particular, still lack fundamental studies on this research field, despite the vast area covered by fig orchards, and the local socioeconomic and cultural importance of this crop.

This study aimed to determine whether climate change and pest invasion affect fig tree yield in Northeast Algeria (Bejaïa province), where figs are renowned to be of high quality at both the national and international level. We specifically investigated: (1) changes in climatic conditions (annual temperature and precipitation) during the last decade; (2) pest invasions in the Bejaïa region using records of regular surveys carried out by Agriculture Services Department of Bejaïa province (ASD), and; (3) the relationship between climate change and the number of pests, and their combined impacts on fig tree yield. This study is timely given the socioeconomic and cultural importance of this crop to the region, and its potential vulnerability to rapid climate change and pest invasions.

2. Materials and Methods

2.1. Study Area

The study was carried out in Bejaïa province, located in the northeastern area of Algeria (36°43′ N, 5°04′ E) and 220 km east of the capital Algiers. Bejaïa has an area of 3268 km^2, divided into 52 communes that vary in altitude and climate (Figure 1A,B, Supplementary data Figure S1). The province is dominated by mountainous massifs on 75% of its surface, which are drained by Soummam River. The climate is typically Mediterranean, which is defined by mild and humid winters alternating with hot and dry summers (Supplementary data Figure S2). The rainy season period runs from October to May, and a dry season period runs from June to September. Studies have shown that climate change has, and will likely continue, to exacerbate warming and drought in the region [45], threatening the sustainability of local agriculture [46].

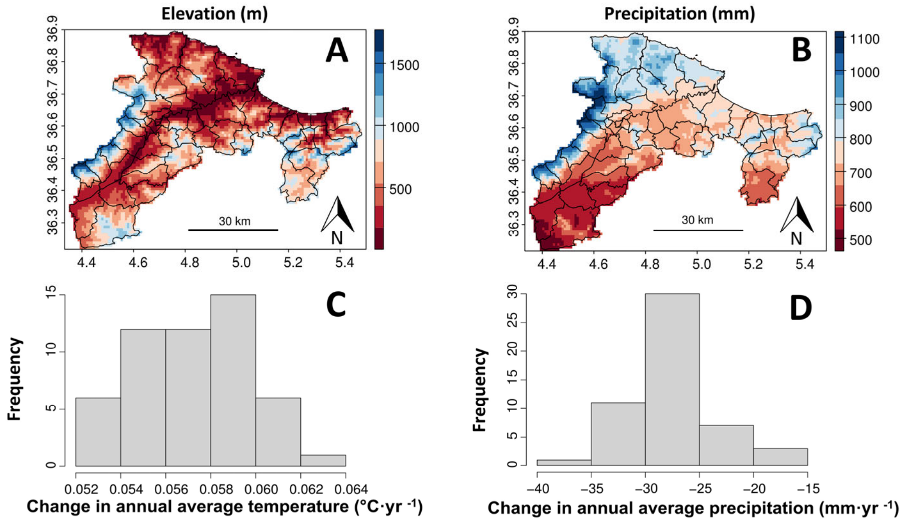

Figure 1. Elevation (**A**), precipitation (**B**), change in annual average temperature (**C**), and change in annual precipitation (**D**) in Bejaïa province, Northern Algeria.

Bejaïa province is primarily agricultural, with a large area of 130,348 ha dedicated to growing a variety of crops, including fruits, cereals, and legumes. Agriculture is an ancestral activity in the region because of its lasting economic value for the local population. Among the various crops grown in Bejaïa, fig cultivation is particularly important, occupying a vast area of 8800 ha with a thriving fig tree population of 823,118 (Supplementary data Table S1). Furthermore, figs produced in Beni Maouche (in the southwestern area of the province) and 10 other communes of the region, gained recognition in the national and international market after receiving a Geographical Indication (GI) label in 2016 [47]. A recent survey conducted by ASD identified the presence of 15 fig cultivars grown in Bejaïa. Among these cultivars, Taamriout, Aberkane, and Azenjar were found to be the most dominant in the region.

2.2. Fig Yield and Pest Occurrence Data

The fig yield dataset was obtained from the Agricultural Services Department of Bejaïa province (ASD) through surveys conducted at the commune level by statistical service agents. The bureau provided annual data on the number of fig trees harvested, surface area cultivated and producing, fresh and dried fig production, and yield per surface area and per tree, for each commune from 2011 to 2020. Datasets provided by the ASD are reviewed by the Ministry of Agriculture and Rural Development's Information Systems, Statistics and Forecasting Department; this organization ensures the quality of the data by implementing various quality control procedures [48].

Data on the annual occurrence of pests in the 52 communes of Bejaïa province for 2011–2022 were collected from the ASD, through an investigation conducted by the Phytosanitary Services in collaboration with the Regional Station of Plant Protection (RSPP) in Tizi Ouzou province, and the National Institute of Plant Protection (NIPP) in Algiers province.

2.3. Climate Data

Climate data including monthly temperature and precipitation (min, max, and mean) from 2010 to 2018 were obtained from WorldClim with 1 km resolution (www.worldclim.org (accessed on 7 December 2022)); this data source is used extensively by researchers in different fields, such as agricultural and ecological sciences, bioclimatic modelling, and eco-hydrology [49–51]. The global data for minimum and maximum monthly and annual precipitation were downloaded as raster files, and then used to extract the average values for each of the 52 communes in Bejaïa province.

To characterize the climate of the region and its spatial variation, WorldClim version 2.1 data were used to calculate the mean annual temperature and annual precipitation for a 30-year period (1970–2000). To determine the historical change in climate, historical monthly weather data for 1960–2018 were obtained from WorldClim [52], and used to calculate the annual values for temperature and precipitation. The spatial resolution of the data was 2.5 min (~21 km^2). The variables used in this study were annual average minimum temperature (°C), average maximum temperature (°C), and total precipitation (mm).

2.4. Statistical Analyses

All statistical analyses were carried out using R 4.2.1 [53]. Before performing our modeling, the data structured into communes were checked for spatial autocorrelation using a Moran test in the package ape [54]. The geographic coordinates of the centroid of each commune were used to build a Euclidean distance matrix. To plot maps and calculate the average annual values of temperature and precipitation based on monthly values, terra [55] and sf [56] packages were used. To determine whether there was a temporal trend in climatic conditions, two linear models were carried out: one model regressed annual average temperature against years (2010–2018), while another regressed annual precipitation against years (2010–2018). The correlation of covariates, such as between annual average temperature and annual precipitation, was verified to avoid collinearity in the used models. To determine whether the total number of pests showed a temporal pattern and was correlated with environmental variables, a negative binomial model using the MASS package [57]) was used; this model included the total number of pests as a response variable, and year and precipitation as explanatory variables. To determine whether fig yield was correlated with years, precipitation, and the total number of pests, a linear model was carried out; this model included yield as a response variable, and year, precipitation, and the total number of pests as explanatory variables. We verified the significance of interactions between covariates in all models with more than one covariate. Non-significant interactions were excluded. Values are mean ± SD.

3. Results

3.1. Spatiotemporal Change in Climate

The annual average temperature across the 52 communes had an average of 16.2 ± 1.1 °C, and varied between 13.2 °C and 18.2 °C (Supplementary data Table S1). This thermal variability is associated with an elevational variability, with a minimum of 127 m and a maximum of 1121 m (Figure 1A). Annual precipitation varied between 541.2 mm and 1000 mm, showing an overall average of 740.7 ± 97.0 mm (Figure 1B). There was a significant warming of the region between 2010 and 2018 (Figure 1C). Annual average temperature for the 52 communes increased on average by 0.057 ± 0.002 °C yr^{-1} with a minimum slope of 0.052 °C yr^{-1} and a maximum of 0.064 °C yr^{-1} (Figure 1C). We recorded a significant decline in annual precipitation between 2010 and 2018 (Figure 1D). Annual precipitation decreased on average across the 52 communes by −27.1 ± 3.94 mm yr^{-1}, with a minimum slope of −38.8 mm yr^{-1} and a maximum of −17.9 mm yr^{-1}.

3.2. Spatiotemporal Change in Pest Occurrence

A total of 11 pest species were identified for the figs between 2010 and 2022, including three fungi (*Diaporthe cinerascens*, *Neocosmospora solani* and *Fusarium* sp.), one nematode (*Paratylenchus* sp.), and seven insects (beetles: *Hypoborus ficus*, *Niphona picticornis*, *Scobicia chevrieri*, *Sinoxylon sexdentatum*, *Hypocryphalus scabricollis*, *Lagria viridipennis*, and *Trichoferus fasciculatus*). *D. cinerascens, N. solani and Fusarium* spp. are fungal pathogens that can cause significant stress to fig trees by infecting them through different types of wounds, such as pruning cuts, sunburn, insect wounds, cracks in the tree crotch, and freezing injuries. These infections can cause crown and root rot, stem cankers, fruit rot, and twig dieback diseases, which can lead to reduced yield, reduced tree vigor, and in severe cases, the death of the tree [58–60]. *Paratylenchus* spp. are nematodes that feed on the roots of fig trees, leading to reduced growth, and wilting branches [61]. Of the beetle species, two are ravaging bark beetles (*H. ficus* and *H. scabricollis*) that feed on the inner bark layer of the fig tree during their larval stage, compromising its health and leading to its death (Figure 2). The other five beetle species are mostly found feeding and developing in dead or dried fig branches [62].

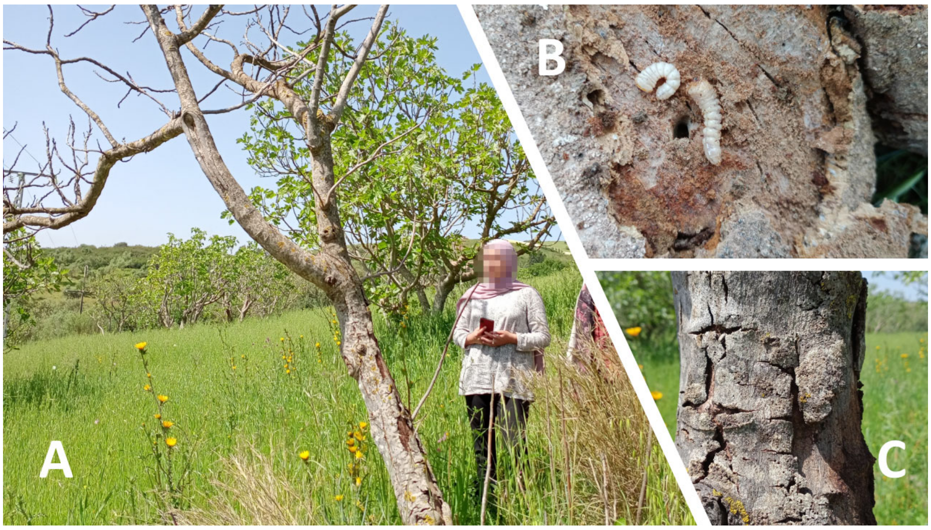

Figure 2. Symptoms of infested fig trees in Bejaïa province, Algeria: (**A**) dead fig tree due to heavy pest attacks; (**B**) beetles' xylophagous larvae damage on the tree trunk under the bark, and; (**C**) fungi and bark beetles attack symptoms on fig tree trunk.

The number of communes where at least one pest was recorded increased from one in 2011 to 15 in 2022 (Figure 3), revealing an annual increase of 1.48 communes per year, or an estimated area expansion of 659.1 ha yr^{-1}. The maximum number of pests recorded per commune was five in 2020 (N = one commune) and 2021 (N = two communes). The total number of communes recorded for each taxonomic group was eight for fungi covering ~1777 ha (in 2020), one for nematodes covering 13 ha, and twelve for beetles covering ~3542 ha.

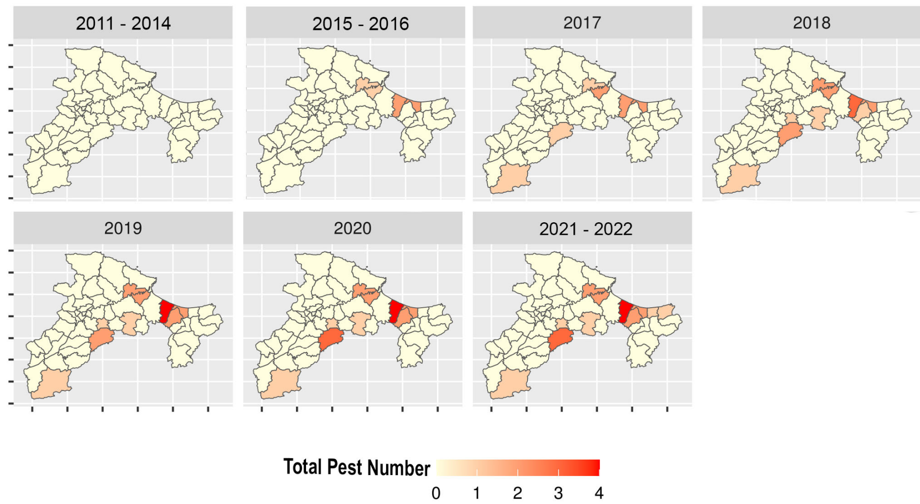

Figure 3. Spatiotemporal distribution of pest occurrence (number of pest species) in fig orchards between 2011 and 2022 in 52 communes of Bejaïa province, Northern Algeria.

The analysis revealed a positive correlation of year (z = 4.26, $p < 0.0001$), and a negative correlation of elevation (z = −2.80, $p = 0.005$) with the total number of pests per commune between 2010 and 2018. Similarly, there was a positive correlation of year (z = 3.08, $p = 0.002$), and a negative correlation of elevation (z = −2.77, p = 0.005) with the total number of pests per commune. For example, the average elevation where at least one pest was recorded was 440 ± 251 m, with a minimum of 127 m and a maximum of 923 m. Neither precipitation (z = 0.97, p = 0.32; z = −0.03, p = 0.97, respectively) nor average annual temperature (z = −1.92, p = 0.05; z = −0.64, p = 0.51, respectively) was correlated with the total number of pests.

3.3. Effect of Climate and Pests on Yield

There was a significant difference in yield per tree across communes, revealed by the significant effect of commune (ANOVA: F52,415 = 1.44, p = 0.02). Average yield per tree varied between 7.41 ± 8.0 kg in Sidi Said commune and 80.5 ± 97.5 kg in Souk Oufella, with an overall average across the province of 23.85 ± 32.66 kg (Supplementary data Table S1). Yield per fig tree was negatively correlated with year, showing a lower yield in later years (t = −8.94, p < 0.0001; Table 1). For instance, yield declined by 25% between 2010, when the average yield per tree was 22.3 ± 14.6 kg, and 2020, when the average yield per tree was 16.6 ± 15.6 kg (Figure 4). The number of species of pests was negatively correlated with fig yield (z = −2.58, p = 0.01) and interacted positively with year (z = 2.56, p = 0.01) (Figure 5A), indicating that, in early years, the occurrence of pests decreased yield more than in later years. Annual precipitation was positively correlated with yield (t = 3.21, p = 0.001) (Figure 5B), revealing that yield was lower in dry conditions and higher in wetter conditions.

Table 1. Summary statistics of the linear model explaining yield (log-transformed) by year, total number of pest species, and annual precipitation.

	Estimate	Std. Error	Df	t Value	p Value
Intercept	1.50	3.30×10^{-1}	3.01×10^{2}	4.544	<0.0001
cYear	-2.86×10^{-1}	3.20×10^{-2}	3.01×10^{2}	−8.944	<0.0001
Total pest	-9.12×10^{-1}	3.53×10^{-1}	3.01×10^{2}	−2.585	0.01021
Precipitation	1.42×10^{-3}	4.42×10^{-4}	3.01×10^{2}	3.211	0.00147
cYear × total pest	3.49×10^{-1}	1.36×10^{-1}	3.01×10^{2}	2.559	0.01098

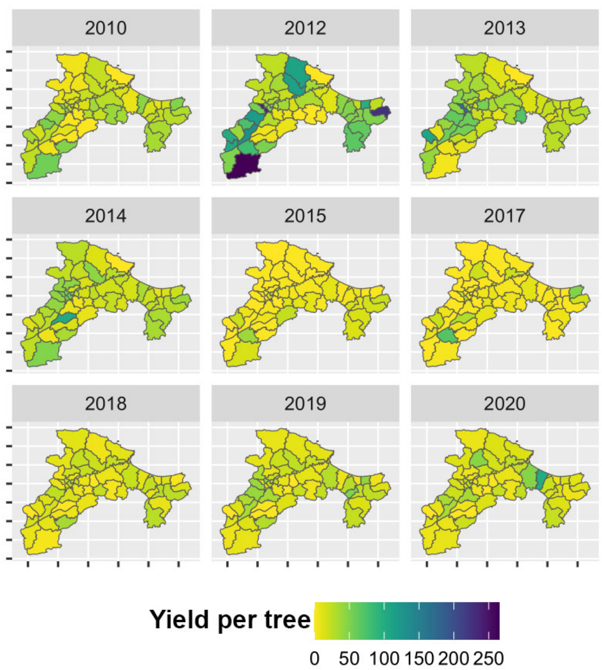

Figure 4. Spatiotemporal distribution of fig yield per tree between 2010 and 2020 in Bejaïa, Northern Algeria.

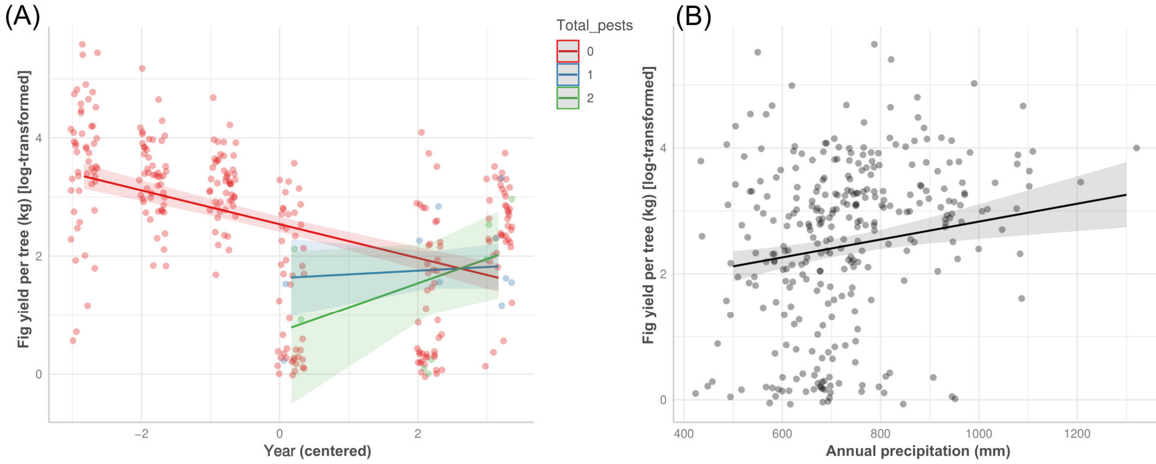

Figure 5. Predicted fig yield per tree across years and total number pests (**A**) and across annual precipitation (**B**) in Bejaïa, Northern Algeria.

4. Discussion

The study aimed to understand the role of climate and pest invasions in determining fig tree yield in Bejaïa province, Algeria, a renowned area for fig production in North Africa. Our analysis revealed several findings during the study period: (1) Bejaïa experienced significant warming and drought; (2) the number of communes affected by fig pests increased, and (3) yield declined throughout the reviewed years and was positively correlated with precipitation and negatively correlated with the number of fig pests. These results indicate that fig agriculture is threatened by both changes in climatic conditions and pest invasion.

The results showed that the annual average temperature increased, whereas the annual precipitation decreased, during the last decade in Bejaïa province. This is consistent with the general pattern of warming and drought in North Africa recorded in other studies [45]. Future projections of climate change predict that both warming and drought will become more intense and longer in the coming decades [63]. Knowing that both extreme heat and drought negatively affect the yield and health of crops [64], it is highly likely that these climatic changes will have severe repercussions on local agriculture and food security [65]. Despite the resistance of fig trees to climate change, the magnitude of changes in both temperature and precipitation could exceed the species' tolerance and threaten tree productivity [66]. Furthermore, in Bejaïa province, forest fires are common (e.g., in 2021, a total area of 11,694 ha was burned in Bejaïa [67]); this threat could also be exacerbated by climate change, affecting crop fields as a result.

The study recorded 11 pest species within the investigated area between 2010 and 2022. This was determined through field surveys providing a comprehensive understanding of the invasion dynamics in the area. The identified pests were fungi (three species), nematodes (one species), and insects (seven species). Some of the recorded species are detrimental to fig trees; fungal diseases (e.g., Canker disease, root rot disease, wilt vascular disease) caused by *D. cinerascens*, *N. solani* and *Fusarium* spp. are known to damage fig trees' lifespan and yield substantially [58,60,68]. While the damage caused by *Paratylenchus* spp. (nematodes) has been well-documented in other crops [61,68], there is a research gap regarding their impact on fig trees. Ravaging bark beetles, such as *H. ficus* and *H. scabricollis*, commonly affect stressed fig trees [69] mostly by their larvae boring through the trunk and branches, compromising tree health and in severe cases, leading to trees' death after a few months of infestation [34]. For instance, fig production in Italy was heavily affected by bark beetles in the last decade [70]. In Malta and Gozo, *H. scabricollis* caused significant damage to fig orchards, resulting in a loss of 50% of the fig tree population within eight years [71]. Although damage from *H. scabricollis* and *H. Ficus* to fig orchards has been studied in a few Mediterranean countries, the impact of the remaining five species remains poorly understood. Few studies have investigated the damage caused by these species, and the available literature is limited [62]. Further research is needed to fully understand the extent of the damage caused by these species, and their ecological impact. The number of pests increased during the study period, indicating a rapid invasion of multiple pests in the region. The causes of such a rapid increase in the number of pests are still not well understood, but our study's analysis indicated that higher-elevation lands were less likely to be invaded by a pest, and that climate did not seem to correlate with the spatiotemporal distribution of pests. As with most pest invasions, human trading of crops could be the direct cause of such a rapid increase in the number of pests in Bejaïa province [72].

The results showed a temporal decline in fig yield during the study period. FAO [43] data on crops and livestock products show that, at the national level, Algeria exhibits a clear decline in the total area harvested but a slight increase in yield, despite year-to-year fluctuations between 2010 and 2020. This suggests that the consistent decline observed during the past decade in Bejaïa might be an idiosyncrasy in the region. Compared to the observed 25% decline in yield in Bejaïa, most Mediterranean countries, such as Egypt, Libya, Tunisia, Greece, Italy, and Spain, did not show a decline throughout the last decade, but rather short-term declines in one year or a few years [43]. There are different factors that could explain the observed decline in yield in Bejaïa. The model assessing factors that correlate with yield showed a positive effect of precipitation, but a negative effect on the total number of pests per commune. Experimental studies showed that the absence of irrigation reduced yield considerably [73–75] (e.g., a 27% decline in non-irrigated treatment compared to a two-day intervals irrigation regime [76]). Therefore, a decrease in precipitation during recent years could in part explain the decline in fig yield in Bejaïa, especially since precipitation was negatively correlated with temperature, revealing that dry years were also warmer. Communes with a higher number of pests tended to show a lower yield, suggesting an additive effect of multiple types of pests on fig trees. Different pests affect different parts of the tree [69], reducing the resources that the tree would allocate to produce more flowers and fruits, and thus a higher yield. The observed negative effect related to the total number of pests is worrying since the number of pests has shown a rapid increase in the region, and this invasive trend could continue in the neighboring provinces. Furthermore, some of the invasive pests, such as *H. scabricollis*, already spread in the southern area of the province where the density of fig trees is important. This invasion even became a serious threat to natural forest ecosystems that surround the area, as *H. scabricollis* is known to be a polyphagous species [34]. Surprisingly, a reduced impact of pests in later years, with respect to earlier years, was unexpected since other studies have shown that in warmer years, the impact of pests on crops was usually higher due to increased population growth and metabolic rate [9]. For instance, in extreme drought events in California, where the climate is similar to the region's study, tree mortality caused by bark beetle infestation was estimated to increase by 30% for each Celsius rise [77]. Some ecological factors that we did not investigate could have come into play. Thus, more field studies are needed to explain the observed pattern.

This study presents some limitations due to the relatively large spatial resolution of the data. The provided data by ASD are collected at the commune level, which is not ideal for depicting microclimatic conditions and fine-scale patterns. In addition, we did not account for some other important factors, such as fig variety, variation in farming practices (e.g., mulching, pruning), fertilizer use, and other agricultural applications. Nevertheless, the studied region was relatively small, and the observed trends based on the communes' data were quite strong. A follow-up study that integrates farm-scale surveys with focal samples of trees, as well as experiments that combine climatic and pest stress, are necessary to deepen the understanding of the mechanisms driving the negative impacts on fig yield in Bejaïa province.

5. Conclusions

The current study revealed key information on the impact of climate change and pest invasion on fig yield in northeastern Algeria. As expected from previous studies on figs and other crops, yield was reduced by a combination of drought and pest occurrence, which were more prominent in recent years. The number of pests, including some that cause major damage to fig trees, increased in multiple communes during the last decade. The recent climate extremes recorded in North Africa, combined with a rapid invasion by multiple pests, induced a considerable level of stress that might threaten the local fig market. The presence of bark beetles and Fusarium species in fig orchards of Bejaïa province could pose a significant risk in the future, as a symbiotic relationship between these species may develop and lead to substantial consequences. Further research is needed to investigate the potential for such a relationship to develop, and the impact it could have on the fig orchards. While fig trees were our focal species, other species of crops in the regions, including cereals, legumes and fruits, will likely be affected similarly. Furthermore, we still have knowledge gaps in our understanding of the mechanisms underlying the physiological responses to combined impacts of climatic and pest effects. Both experimental studies and field surveys are necessary to gain insights into the physiological and fitness consequences of multiple stressors on fig trees and other crops. Experts in agronomy, climatology, and ecology should work together to develop a sustainable farming system that increases the resilience of agroecosystems to multiple sources of stress; preferably using nature-based solutions that maintain the ecosystem functions, and satisfy the socioeconomic needs of the farmers and local people.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15075820/s1. Figure S1: Distribution of the communes of Bejaïa province; Figure S2: Visualizing precipitation and temperature patterns (2010–2018) within Bejaïa Province using an Umbrothermal Diagram. Table S1: Characteristics of fig agriculture and climate of Bejaïa communes.

Author Contributions: Conceptualization, M.K.M. and R.K.; methodology, M.K.M. and R.K.; software, R.K.; validation, R.K. and M.K.M.; formal analysis, R.K.; investigation, M.K.M. and A.C.; resources, N.D.; data curation, M.K.M. and R.K.; writing—original draft preparation, R.K. and M.K.M.; writing—review and editing, R.K., M.K.M. and K.M.; visualization, R.K. and M.K.M.; supervision, K.M.; project administration, K.M.; funding acquisition, K.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Data will be deposited in a public repository upon acceptance.

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Conflicts of Interest: The authors declare no conflict of interest.

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