Climate change-induced ecosystem disturbance: a review on sclerophyllous and semi-deciduous forests in Tunisia

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ABSTRACT

According to the IPCC sixth assessment report of the Intergovernmental Panel on Climate Change, global climate change is now unequivocal. Tunisia, like many other countries, has been affected by climate changes, including rising temperature, intense heat waves, and altered precipitation regimes. Tunisia's mean annual temperatures rise by about +1.4 °C in the twentieth century, with the most rapid warming taking place since the1970s. Drought represents a primary contributing factor to tree decline and dieback. Long-term drought can result in reduced growth and health of trees, thereby, increasing their susceptibility to insect pests and pathogens. Reported increases in tree mortality point toward accelerating global forest vulnerability under hotter temperatures and longer, more intense droughts. In order to assess the effect of these climate changes on the current state of forest ecosystems in Tunisia and their evolution, an investigative study seems necessary.

Here, we review the current state of knowledge on the effects of climate change on sclerophyllous and semi-deciduous forest ecosystems in Tunisia. Natural disturbance during the last years as well as the adaptability and resilience of some forest species to climate change were surveyed. Standardized Precipitation Evapotranspiration Index (SPEI) is a multi-scalar drought index based on climatic data has been used to analyze drought variability.

SPEI time scale analysis showed a negative trend over the 1955-2021 period in Tunisian forest regions. In 2021, Tunisia lost 280 km^2 of tree cover ravaged by fires, which equivalent to a 26 % of the total loss area between 2008 and 2021. Changing climatic conditions have also affected phenological parameters with an advance of the start of the green season (SOS) by 9.4 days, a delay of the end of the green season (EOS) by 5 days, with the consequent of the extension duration of the green season (LOS) by an average of 14.2 days.

All these alarming findings invite us to seek adaptation strategies for forest ecosystems. Adapting forests to climate change is therefore a challenge for scientists as well as policy makers and managers.

Keywords: Climate change, drought effects, fires, disturbances, tree mortality, forests, Mediterranean ecosystems, resilience and adaptation

INTRODUCTION

Human society and the global economy are inextricably linked to forests dynamics. More than 1 billion people depend on forests for their livelihoods. Forest ecosystems play a critical role in climate stabilization, through CO_2 capture, while providing food, water, wood products, and essential medicines to humans, and maintaining much of the world's biodiversity (FAO 2022). Despite decreased deforestation rates in some regions, forest ecosystems are still under great threat. From 2000 to 2020, 5.7 % of global forest cover (40.6 billion km^2) has been cleared, while 7.6 % has been degraded (GFW 2022). Adapting forests to climate change has been the focus of a fair amount of work in the forest sector. One comprehensive study carried out by Seppälä *et al.* (2009) from the International Union of Forest Research Organizations (IUFRO), entitled "*Adaptation of Forests and People to Climate Change—A Global Assessment*", highlighted possible changes in forest ecosystems due to climate change. It also documented how the response of forests systems varied regarding climate change.

Monitoring forest damage is a challenging research issue that has been addressed by many authors (Wilson *et al.* 2019; Touhami *et al.* 2020; Forzieri *et al.* 2021). Drought has become a recurrent phenomenon in Mediterranean basins and particularly in the North Africa over the past 50 years (Bazza *et al.* 2018; Trisos *et al.* 2022; Toreti *et al.* 2022). In the Mediterranean basin, the expected changes are even greater since the sixth report (AR6) points to this area as one of the regions that will be particularly affected by climate change (Trisos *et al.* 2022). Over the last few decades, North Africa, including Tunisia has undergone a significant decrease in the amount of precipitation received in winter and early spring (Trisos *et al.* 2022). The review focuses on changes in temperature and precipitation over Tunisia suggesting a hotter, drier, and less predictable climate with increasing temperature, declining rainfall and water availability, and more intense and frequent extreme weather events (droughts and floods) over the century (Verner 2012, 2013).

In Tunisia, forests areas cover about 13000 km^2 that represent 8 % of the Tunisian territory). It includes 10000 km^2 of forests and 3000 km^2 of shrubs and other woody area. Around half of them are pure forest stands with an annual increase of 1.9 % during the period 1990-2015. Based on FAO forest report (2010), naturally Tunisian forests represent 3160 km^2 while 6900 km^2) are plantation forests. The management of forests areas is basically done by the Tunisian government via the General Directory of Forests (DGF). This forest area is mainly located in

the north-west, central-west, and northern regions (FAO 2010). Tunisian forests are situated mainly in .The northern parts of the country is dominated by cork oak (*Quercus suber*) and zean oak (*Quercus canariensis*) covering the mountains of the Kroumery and Mogod. In the central part and on the Dorsal Mountains Tunisian forests are mostly covered by coniferous species (55 % of the forest area), dominated by *Pinus halepensis*. Pine species are among the most widespread coniferous species and are afforded special attention in the country's reforestation strategies. Together Pinus *pinea* and *Pinus halepensis* cover early 40 % of all Tunisian forests, meaning that they occupy a prominent place in forestry production (Fkiri *et al.* 2020). This survey paper presents a review of relevant knowledge about potential climate change impacts in Tunisian forests. In addition, it aims to understand the resilience capacity of some forests and trees species to cope with a changing climate.

OBSERVED CLIMATE CHANGES ON TUNISIAN FOREST ECOSYSTEMS

Observed changes in temperature and precipitation

Africa's annual temperature has increased by 0.12 °C per decade since 1910 (NOAA 2020). However, with an increase of 0.31 °C per decade since 1981 the rate of temperature change has more than doubled (NOAA 2020). Local and seasonal changes in temperature and precipitation could be even greater (Verner 2013). However, these trends must be seen in the context of great variability from year to year and decade to decade in the future (Verner 2013). Global climate models predict an increase in the temperature and a pronounced decrease in the precipitation for the Mediterranean region (Fiseha *et al.* 2012; Wang *et al.* 2017). This area is considered to be a hotspot for climate change (Paeth *et al.* 2017), which corresponds to an intensification in frequency, intensity and duration of drought, mainly during the warm season (Pendergrass *et al.* 2017). Aridity, the ratio of potential evaporation to precipitation, has increased over the Mediterranean and North Africa due to significant decreases in precipitation (Greve *et al.* 2019). Consequently, this region will be exposed to high water stress conditions, undergoing a reduction in plant production.

In the same way Tunisia's annual rainfalls have declined by 5 % per decade in the northern part of the country since the 1950s, while heavy rainfall events have become more frequent (Mitchell *et al.* 2002). The most rapid warming was observed during summer (+1.8 °C) and the least was recorded in the spring (+1.2 °C) (Cramer 2021). There are indications that the

number of droughts has increased in some regions, and will continue to become more frequent in the future (Verner 2013). Regional climate change scenarios suggest that warming and drying trends could continue in the coming decades, potentially exacerbating current water scarcity and putting more pressure on forest and agricultural ecosystems. According to climate models from IPCC, the Representative Concentration Pathway-RCP4.5 scenario suggests an increase in mean temperatures by 1.4 °C to 2.5 °C and precipitation could be reduced by 5 to 15 % by the 2050s. Climate change is expected to have major impacts on Tunisia forests, agriculture, economy, and households from both global and local perspectives (Verner *et al.* 2018; Amamou *et al.* 2018). Drought is most often cited as the stress that causes trees decline and dieback (McDowell e*t al.* 2008; Allen *et al.* 2010; Touhami *et al.* 2020). Annual average precipitations conceal significant spatio-temporal variations across Tunisia, particularly for extreme events (Berndtsson & Niemczynowicz 1986). Kingumbi *et al.* (2005) reported a notable dry period in central Tunisia during the years 1976-1989. Consistently, spring precipitation decreased in most areas but especially in the eastern half of the country. Fall precipitation decreased the most in the south. In contrast to temperatures, the more recent decreases in total precipitation are only statistically significant in northern Tunisia (Verner 2013; Trisos *et al.* 2022). Satellite data from the Tropical Rainfall Measuring Mission-TRMM (Simpson *et al.* 1996; Huffman *et al.* 2007; 2010) provide further evidence of rainfall variations across Tunisia (Verner 2013; Medhioub *et al.* 2019).

The results presented in Figure 1-A predicts a decrease in rainfall of up to 24 % (upper bound) for the projected period 2070-2100 relative to the reference 1960-1990 period under RCP8.5 scenario (Rouabhia 2019). The mean annual precipitations are around 634 mm in the northern parts of Tunisia. The decrease in precipitations will be observed mainly in spring (April and May), which coincide with the optimum of the vegetation cycle in Tunisian forests putting certain trees species under stress. This decrease in precipitation is predicted for all scenarios (2040-2070 and 2070-2100). The analysis of the results in Figure 1-B shows a general trend of increasing maximal and minimal temperature levels from 1960-1990 to 2040-2070, under the RCP4.5 and RCP8.5 scenarios. The increase of maximum temperature (Tmax) compared to the reference 1960-1990 period is +1.4 °C for the 2010-2040 period, +2 °C for the 2040-2070 period and +2.3 °C for the 2070-2100 period under the scenario RCP4.5. This increase is very pronounced under the RCP8.5 scenario.. The analysis of the observed temperatures during the period 1964-2015 for two main weather stations (Tabarka and Jendouba) in northern Tunisia shows a general trend of increasing mean annual

temperatures (Figures 1-C and 1-D). A regional-scale analysis also showed that northern and southern regions of Tunisia have experienced a more rapid warming than central Tunisia. There is a clear trend of temperature increase of 0.05 °C to 0.07 °C per year during the historical period 1979-1999 across Tunisia.

Drought index analysis

The Standardized Precipitation Evapotranspiration Index (SPEI) is a multi-scalar drought index based on climatic data. It can be used for determining the onset, duration and magnitude of drought conditions. The SPEI defined by Vicente-Serrano *et al.* (2010), Beguería *et al.* (2010, 2014) provides near real-time information on global drought conditions with a spatial grid resolution about 1° × 1° (approximately 111 km × 111 km at the equator) and a monthly temporal resolution. With this same spatial resolution (one degree), all Tunisian forest areas have been covered by about 8 grids. The time-scales of SPEI range from 1 to 48 months. The calibration period for the SPEI is from January 1950 to December 2010. In order to provide common information at the different time-scales of the SPEI, the starting date of the dataset is fixed to 1955 (refer to https://spei.csic.es/database.html for more details). Currently, the SPEI is based on the Thornthwaite equation to estimate potential evapotranspiration (PET). Figure 2 shows the dynamics characteristics of the SPEI time-scale for the 1955-2021 period over major forest regions in Tunisia, which indicates the changes in SPEI values for the cumulative 48 months period. The temporal pattern of drought based on SPEI-48 time scale was explored in different forest regions in Tunisia during 1955-2021. The SPEI-48 time scale analysis showed two main contrasted periods (Figure 2). The first period from 1955 to 1986 concern the three regions of Jendouba, Bizerte and Cap Bon. In this first period, the SPEI-48 time scale is characterized by a slight positive trend signaling a stabilization of climatic conditions interrupted by two major floods in 1969 and 1973 throughout the country. In the second period (1987-2021) this positive trend is reversed towards a long dry period of drought. This second period, characterized by more frequent, intense and longer drought occurred in the decades of 1990, 2000, 2010 and 2020, is still marked in the minds of Tunisian farmers. This prolonged drought is defined as a period with an abnormal precipitation deficit in comparison to the long-term average conditions for these regions, affecting agricultural crops as well as forests productivity. The central part of Tunisia (Béja, Siliana and Kasserine) experienced the same conditions for the first (1955 to 1979) and second (1980-2021) period with, however, an earlier period of drought which began in the 1980s (Figure 2). Since the magnitude of the

drought is proportional to the duration, this statement indicates a higher risk of drought especially for the central region where most of Tunisia's agriculture and forest areas are concentrated. A higher magnitude would therefore imply a more severe water deficit that negatively affects plants physiology and photosynthetic capacity. According to predictions, meteorological drought over Mediterranean North Africa in CMIP5 and CMIP6 models are projected to increase in duration from approximately 2 months during 1950–2014 to approximately 4 months in the period 2050–2100 under RCP8.5 and SSP5-85 model (Ukkola *et al.* 2020). Increasing drought could affect the state of the vegetation cover in different forest ecosystems. Droughts negatively influence multiple processes in trees and forests, including gas exchange, carbon allocation, growth, survival, and regeneration (Flexas *et al.* 2006; McDowell *et al.* 2008). Stiti *et al.* (2005) investigated the potential regeneration of the cork oak forest, northern Tunisia. They reported that 52% of total stands (71 studied trees) show 25% of regeneration. The main conclusion of this study is that cork oak regeneration is affected by the availability of water and long-term drought. In studying the impact of plant cover dynamics in tow natural areas in southern Tunisia, Ben Salem *et al.* (2007) stated a strong impoverishment of the floristic diversity attributed to drought effects. Despite all these negative effects of drought on plant growth, it has been shown that plants species could develop a variety of complex resistance and adaptation mechanisms, including physiological and biochemical responses to deal with water scarcity (Seleiman *et al.* 2021).

CLIMATE AND ANTHROPOENIC IMPACTS ON TUNISIAN FOREST ECOSYSTEMS AT REGIONAL SCALE

Climate-induced phenology shifts in Tunisian forest ecosystems

Phenology is the timing of seasonal activities of plants and animals such as flowering or breeding. Phenology remains primarily dependent on temperature and very likely will be influenced by climate change. The perturbation induced by climate change would disrupt the way that species interact and the overall functioning of ecosystems. Plants may adjust the timing of certain phenological events, such as tree flowering, in response to changing weather conditions (Menzel *et al.* 2006). Therefore, it is now important to better understand how the timing of phenological events evolves over long periods in response to climate changes. Although some plant species appear to be able to adapt to climatic events such as temperature increases, extension of the drought periods, and extreme storms, their rates and means of

adaptation are different from one species to another (Wadgymar *et al.* 2018; Dickman *et al.* 2019). Evidence of phenological changes in many plant and animal species due to climate change is abundant and increasing (Fitter & Fitter 2002; Visser & Both 2005; Menzel *et al.* 2008). Assoul *et al.* (2021) and Touhami *et al.* (2022) investigated changes in Land Surface Phenology (LSP) in relation to climate variables in Mediterranean forests in northeastern Tunisia from 2000 to 2017 by coupling remotely sensing datasets. They showed that the climatic variables, including precipitation, temperature, and drought play a dominant role in the phenological dynamics. They found an average advance of 9.4 days of the start of the green season (SOS), an average delay of 5 days of the end of the green season (EOS), and an extension of the duration of the green season (LOS) by an average of 14.2 days (Table 1). These conditions may increase biomass accumulation and photosynthesis activities in plant species under good water conditions according to Zohner *et al.* (2021). Autumn and spring precipitations coupled with maximum temperature represent the best climate parameters to explain the changes in LSP according to Touhami *et al.* (2022). By investigating the effects of increased water deficit on the phenological response of cork oak seedlings between different origins from Tunisia, Ennajah *et al.* (2013) showed that the apical stressed bud break shifted 1 week compared to the controls. By the end of the experiment, they noted a delay of 1 week in bud break. The burst rate of apical buds reached 100 % in the controls and declined to 40 % under stressed conditions. Another work conducted by Ben Yahia *et al.* (2016) following the buds of the same species in the north of Tunisia in three sites over two years of observations concluded that the variability of the phenological character observed between populations is linked specially to both the effect of the environment and the genetic structure of the population.

Parmesan and Yohe (2003) reported that 62 % of the total plant species (677) assessed showed an average advance of spring events of 2.3 days/decade based on quantitative analyses of phenological responses. Root *et al.* (2003), in a similar quantitative study, estimated an advanced value of 5.1 days per decade. Parmesan (2007) investigated the discrepancy between these two estimates and noted that once differences between studies in selection criteria for data incorporation were accounted for, the two studies supported each other, with an overall spring advance of 2.3 to 2.8 days/decade found in the resulting analysis. However, in the latter study, latitude explained only 4 % of the overall variation in phenological changes while it is strongly associated with the magnitude of warming trends. This latter observation may be related to the magnitude of climate change relative to the

natural range of climate variability.. Understanding the behavior of species in the face of climate change to better assessing the resilience of our forests is a key element in making accurate management decisions (Messier *et al.* 2013; Nikinmaa *et al.* 2020).

Climate change imprints in dendrochronological and phenological analysis

Drought-induced tree decline and mortality are increasing in many regions around the world, which could fundamentally alter the forest composition (Engelbrecht *et al.* 2007; Zheng *et al.* 2019), structure (Allen *et al.* 2010), and biogeography (D'Orangeville *et al.* 2016). To develop mitigation strategies and to maintain forest sustainability and productivity, it is important to understand how forest species will respond to severe drought. Dendrochronolgy's studies on five cork oak populations in the Kroumirie region, northwest Tunisia, highlighted the dependence of cork oak growth on climatic conditions and the acute sensitivity of their variability (Ennajah *et al.* 2010). The results indicated that precipitation was of major importance during the period before the growing season and varied according to site. This dependency has also been verified on other sites (in Bellif, northwest Tunisia; Figure 3-A and B) using a long-term tree-ring-width chronology showing strong dependence of cork oak to the climatic parameters (precipitation and temperature) controlling the water balance (Zribi *et al.* 2016). The results of these two studies highlighted that the dependence of cork oak growth is very strong during the post-growth season compared to that of the vegetation season (spring and summer conditions). The direct relation between annual tree growth and the autumnal precipitations of the previous year could be explained by the benefits from these favorable conditions for synthesizing and storing carbohydrates reserves since initial cambial divisions in the growing season are fueled by energy reserves held through the previous dormant season (Barbaroux & Bréda 2002; Smith 2008). For the evergreen *Quercus* species in general, carbohydrate storage mainly occurs in autumn, and spring mobilization is especially high (Barbaroux & Bréda 2002; Lacointe 2000). Bouachir *et al.* (2017) reported that *Pinus halepensis* stands in Tunisian sub-humid area is growing under intense water stress during the growing season. Growth was positively correlated with precipitation and negatively with maximal temperature (Figure 3-C and D). This situation of stress is manifested by a radial growth reduction and an increase in absent rings in stressed sites compared to control sites. It is mainly related to altered structural characteristics affecting the crown and needles, leading to tree dieback in the most stressed sites.

Several phenological studies on many tree-species have been carried out in Tunisia. Ben Yahia *et al.* (2016) analysed the seasonal progression of phenological events on cork oak and showed that phenological stages seem to be well correlated with temperature. In this study the authors concluded that this synchronization of phenophases corresponds to an adaptation of plant life forms. Zribi *et al.* (2016) investigated the relationship between increasing winter temperatures and earlier prolonged summer drought, by using the wood growth phenology approach (Figure S1). Based on the spring stem growth duration Δt (t0-t1), which is defined as the length of the period between the onset of spring stem growth (t0) and the date of growth cessation caused by summer drought (t1). After the dry period, the day of the year (DOY) when growth restarts is t2. This technique based on the climatic limits for cell division and elongation and which helps to follow the temporal delimitation of tree growth duration is an innovative way of improving the simulation of forest carbon sink response to climate change (Fatichi *et al.* 2014). Based on this technique, Zribi *et al.* (2016) reported that the start of the drought period (t1) was significantly earlier from DOY 215 to 201 over the study period (1975-2002) in the Bellif forest. The observed decreasing winter precipitation could affect both the length of growing period and the drought period. The start of the growing season (t0) also moved toward an earlier start date as a consequence of warmer winter temperatures, compensating for the earlier (t1) and leading to a constant (t0-t1) growth period (Figure S1). Lempereur *et al.* (2016) pointed out the same trend for *Quercus ilex* in southern France. The same conclusion is also reached for the summer drought intensity WSI, for which the earlier drought start is compensated by a slightly earlier drought offset (t2).

It is important to note that despite no significant major trends in the two key drivers of tree growth (growth period and carbon assimilation); these two drivers could be controlled by climate variables with compensating effects (Zribi *et al.* 2016). This could also potentially lead to the shortening of the phenological period of growth, in response to prolonged drought at the end of the dry season as predicted by some models in the same region (Terink *et al.* 2013; Saadi 2015).

Forest cover loss

Assessing forest cover using spatial analytical tools can provide critical information of sustainable management strategies. The forest cover loss data (Figure 4-A) uses Landsat satellite imagery to map annual forest cover loss at a resolution of 30-meters per pixel (GFW

2022). It shows year-by-year tree cover loss, defined as stand-level vegetation replacement of over a distance greater than 5-meters, in the selected area. More information on the methodology can be found in Hansen *et al.* (2013). Tunisia lost more than 280 km^2 of tree cover in 2021, which equivalent to a 26 % of the total area burned (1090 km^2) by fires between 2008-2021 period (GFW 2022). The results of a spatio-temporal analysis of Tunisian forests over the 8 years from 2007 to 2014 (Achour *et al.* 2018) show that forest losses have almost tripled from 32 km^2 in the 2007-2010 period compared to 90 km^2 for the 2011-2014 period, with an estimated annual loss increase about 3.06 km^2 per year. According to the FAO (2020), Tunisia had 1690 km^2 of tree cover in 2010, covering over 1.1% of its area. The latest estimates for 2020 suggest a loss of about 10.06 km^2 of tree cover. The two regions that lost more forest (Bizerte and Jendouba) have experienced 56 % of the total loss of tree cover between 2000 and 2020. Bizerte had experienced the greatest loss of tree cover with a rate of 106km^2 against an average of 16.5 km^2 (GFW 2022). Considering the annual precipitation anomalies (Figure 4-B) between the averages of the 2 periods 1900-1940 and 2000-2020, it is important to highlight that the major decrease in precipitation is concentrated in the northwest of Tunisia, which contains the most forest area in the country. Accordingly, the projected decrease in rainfall may disproportionally affect tree recovery and viability. The year by year loss of forest cover in Tunisia between 2000 and 2020 shows that the highest level of forest cover loss was marked in 2017 with a maximum loss of land cover mainly by forest fires, of 180 km^2 (GFW 2022).

Forest fires

In Tunisia the forest fire season extends from May to October each year. According to the General Directorate of Forests (DGF) at the Tunisian Ministry of Agriculture, 458 fires (Figure 5-A) were recorded in 2021, which ravaged 258.22 km^2 of forests (Figure 5-B). A very close number (438 fires) was also reported by Global Forest Watch in 2021, which ravaged about 395.99 km^2 of forests. However, the European Forest Fire Information System- EFFIS reported a number of 57 fires in 2021, and 284.93 km^2 of burned surface. Despite this difference between the sources, is that the number of fires in Tunisia, for the year 2021, was higher than that recorded during the last 5 years, from 2009 to 2013 (Figure -5-A). Achour *et al.* (2022) studied the performance of the Sentinel-2 and Landsat 8 sensors to map forest fires northwestern Tunisia in 2017. They conclude that both sensors could be a good

alternative to EFFIS data, particularly when there is a need to detect details inside the burned areas. According to the Tunisian forest service (Directorate General of Forestry), the period from July 22 to the early August (first week), constitutes the most critical period where the frequency of fires experienced the greatest increase. During this period, fifty-five (55) fires occurred in the governorates of Beja, Jendouba, Kef, Siliana, Bizerte, and Zaghouan each year (Figure 5-C; Figure S2).

This is explained by the fact that in 2021, the weather was warmer than usual putting the risk of fires very high. The current dry and hot weather conditions in Tunisia are considerably increasing the risk and extent of wildfires (Ruffault *et al.* 2020). In Tunisia, 95 % of forest loss is due to forest fires (DGF 2010) could be a direct consequence of these climate changes. Forest fire risk depends on several factors, including temperature, atmospheric humidity, soil moisture, the presence of high density of trees and shrubs species and also the lack of forest management. All these factors are shown to be strongly linked directly or indirectly to climate variability and climate change (Pausas 2004). Warmer temperatures and drier conditions can enhance fire spread and make fires more difficult to extinguish. Such a situation characterized the climate of northern Tunisia in June and July 2021 and which caused great forest fires devastating many forest areas during this year (Figure S2). Belhadj-Khedher *et al.* (2020) studied the regional effect of Saharan Sirocco events in Tunisia over the period of 1985–2006; and found high inter-annual variability in burned areas in Tunisia.

In Tunisia, the peak fire season typically begins in late June and lasts approximately 12 weeks. Based on GFW, information from the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor is collected and processed with a fire detection algorithm to identify active fires. The VIIRS data replaces the active fires data from MODIS. The higher spatial resolution of the VIIRS data (375-meter pixels vs. 1-kilometer pixels) improves detection of smaller fires and provides a more reliable estimate of fire perimeters. Based in this technique, Tunisia experiences between October 15, 2019 and October 13, 2020 a total of 3,067 VIIRS fire alerts (GFW 2022) and 525 fire alerts in 2021 considering only high confidence alerts. Example of fire alerts between July 10, 2021 and October 8, 2021 is illustrated by Figure 5-C. The number recorded between 2019 and 2021 is considered relatively high compared to previous years going back to 2012.

Drought-induced tree mortality

Droughts affect trees directly and predispose forests to damage by insects, diseases, and wildfires. It could potentially lead to shifts in species distributions and large-scale changes in both forest community composition and structure (McDowell *et al.* 2008; Breshears *et al.* 2009). The extreme dryness from 1999 to 2002 in North Africa (Touchan *et al.* 2008) was linked to severe mortality that affected all the age classes of Atlas cedar (*Cedrus atlantica*) from Morocco to Algeria (Bentouati 2008). Whereas all Algerian cedar forests were affected, the magnitude of mortality varied along a steep moisture gradient, with die-off being greatest (up to 100 %) in the drier mountains nearer the Sahara, and dropping too much lower mortality rates in moister coastal mountains (Chenchouni *et al.* 2008). This drought has also triggered substantial mortality in other Algerian tree species, including *Quercus suber*, *Quercus ilex*, *Pinus halepensis*, and *Juniperus thurifera* (Allen *et al.* 2010). In recent years, many regions located in northern Tunisia have been largely influenced by frequent prolonged dryness periods (Figure 6-A, B, and C). Droughts were found to consistently have a more detrimental impact on the growth and mortality rates of cork oak populations causing the death of up to 61 268 trees mortality between 1988-2000 (Touhami *et al.* 2020).

Insects, pests and pathogens

Climate change affect forests cover, its health, and its biodiversity and these impacts vary across regions, with some forest types being more vulnerable than others (Lucier *et al.* 2009; FAO, 2010). Regarding forest ecosystems in Mediterranean regions, the most important risks are drought, forest fires, and insect attacks (Lindner *et al.* 2010; Dupuy *et al.* 2015). Massive insects and phytopathogens attacks can be major risk factors for the vitality of fruit trees and forest trees. In Morocco, more than 60 % of the Moroccan palm grove has disappeared because of the fungus *Fusarium oxysporum* f. sp. *albedinis*, causative agent of "the Bayoud" disease in date palm (Zeino-Mahmalat & Bennis 2012). In Tunisia, as a result of the increase in temperature and the decrease in rainfall during the 20th century, cases of expansions of insects and pathogens have been observed in the early 1960s, when a water deficit in the Cap Bon region (northeast Tunisia) caused the appearance of the eucalyptus borer *Phoracantha semipunctata*, and losses in the eucalyptus plantations exceeded 60 % (Chararas 1969). In recent years, many eucalyptus forests have again been affected by *Phoracantha semipunctata* (Figure 7-A, B, C, and D). The lepidopteran *Lymantria dispar* is the main pest of cork oak

forests, the defoliated areas were about 22000 ha in 1992 (Ben Jamâa *et al.* 2002). Touhami *et al.* (2020) reported that the survey of insect pests in the Kroumirie region, northern Tunisia, showed that, since 2010, *Tortrix viridana* (Figure 7-E) is the main defoliator observed in most cork oak forests. The extent of the infected pest was very high, with 6642 dead tree. In 2005, about 500 ha of the Jebel Abderrahmane shrub (northeastern Tunisia) were completely defoliated by the lepidopteran *Orgyia trigotephras* (Ezzine *et al.* 2010) (Figure 7-F). In 2020, investigations in Rimel forests of Bizerte (northern Tunisia) showed that 30% of the mortality of lentisques (*Pistacia lentiscus*) was caused by the attack of two pathogenic fungi, *Diplodia seriata* and *Diplodia africana* (Hlaiem *et al.* 2020).

Among the disturbances of forest ecosystems in the context of climate change, the change in insect ranges is one of the most observed, especially due to climate warming (Carroll *et al.* 2003; Robinet and Roques 2010; Roques *et al.* 2015; Andersen *et al.* 2019). Specifically, it is shown that the Pine processionary, *Thaumetopoea pityocampae* (Figure 7-G), has expanded its range in the northern part of its distribution due to increased winter temperatures (Battisti *et al.* 2005, 2006). In Tunisia, since 2014, surveys have shown that the Pine processionary has not been detected in southern governorates of Tunisia. This can be attributed to the extreme temperatures from July to September that can exceed 45 °C (Azizi 2015, Bourougaaoui *et al.* 2021).

Anthropic pressure and forest mismanagement

Deforestation is one of the main causes of climate change. When forests are destroyed, a large portion of the stored carbon is released into the atmosphere as carbon dioxide (CO_2), which contributes to global warming. In turn, climate change can impact forest health, and lead to deforestation and degradation (Lawrence *et al.* 2022). The rapid increase in Tunisia rural population has led to the conquest of new lands through clearing, resulting in a few ridge lines and narrow valleys at the expense of scarce wood and shrubs. Between 2001 and 2021, 300 km^2 of forest areas were cleared, which correspond to 2.63 % of the total forest area (1146,28 km^2) (GFW 2022). Illegally cut *Quercus canariensis* trees over 400 trees) were reported in northwestern Tunisia (regions of Aïn Hmairia and Aïn Salem) in April 2020, whose age exceeds for some trees the 200 years (Figure 6-D and E). This forest species represents a natural and cultural heritage that must be preserved for future generations. The regression of shrubs in favor of steeply sloping cereal crops has affected almost all deforested watersheds,

making them highly vulnerable to the erosive action of water runoff. In Tunisia, people living in or nearby forests are estimated at 1 million people representing 10 % of the total population (INS 2021). Boussaidi (2005) concluded that cork oak stands in areas of high anthropic pressure had higher rates of degradation (high vulnerability) than cork oak stands in areas of low anthropic pressure. The negative impact of overgrazing on the cork oak forest of Kroumirie has led to a dysfunction of natural ecosystems (Touhami et al. 2020). The presence of animals (overgrazing) reduces natural regeneration and increases soil compaction, which reduces its permeability. The rate of overgrazing represents 77 % (El Hamrouni 1992). High density and lack of effective silvicultural practices to provide conditions for healthy stand growth have had a negative impact on cork oak growth (Boussaidi 2005). Lacks of silvicultural practices that can protect, renew and maintain the balance of forest species aggravates the phenomenon of tree dieback (El Hamrouni 1992; Hasnaoui 1998; Ben Jamâa et al. 2005). In the Kroumirie cork oak forest, there is a need for a new strategy to preserve cork oak forest resources by applying effective silvicultural management practices to the forest in a climate change context.

RESILIENCE AND ADAPTATION OF TUNISIAN FOREST TO CLIMATE CHANGE

Climate change presents significant potential risks to forests and more challenges to forest managers (Keenan 2015). The lack of adaptive responses of trees to environmental change makes forests sensitive or vulnerable to climate evolutions (Linder et al. 2010; Richter et al. 2012). Thus, adaptation to climate change involves monitoring and anticipating expected modifications (Keenan 2012). Indeed, the forests that are regenerating today will have to cope with climatic conditions that become more and more severe for several decades, even more than a century (Dale et al. 2001; Trumbore et al. 2015). It is difficult to predict the impact of climate change without a better understanding of the effect of increasing atmospheric CO_2 concentration and drought periods (Keenan 2015). To cope with such scenarios, it is essential to adopt previous management practices to conserve forests. Some of them consist in favoring the species most resistant to heat and drought at the expense of the more vulnerable species (Mezgebu & Workineh 2017; Maguire-Rajpaul et al. 2016; Wilson & Cagalanan 2016). Although the enhancement of species diversity (e.g., by planting native species) may in other cases be advisable to face an uncertain future (Potter et al. 2017; Serra-Varela et al. 2017).

Physiological implications inferred from radial growth and water-use efficiency

The main physiological mechanisms of trees to challenge with severe drought consist in their capacity to accumulate sufficient carbohydrates (McDowell *et al.* 2011; Breshears *et al.* 2005: Salmon *et al.* 2022), a lower vulnerability to hydraulic failure (Bréda *et al.* 2006, Meinzer *et al.* 2009, 2010), or a combination of both (McDowell *et al.* 2011; Adams *et al.* 2017). In the case of some evergreen tree species, chronic water stress and prolonged stomatal closure may likely lead to a reduced photosynthetic rate that also results in a further decrease in stored carbon as respiration continues (Zheng *et al.* 2019). Carbohydrate reserves can be then further reduced as carbohydrates are still required to drive phloem transport, maintain turgor, and refill embolized xylem during a drought exposure (McDowell *et al.* 2011; Torres-Ruiz *et al.* 2015). Thus, reduced carbon storage and available water also affect tree's defensive ability, and mortality occurs as soon as one or more of these processes reach a threshold, with feedback mechanisms potentially hastening this process (McDowell *et al.* 2011). The xylem pressures corresponding to 50 % loss of hydraulic conductivity (P_{50}, MPa) is a key parameter to measure the vulnerability of tree species to drought (Cochard *et al.* 2008). Hydraulic traits, such as the water potential at which 50% of hydraulic conductivity is lost (P_{50}) provides an indicator of xylem embolism resistance and has considerable adaptive variation across species and biomes (Anderegg 2015). P_{50} may imply a distinct ordering of co-occurring species' risks to drought mortality (Trugman *et al.* 2021), making it potentially relevant for modeling of forest die-off under climate change scenarios. By analyzing the impact of the extreme 2018 summer drought on Central European forests, Schudlt *et al.* (2020) suggest that hydraulic failure through tissue dehydration and partial or complete loss of xylem functionality are involved in drought-induced mortality that may also predispose trees to subsequent pest attacks.

According to Lobo *et al.* (2018), the two Mediterranean species with lowest hydraulic conductance and hence more resistant to xylem embolism were *Q. ilex* (-7.13 MPa) and *Q. suber* (-5.52 MPa). In the same way, Vaz *et al.* (2012) recorded a P50 of -5.02 MPa for a Portuguese cork oak population. Values of P_{50} slightly varied between three Tunisian pine species (-4.19 MPa for *Pinus halpensis*; -3.7 MPa for *Pinus brutia* and -4.08 MPa for *Pinus canariensis* (Cherif *et al.* 2019). It is interesting to point out the scarcity of data on xylem water potential that leads to a 50 % loss in hydraulic conductivity for Tunisian forest trees

species. Unpublished data (T. Rzigui) showed that no significant difference exist between two Tunisian contrasting populations of *Q. suber* concerning P_{50}. Moreover relative water content (RWC) and leaf water potenatial (Ψ_{leaf}) at which the turgor pressure is lost does not differ between the two studied populations. In the same context, Lobo *et al.* (2018) found no significant genetic differentiation in resistance to embolism among different provenances originating from different climatic regimes within *Q. petraea*.

Tunisian forests are mostly covered by coniferous species with *Pinus pinea* and *Pinus halepensis* representing together nearly 40 % of all forest stands and occupying a prominent place in forestry production (DGF 2010). The use of *Pinus brutia*, an Eastern Mediterranean species, in reforestation has yielded highly encouraging results, especially in humid and subhumid climates (DGF 2005). Studies that have addressed the response and adaptation of pine species to changes in climate are less than those who have studied cork oak in relation to climate change. Dendrochronological approach and gas exchange techniques were used to study the adaptation of *Pinus halepensis*, *Pinus pinea*, and *Pinus brutia* growing in a 47-year-old common garden experiment to the local subhumid climate in Northeastern Tunisia (Fkiri *et al.* 2020). The transpiration rate is an important component of water-use efficiency (WUE), and is assumed to play a fundamental role in adaptation, productivity, and survival under drought conditions (Lauteri *et al.* 1997). Table 2 shows that *Pinus halepensis* and *Pinus brutia* had the same WUE, which was less than that of *Pinus pinea*. There was a positive relationship between WUE and growth in the studied three pine species. The response of the growth pattern to the climate depended on the species, and *Pinus pinea* showed the highest radial growth and water-use efficiency. So, *Pinus pinea* was the best suited to the pedoclimatic conditions in the sub-humid bioclimate in Northeastern Tunisia (Table 2). Fkiri *et al.* (2020) provided useful results for developing appropriate pine species management strategies in an area where the climate is shifting towards longer summer drought periods, higher mean temperatures, and altered seasonality of moisture availability.

In Kroumirie forest, northwestern Tunisia, Nasr *et al.* (2011) measured WUE in a *Quercus suber* forest as an attempt to explain the forest decline. The result of this study demonstrated that elevated light intensity reduces the WUE during the growing season and alters the water transit on cork oak trees and forest. These conditions caused a physiological imbalance on the individual trees and ultimately had shown the visible phenomenon of dieback. They concluded that the elevated light intensity has severe effects on WUE of the cork oak forest.

The dieback phenomenon has been observed in many populations during the last years. Tlili *et al.* (2014) studied the impact of climate and environmental conditions on the distribution of cork oak populations under adverse conditions like water and temperature stresses. They reported a significant increase in leaf mass per area (LMA) according to decreased water availability and increased temperature. LMA decreases usually imply more rigid and thicker leaves. The study classed the occurrence sites of cork oak by fertility based on the LMA and dendrometry measurements in Tunisia based on environmental conditions. The results obtained are important to choose the best ecotypes of cork oak in reforestation programs.

Variability in drought response at the population level

Climate change induces in the Mediterranean region more frequent and extreme events, namely, heat waves and droughts, disturbing forest species and affecting their productivity and product quality (Leite *et al.* 2020). The impact of drought on Tunisian cork oak physiology and growth was addressed in numerous studies. Rzigui *et al.* (2018) investigated how the geographical origin of seeds might affect early responses to drought stress in cork oak seedlings (Figure S3). They showed that provenance exhibiting lower stomatal and hydraulic conductance had better tolerance to water deficit. These physiological changes are likely to be the consequence of divergences between populations and phenotypic plasticity.

In the Mediterranean basin, the forest is constrained by water availability as a limiting factor and high temperature during the summer. As an example, 2021 summer temperatures in cork oak forests in Tunisia reached 49 °C with an average maximum temperature of about 36.7 °C in August. A global understanding of the ability of cork oak populations to deal with summer drought stress and to adapt to extreme temperatures is crucial for assessments of the future of cork oak forests as a major ecosystem in the Mediterranean basin. In this sense, Jazzar *et al.* (2019) examined the effect of summer drought on photosynthetic capacity in three *Quercus suber* populations all native to different regions with various ecological conditions. The finding confirmed previous studies showing a large population-level differentiation in cork oak with population from dry sites exhibiting a higher tolerance (Figure S3).

Forest thinning and natural leguminous species/cork oak association to mitigate drought stress

Identifying physiological indicators such as water use efficiency under different forest managements is crucial to predict how plants will respond to climate variations. Ennajah *et al.* (2016) estimated the carbon stock and the water stock in the soil using thinning practices in pine forests. Results showed that the dendrometric parameters, the carbon stock, the water storage are significantly higher at the site with thinning than into the site without thinning. These results indicated that a silvicultural practice of thinning can significantly affect the efficiency of water and carbon use and the light interception into an environment that is increasingly characterized by a water deficit and give our forest ecosystems more resilience to the global changes already underway.

Cork oak is one of the main species of Mediterranean ecosystem woodland and has high socioeconomic and environmental values especially in Tunisia. A recent study was carried out on the cork oak forest in Ain Draham (northeast Tunisia) with different types of association (Ennajah *et al.* 2020). The association of the cork oak with native plant species is considered by INRGREF institute to sustainable management tools for forest areas. Recent research's aimed to test the impact of this type of plant association on the loss of hydraulic conductance (Ennajah *et al.* 2018, 2020) on morphological (height, circumference) and ecophysiological (stomatal conductance, transpiration, etc.) parameters. Tree experimental blocks (square 20mX20m) were tested. Photosynthetic response to light levels and transpiration were carried out using an open infrared gas analysis system (Li-Cor 6400-40 equipped with a red-blue LED source; Li-Cor Inc., Lincoln, NE, USA). Measurements were developed at the natural ambient CO_2 concentration (400 ppm) and at 25 °C. Hairybroom (*Cytisus villosus Pourr.*, syn. *Cytisus triflorus* L'Hérit) is a perennial shrub of the Fabaceae family within the tribe Genisteae. This legume able to fix nitrogen in the soil and, therefore can play a very important role in revegetation programmes due to its biological features and the association of Cytisus with cork oak can increase soil fertility and the primary productivity of the forest ecosystem by providing the mineral elements to the cork oak trees (Ennajah *et al.* 2020). The highest regeneration values were observed at the block in which oak associated with *Cytisus villosus* exhibit a better eco-physiological behavior (Figure 8-A and B). Concerning the morphological parameters, an increase in the oak tree growth in diameter and height both in association with and without the *Cytisus villosus* was observed (Figure 8-C, D, E and F). The study concluded that the improvement in oak growth by *Cytisus villosus* mainly affected ecophysiological and morphological parameters. This study clearly showed the importance of preserving this type of forest heritage. The association of oak trees and *Cytisus villosus* presents a better sanitary

status and therefore a better economic, social, and environmental value, which can contribute to the conservation of the cork oak ecosystem.

CONCLUSION

Natural ecosystems have been affected by climate changes, including rising temperature and altered precipitation regimes. Warmer temperatures lead to increased water losses and can result in reduced water use efficiency of plants. In these conditions, shallow-rooted trees, as well as species growing in shallow soils, are more susceptible to water deficit. Also, the water availability represents one of the most important factors that affect plant physiological processes at the individual and ecosystem scale.

In Tunisia, climate change will have complex effects on cork oak forest ecosystems, especially with extreme drought events. Cork oak forests in Tunisia have been mainly affected by drought and warmer temperature and we estimate that their vulnerability will be more aggravated in the future. Disturbances like insect infestations and wildfires are predicted to increase in frequency and severity and will exacerbate direct climatic stresses, which could induce tree decline and mortality. Currently, it is believed that 95% of Tunisia's forest destruction is due to forest fires alone. Development of wildfire prevention plans is highly recommended. Pine species and cork oak occupy a special place in reforestation strategies in Tunisia. The adaptation and resilience of these species (pines and cork oak) to climate change has been the subject of numerous researches. We recommend selecting appropriate seeds source and suitable planting sites based on future climate projections. Planting tree species that are more likely to survive will help increase forest resilience.

This review paper suggests that environmental conditions variation should be included as selection criteria when selecting appropriate species for reforestation programs. When timber or carbon sequestration potential is a priority, tree growth can be maximized at less seasonal sites for most species. To this purpose it is recommended to enhance mutualistic relationships between species by unravel the interactions among these species in order to increase their capacities to cope with drought conditions. Further studies are needed to evaluate whether the impacts of geographic variation on physiological functions can be improved by planting association species, especially in areas that experience severe dry seasons. To mitigate climate change, we recommend foresters to enhance genetic and silvicultural management practices,

such as management of density via thinning treatments, which target the most vulnerable sites, life stages, traits and process to increase forest adaptability. .

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

AUTHOR CONTRIBUTIONS

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by I. Touhami, L. Zribi, T. Rzigui, and H. Aouinti. The first draft of the manuscript was written by I. Touhami and all authors commented on previous versions of the manuscript. All authors revised and approved the final manuscript.

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List of tables

Table 1. Values of LSP metrics of different land cover in days/years. Start of green season (SOS), end of the green season (EOS) and green season length (LOS) have been determined using NDVI thresholds in the forest area of Sidi-Zid, North-east Tunisia during the 2000-2017 period (Touhami *et al.* 2021).

Table 2. Mean Radial Growth (MRG), Net photosynthesis (An), Stomatal conductance Gs; Transpiration (E); Water Use Efficiency (WUE), Carboxylation Efficiency (CE) of three species of pine growing under sub-humid bioclimate in Northeastern Tunisia. Different letters indicates significant difference between species ($p<0.5$) (Adapted from Fkiri *et al.* 2020).

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	SOS	EOS	LOS
Tetraclinis articulata	+11.2	-7.2	-18.4
Pinus halepensis	+6.5	-2.0	-8.5
Other species	+5.7	-5.8	-11.5
Quercus suber	+13.5	-5.8	-19.4
Maquis and garrigues	+14.5	-4.4	-18.9
Average	+9.4	-5.0	-14.2

Species	MRG (mm)	An (μ mol.m^{-2}.s^{-1})	Gs (mmol.m^{-2}.s^{-1})	E (mmol.m^{-2}.s^{-1})	WUE (umol.mol^{-1})	CE (mol. m^{-2}.s^{-1})
P. halepensis	1. 97±0.02[a]	15±1.9[a]	0.09±0.0017[a]	1.66±0.2[a]	9.037±1.2[a]	0.052±0.006[c]
P. brutia	2.05±0.012[a]	10.28±1.32 [b]	0.075±0.003[b]	1.15±0.045[b]	8.94±08[a]	0.06±0.004[b]
P. pinea	2.69±0.015[b]	14.45±0.2[a]	0.07±0.001[c]	1.11±0.2[c]	10.71±1.1[b]	0.068±0.003[a]

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Figure captions

Figure 1. (A) Percentage difference in mean precipitation from the baseline period under the two scenarios RCP4.5 and RCP8.5 for northern Tunisia. Data were extracted from the online Climate Information Platform-CIP at http://cip.csag.uct.ac.za/webclient2/datasets/africa-merged-cmip5/ (B) Variation of maximal and minimal temperature for the north of Tunisia, under the two scenarios RCP4.5 and RCP8.5. Mean value of 19 meteorological stations (over Tunisia) and 11climatic models (MIROC-ESM, CNRM-CM5, CanESM2, FGOALS-s2, BNU-ESM, MIROC5, GFDL-ESM2G, MIROC-ESM-CHEM, GFDL-ESM2M reported by Taylor *et al.* 2012), (C) and (D) Temperature anomalies for the principal meteorological stations of Tabarka and Jendouba, northern Tunisia, respectively.

Figure 2. Dynamic characteristics of SPEI time scale-48 for the 1955-2021 period for the principal forest regions in Tunisia. Graphic 1- Bizerte: *Eucalyptus and Pinus pinea* L. forests; graphic-2 Béja and graphic 3- Jendouba: *Quercus suber* L. forests; graphic 4-Cap Bon: *Tetraclinis articulata* (Vahl) Mast. forests; graphic 5-Siliana and 6-Kasserine: *Pinus halepensis* Mill. forests. Tunisian map shows an example of the spatial distribution of SPEI-48 for the year 2022. Data maps were extracted from the website at https://spei.csic.es/database.html

Figure 3. Response function analysis of the residual tree-ring chronology of *Quercus suber* in the Bellif forest, northern Tunisia, to monthly climatic data from October (t $_{-1}$) to September (t) for the period 1974–2002: (A) monthly average precipitation (in blue) and maximum temperature (in black) and (B) monthly average precipitation (in blue) and minimum temperature (in grey) (adapted from Zribi *et al.* 2016); (C) and (D) represents the response functions for *Pinus halepensis and Pinus pinea* in Bizerte region, northern Tunisia, with monthly average precipitation (in blue) and maximal temperature (in black) from the period 1950-2014 (adapted from Bouachir *et al.* 2017). Values are significant at 90%, 95%, and 99% levels.

Figure 4. (A) Forest cover loss (a change from a forest to non-forest state) in Tunisia between 2000 and 2020 (Data extracted from the Global Forest Watch web site at https://www.globalforestwatch.org/), and (B) Average precipitation anomalies between 2000-2020 period based in the reference 1900-1940 period. Climatic data were provided by the NOAA/ESRL Physical Sciences Laboratory, Boulder Colorado from their web site at https://psl.noaa.gov/ and based in the work of Willmott and Matsuura (2001).

Figure 5. (A) Number of fires; (B) Burned area in km². Data extracted from the European Forest Fire Information System- EFFIS at https://effis.jrc.ec.europa.eu/; (C) Fire alerts, represented by yellow dots based in Visible Infrared Imaging Radiometer Suite-VIIRS from 10 July 2021 to 08 October 2021. Data extracted from the Global Forest Watch-GFW at https://www.globalforestwatch.org/

Figure 6. (A) *Quercus suber* L. affected by prolonged drought Tebaba, North Tunisia. Octobre 14, 2021; (B) *Cupressus sempervirens* L. affected by drought, South orientation (Ennahli Park). December 02, 2020; (E) *Pinus halepensis* Mill. affected by drought in northern Tunisia (Boukornine National Park). May 13, 2019, Orientation Sud-East. (D) and (E) deforestation more than 400 *Quercus canariensis* Willd. trees cut illegally in northwestern Tunisia (region of Aïn Hmairia and Aïn Salem, delegation of Aïn Draham. April 2020. Photos

by I. Touhami.

Figure 7. (A) Eucalyptus dieback; (B) Phoracantha damages on the eucalypt tree; (C) Phoracantha larva boring into tree eucalypt wood; (D) Adult Phoracantha semipunctata. Nefza, Northern Tunisia. August 2020. Photos by S. Dhahri; (E) Tortrix viridana (http://home.tiscali.be/entomart.ins); (F) Orgyia trigotephras. Photo by Paul Bonfils. June 2021; and (G) Larva of Thaumetopoea pityocampae.

Figure 8. A) Net photosynthesis-PN in (μmol CO_2 m^{-2} s^{-1}); B) Transpiration rates in (mmol H_2O m^{-2} s^{-1}); C) Diameter at Breast Height (DBH) in (cm); D) height in (m); E) Growth Unit Length in (cm) and (F) Leaf Mass per Area (g/m^2) of *Quercus Suber* in the three blocks: S1 (cork oak with *Cytisus villosus*); S2 '(cork oak alone); S3 (cork oak with scrub). Cork oak density = 40 oak tree in block 1, 35 in block 2 and 20 in block 3.Values followed by the common letter, between blocks, indicate that there are no significant differences. However, means followed by a different letter are significantly different according to Tukey's Least Significant Difference (LSD) test (*P < 0.05, **P < 0.01, and ***P < 0.001).
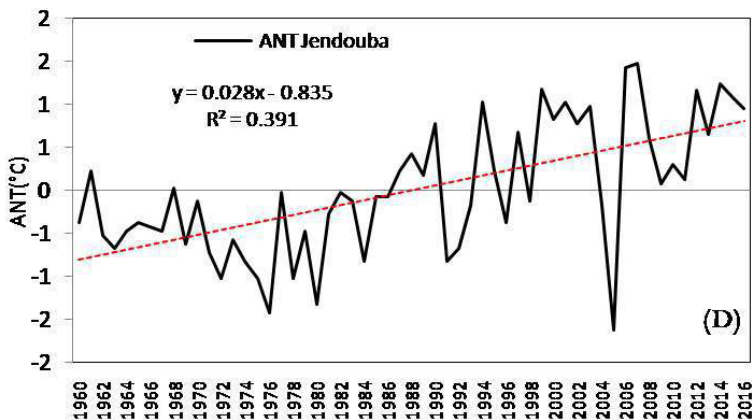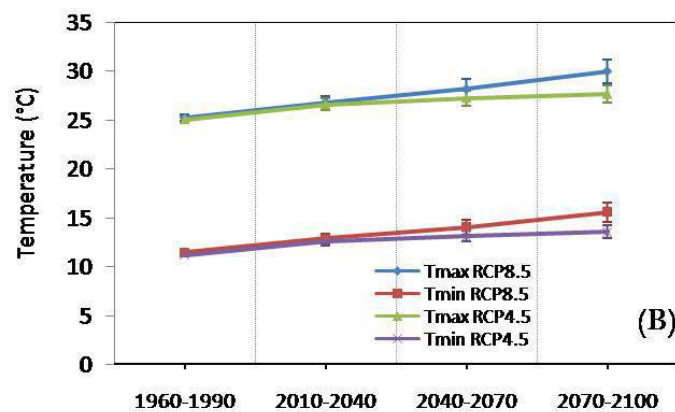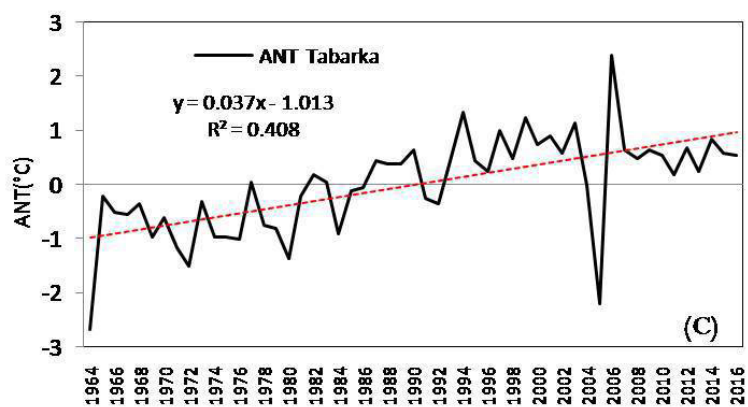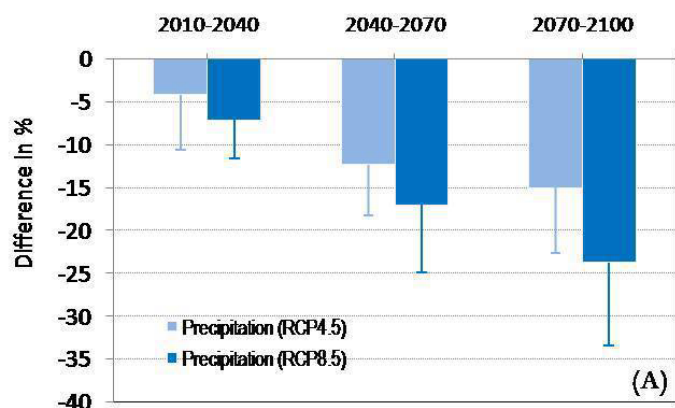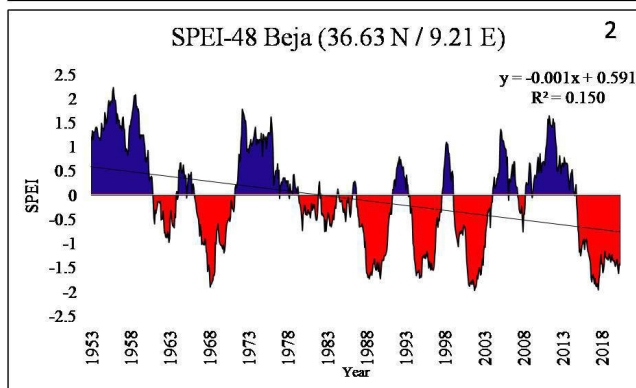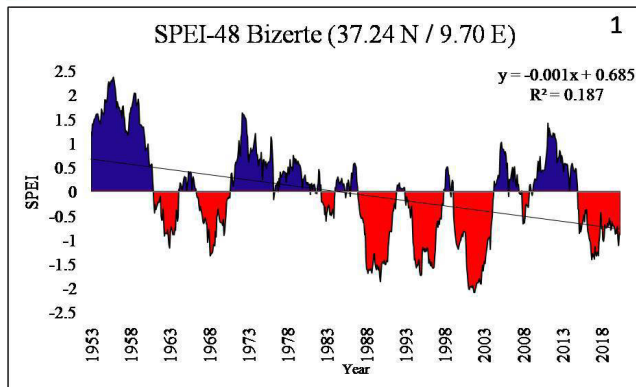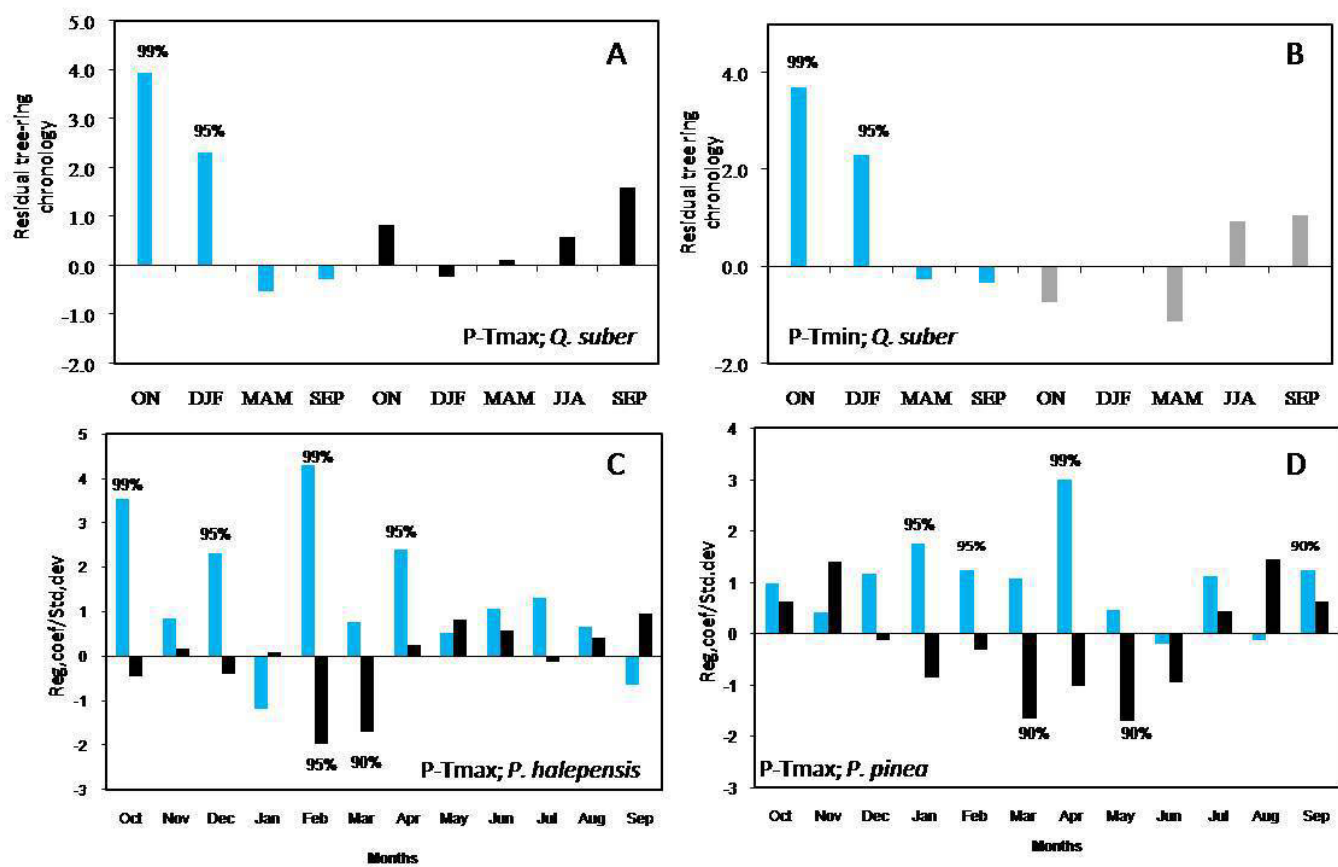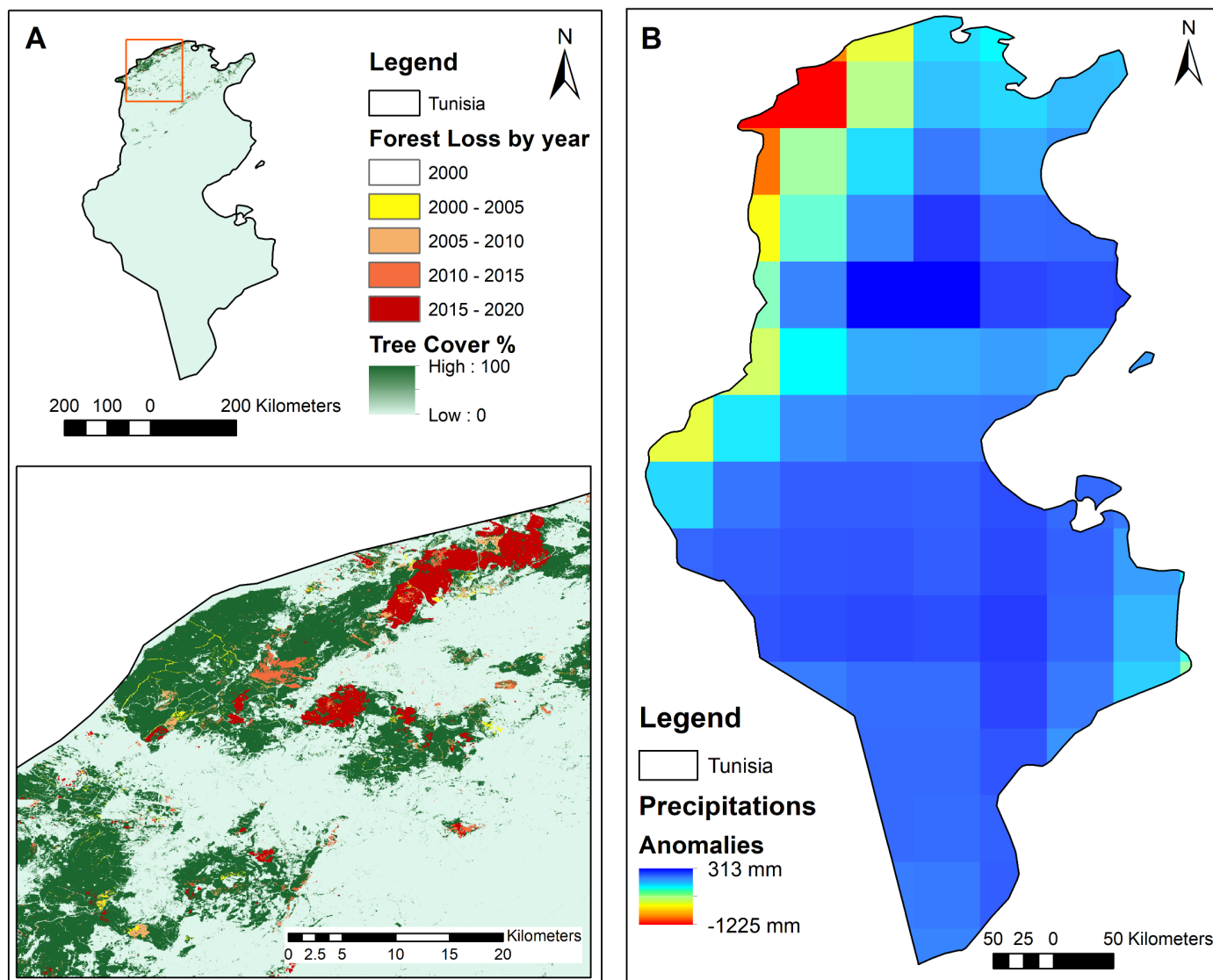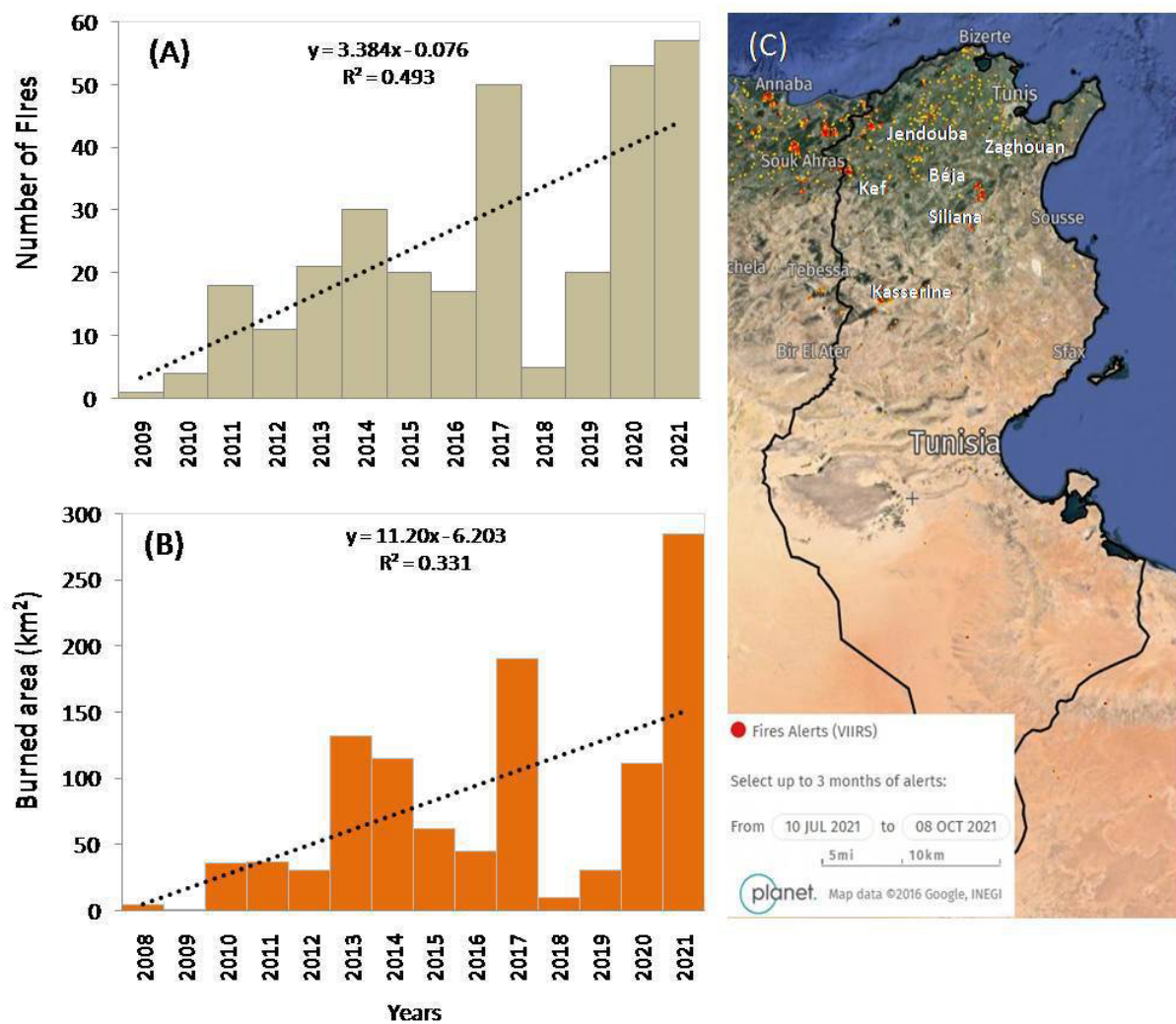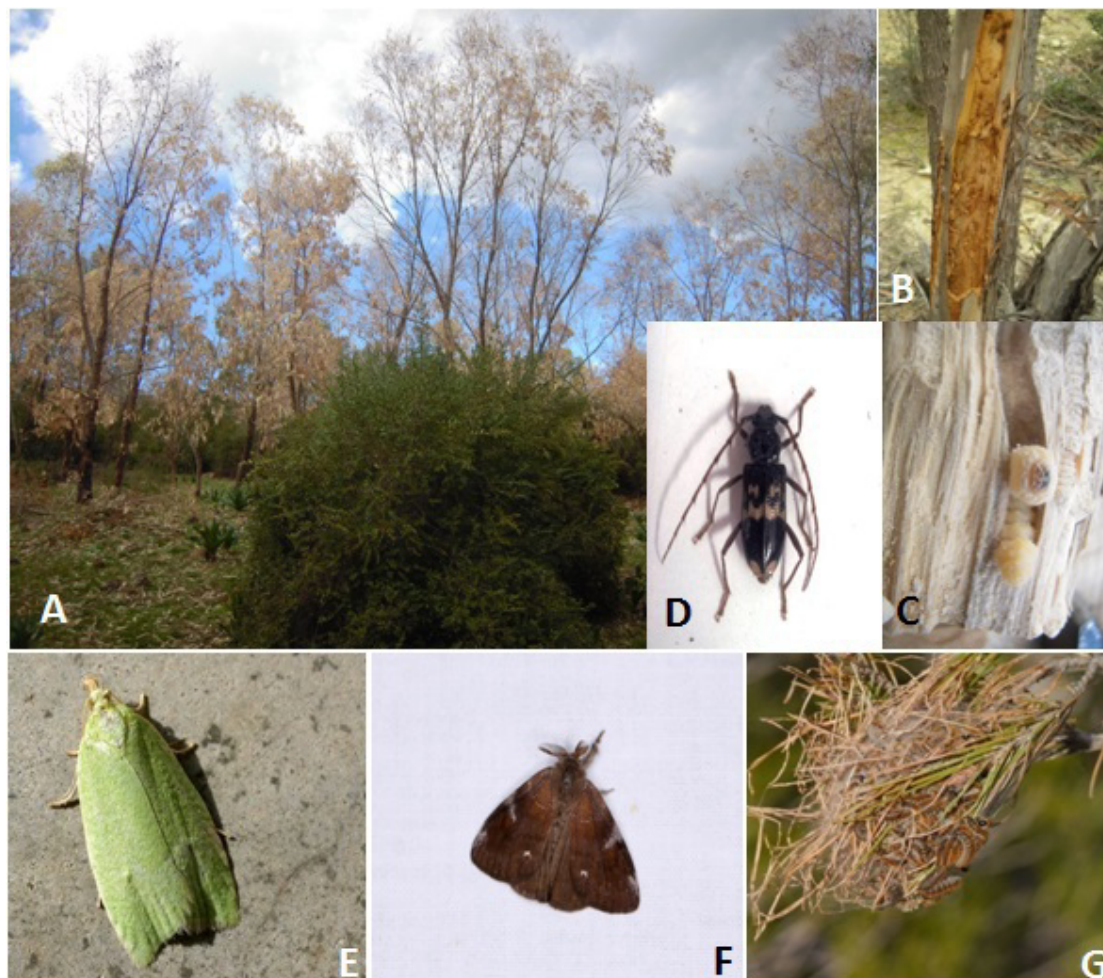
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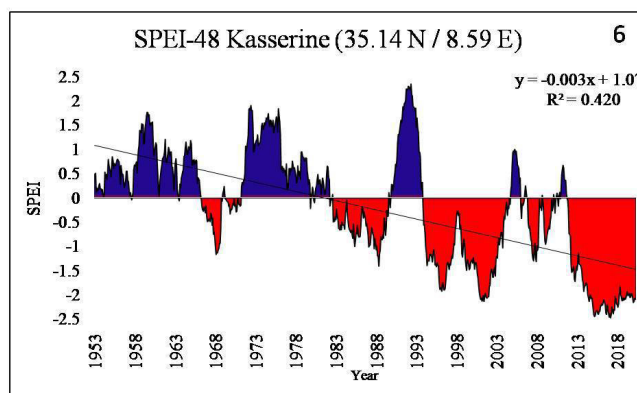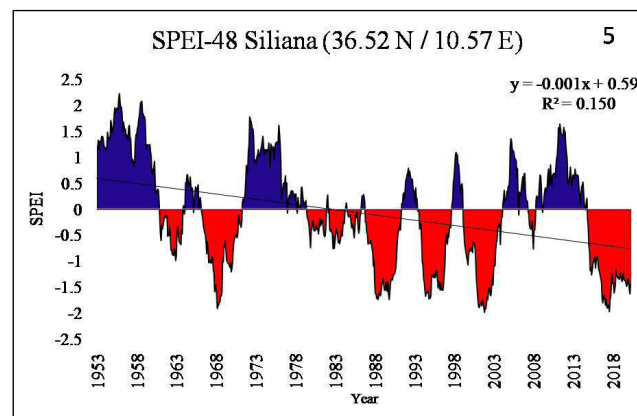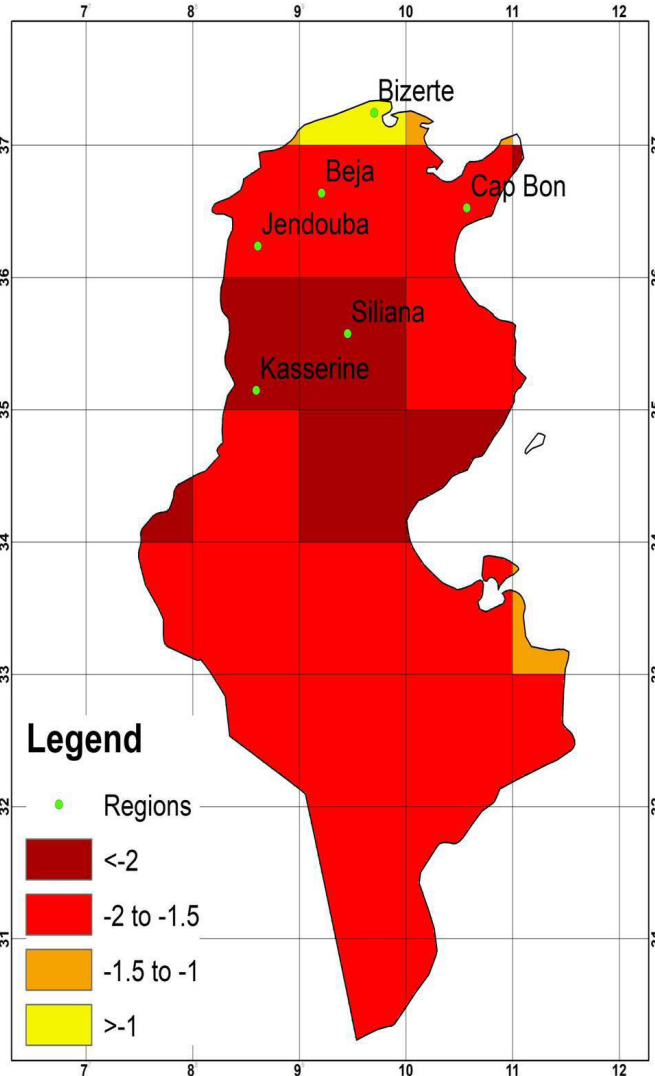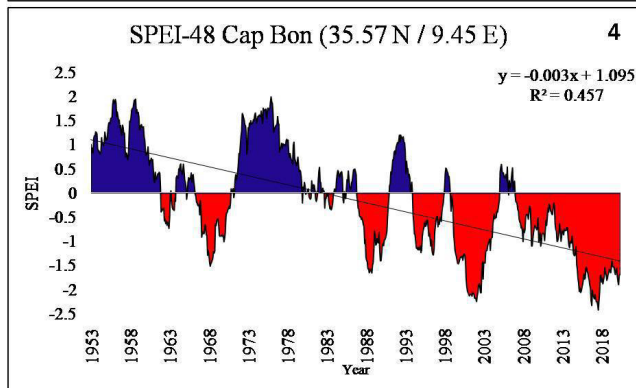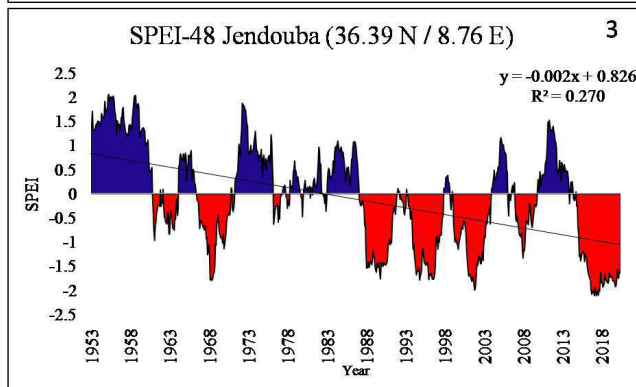
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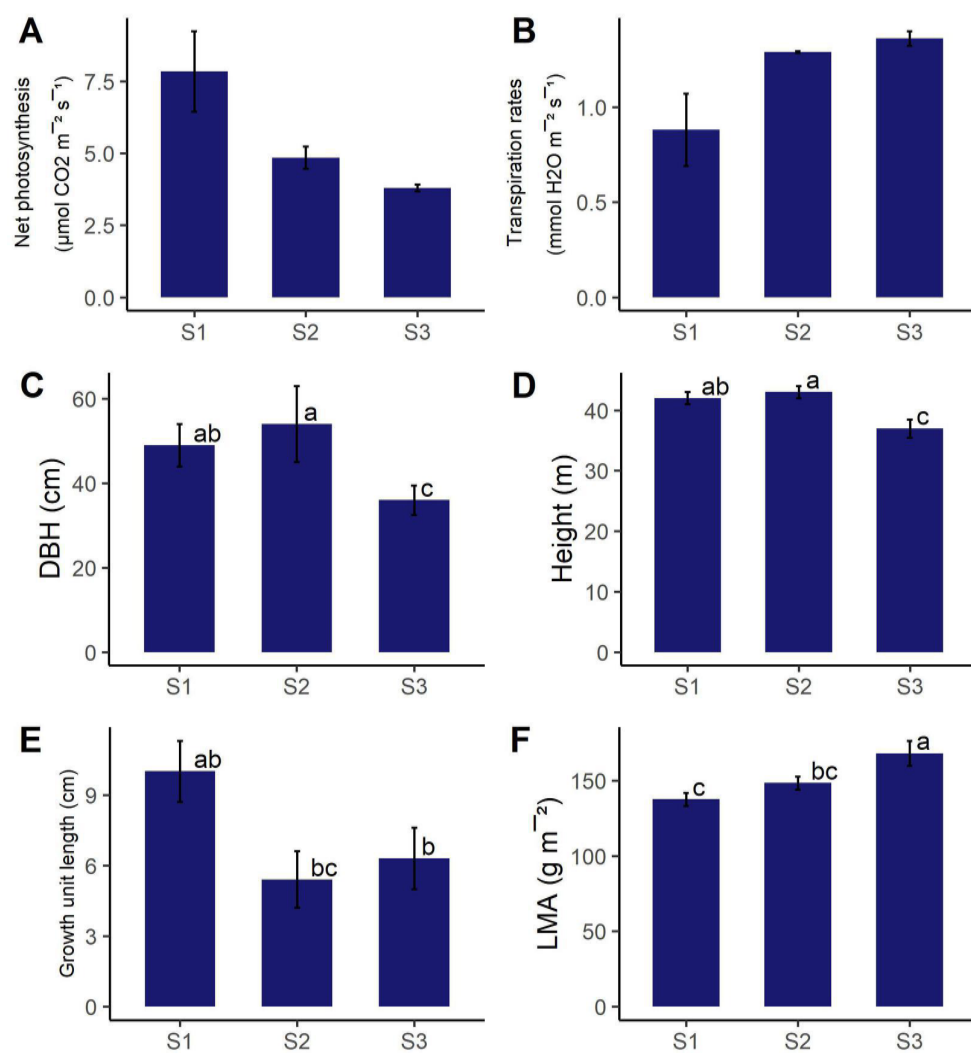Figure 3.jpg

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