

Effect of climate change on the spatial distribution and cork production of *Quercus suber* L., the risk of exclusion by the Aleppo pine expansion, and management practices to protect *Q. suber* habitat: A review

Kaouther MECHERGUI^{1*}, Amal S. ALTAMIMI², Wahbi JAOUADI^{1,3},
Souheila NAGHMOUCHI¹, Youssef AMMARI¹

¹University of Carthage, National Institute of Research in Rural Engineering, Waters and Forests, B.P. 10, Hédi Karray Street, Menzeh IV, Ariana 2080, Tunisia; mecherguikaouther2015@gmail.com (*corresponding author);
den_souheila@yahoo.fr; ammari_youssef@yahoo.fr

²Princess Norah Bint Abdulrahman University, Biology Department, College of Science Riyadh, Saudi Arabia; amal.alfawaz@gmail.com

³University of Jendouba, Silvo-Pastoral Institute of Tabarka, B.P. 328, 8110 Tabarka, Tunisia; jaouadiwahbi@gmail.com

Abstract

Climate change represents an important challenge for forest management and the silviculture of stands and it is known that climate change will have complex effects on cork oak forest ecosystems. North Africa and the Mediterranean basin are especially vulnerable to climate change. Under the effect of climate change, cork oak will disappear from a large area in the future, and the rest will migrate to higher altitudes and latitudes. This study aimed to evaluate the effect of climate change on the spatial distribution of *Quercus suber* L. and cork production in the Mediterranean area, and the risk of its exclusion by the Aleppo pine (*Pinus halepensis* Mill.) expansion. The literature review showed that up to 40% of current environmentally suitable areas for cork oak may be lost by 2070, mainly in northern Africa and the southern Iberian Peninsula. Temperature directly influences atmospheric evaporative demand and should affect cork productivity. Precipitation is the main factor that positively influences cork growth and several authors have confirmed the negative effect of drought on this growth. Currently, cork oak habitats are colonized in several places mainly by the Aleppo pine. Under climate change, Aleppo pine is projected to occupy higher altitude sites and several authors have predicted that current and future global warming will have a positive influence on Aleppo pine growth in wet sites. In the future and under climate change, there is a strong possibility that the Aleppo pine will colonize cork oak habitat. Finally, we proposed management practices to protect cork oak against climate change and Aleppo pine expansion.

Keywords: Aleppo pine; climate change; cork oak; cork production; expansion; management practices; potential distribution

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Introduction

Climate change represents an important challenge for ecologists, biologists, and modelers, whose research interest is the study of the potential effect of climate change on ecosystem services provided by forests (Deal *et al.*, 2017; Fréjaville *et al.*, 2019). A rise in the mean temperature and variation in rainfall patterns could modify the current distribution of plant species (Lopez-Tirado *et al.*, 2018). Over the last few decades, the scientific community has become increasingly concerned with climate change. More extreme climatic conditions, such as rising mean temperatures and variations in rainfall patterns, are expected within the present century (IPCC, 2014). The Mediterranean basin is especially vulnerable to climate change (Goubanova and Li, 2007). Recent climatic projections for the Mediterranean basin predict an air temperature increase and a decline in rainfall, mainly during the summer period, resulting in extended periods of soil water deficit (Gratani *et al.*, 2016; IPCC, 2014). Prolonged dry periods result in a negative soil water balance as the amount of water that evaporates overcomes the amount of water intercepted by the soil through rainfall and summer humidity (Brunetti *et al.*, 2002; Moretti *et al.*, 2015). Species might undergo a marked risk of local extinction with a consequent fragmented distribution, especially in North Africa and Iberia (Benito Garzón *et al.*, 2008; Klausmeyer and Shaw, 2009). If the habitable area is reduced for this species, or the potential for its permanence is predicted to be limited in a given location, other species may establish within the ecosystem (Pons and Pausas, 2006; Lopez Tirado and Hidalgo, 2016a). Tree species may undergo shifts in distribution within a short time owing to the effect of global change. This is especially important for species growing at the boundaries of their current distribution Lopez-Tirado and Fidalgo (2016a). Despite the massive impact of global warming predicted by the models in the southern Mediterranean, some areas would maintain their suitability for species occurrence, thus assuming an important role in terms of biodiversity conservation. These areas might be worthy of a deeper scientific investigation and public awareness for preserving cork oak from extinction. Global climate change affects ecosystems worldwide (Parmesan and Yohe, 2003; Parmesan, 2006). Forest ecosystems are particularly susceptible to shifts in natural disturbance regimes induced by climate change (Dale *et al.*, 2001; Trumbore *et al.*, 2015). Given this, the niche modeling approach could be considered as a promising tool for planning, monitoring, and managing native populations and their habitats (Araujo and Williams, 2000; Costa *et al.*, 2010; Lemes *et al.*, 2014). Climate change will inevitably affect species geographical distribution, change species composition and richness, impact biodiversity, and influence the structure and function of ecosystems (Thuiller *et al.*, 2011; Scheffers *et al.*, 2016). Dyderski *et al.* (2018) quantified changes in the habitats of 12 European forest tree species, demonstrating that most of these species would face severe habitat contraction due to climate change. Several authors have worked on the decline and dieback of cork oak (*Quercus suber* L.) forests in the Mediterranean basin: (i) Climate change impacts on cork forest decline in the Mediterranean basin: Cases of drought and/or heat-induced forest mortality, elevated CO₂ concentration, high temperatures, water deficit, and (ii) Other factors affecting cork oak forest decline: Anthropogenic pressure and wildfire insect epidemics and disease problems of cork oak forest regeneration. These authors ignored the phenomenon of the expansion of cork oak forests by other species (colonization), mainly the Aleppo pine in North Africa and in the Mediterranean area, which happens to be the main factor in the degradation of cork oak forests. In this study, we show the following:

- (i) Several studies have shown that under the effect of climate change, cork oak will disappear from a large area in the future and the rest will migrate northward as well as to higher altitudes.
- (ii) Other studies have shown that the Aleppo pine is too plastic a species and will move in the future to areas with a humid climate.
- (ii) Other authors have shown that currently cork oak habitats is colonized in several places mainly by the Aleppo pine.

The questions posed in the present study are as follows: 1) In the future, will Aleppo pine colonize the cork oak habitat under the effect of climate change? 2) Will the studies and modeling of the spatial distribution under the effect of climate change of cork oak and Aleppo pine justify existing hypotheses?

We aimed to answer the above questions based on current localities and in several others that seem apt for the Aleppo pine to invade cork oak forests under the effect of climate change. We intended to better understand if this is a true threat to cork oak forests in Northern Africa and the Mediterranean basin.

Potential impact of climate change on the spatial distribution of cork oak forest

The genus *Quercus* comprises 531 species worldwide (Govaerts and Frodin, 1998). Oaks are widely represented in the northern hemisphere, where they constitute one of the most important groups in terms of ecology, biodiversity, and economy (Axelrod, 1983; Menitsky 2005; Cañellas *et al.*, 2005, 2007; Nixon, 2006). Cork oak (*Q. suber* L.) is a strictly Mediterranean species distributed in the western Mediterranean basin, between southwestern Europe and northern Africa (Figure 1), a climatic, ecological, and socioeconomic sensitive region (Costa *et al.*, 2014). Cork oak woodland is considered a keystone ecosystem (Vicente and Alés, 2006) while enhancing other important provisioning and regulating ecosystem services (Plieninger *et al.*, 2014). Moreover, cork oak woodland is an important biodiversity hotspot where cork oak is harvested throughout their lifetime for their bark (Oliveira and Costa, 2012), the cork being a valuable global non-timber forest product (FAO, 2013). Cork oak is an evergreen tree characterized by a thick bark, which grows in Mediterranean sclerophyllous forests (Hidalgo *et al.*, 2008). Cork oak woodlands are agro-silvopastoral systems of high socio-economic and conservation value, typical of the western Mediterranean Basin (Figure 2). They cover approximately 1.5 million hectares across Portugal, Spain, Italy, and France, and 1 million hectares in North Africa between Morocco, Algeria, and Tunisia (Díazetal, 1997; Bugalho *et al.*, 2011). North-facing slopes, abundant annual rainfall, and the original stones that produce acidic soils were the main explanatory variables for cork oak distribution in southwestern Spain (Hidalgo *et al.*, 2008).



Figure 1. Geographic location of Cork oak in the world (Caudullo *et al.*, 2017)



Figure 2. Stand of cork oak in North Africa (Tunisia)

Most of the studies carried out on oak decline in Italy and Spain reported drought as the main driving factor. Although this phenomenon seems generalized and strictly related to site-specific conditions, drought, and in general, ongoing climate warming is identified as the main threat to declining oak stands (Gentilesca *et al.*, 2017). The increase in temperature values and the decrease in precipitation expected for the southern part of the Mediterranean would reduce the habitable areas for cork oak (Vessella *et al.*, 2017). The future distribution of evergreen oaks is most likely driven by climate change (Schirone *et al.*, 2015). Under climate change, the first species that disappears is *Q. suber* a species that does not withstand very low temperatures in continental areas (Costa Tenorio *et al.*, 2005), followed by *Quercus coccifera* in the inner continental areas (Lopez-Tirado *et al.*, 2018). Using maximum entropy modeling (MaxEnt), Correia *et al.* (2017) predicted environmentally suitable areas for cork oak (*Q. suber*) woodlands, a socio-economically important forest ecosystem protected by the European Union Habitats Directive. The authors showed that up to 40% of current environmentally suitable areas for cork oak may be lost by 2070, mainly in northern Africa and the southern Iberian Peninsula. Almost 90% of new cork oak stands are predicted to lose suitability by the end of the century, but future plantations can take advantage of increasing suitability in the northern Iberian Peninsula and France. According to Lopez-Tirado *et al.* (2018) in the predicted future scenarios, cork oak is the species with poleward migration, barely reaching France (only a small suitable area on the Atlantic coast). The authors showed that under climate change, *Q. suber* dominates mainly in Portugal and along a belt following the south Atlantic coast of Spain. Vessella *et al.* (2017), in a study of cork oak in the face of climate change in the Mediterranean area, showed that the results of eight combined ecological modeling techniques and two global circulation models highlight a broad contraction of the species potential range over the twenty-first century, both under intermediate and high emissions scenarios. The authors found that coupled northward and upward shifts were predicted, mostly pertaining to Iberia and North Africa and the potential areas detected at Levantine will likely undergo disappearance. The Mediterranean region is projected to be extremely vulnerable to global change, which will affect the distribution of typical forest types such as native oak forests (Acácio *et al.*, 2016). Climatic extremes are also important predictors of oak forest changes, namely extreme temperatures for evergreen oak forests and deficit of precipitation for deciduous oak forests (Acácio *et al.*, 2016). In fact, according to Lopez-Tirado *et al.* (2018), evergreen oaks could benefit from global change, making up larger mixed forests than the current ones. The influence of global warming is also imprinted into the upward shift in elevation, which would be experienced by cork oak, mostly in the southwestern part of its potential suitable area (Vessella *et al.*, 2017).

The increased concentration of greenhouse gases in the atmosphere is acknowledged as one of the main reasons for the observed global climatic change. This phenomenon significantly affects the species geographical distribution and changes their richness distribution pattern (Sun *et al.*, 2020). Costa Tenorio *et al.* (2005) showed that although holm oak and cork oak forests are estimated to have spanned up to 30 million hectares in the past, their current distribution is limited to about 2-3 million hectares worldwide. However, according to Vericat *et al.* (2012), Mediterranean oak formations presently occupy around 7.3 million hectares. Drought and temperature instability could pose a threat to the distribution of *Q. suber*L., inducing shifts and reductions of distribution ranges, thus eventually changing the richness distribution pattern (Sun *et al.*, 2020). The authors showed that the distribution center of *Q. suber*L., is migrating towards the northeast in response to climate change. This has also been confirmed by numerous studies of different species in different regions (Peñuelas and Boada, 2003; Vessella and Schirone, 2013; Dyderski *et al.*, 2018). Under climate change, the southern areas of the current distribution of oak corks will be the most affected, including Alentejo and Algarve in Portugal, Extremadura, and Andalucía in Spain, and most of North Africa (Correia *et al.*, 2017). In the southernmost region, which includes North Africa and parts of Iberia, the expected decrease in suitability is so great that resources should be concentrated in the preservation of the few refuges where microclimatic conditions will maintain long-term suitability for the species (Dobrowski, 2011). In the Mediterranean climatic region, a warming condition is forecasted, and the distribution of native oak forests could be affected (Lopez-Tirado *et al.*, 2018). In the period between 1966-2006, a given area of cork oak forest in Portugal was altered mostly to pine and eucalyptus (Acácio *et al.*, 2016). Pecchi *et al.* (2020) showed that the analyses reported an unchanged amount of total land suitability for forest growth in mountain areas, while smaller values were predicted for valleys and floodplains compared to high-elevation areas. The authors showed that pure woods were predicted as the most influenced when compared with mixed stands, which are characterized by greater species richness. Therefore, a higher level of biodiversity and resilience reduces the threats of climate change on a forest. In southern Spain, Lopez-Tirado and Fidalgo (2016a) showed that under climate change effects, cork oak and gall oak underwent a drastic potential reduction. On the other hand, the Pyrenean oak and Algerian oak might find shelter at higher elevations. By exception, holm oak exhibited the opposite trend and was favored by projected global warming. This projection is rather adverse for biodiversity and oak-dependent ecosystems. Acácio *et al.* (2016) showed that under increasing human pressure and forecasted climate change, evergreen oak forests will continue to decline and deciduous oak forests will be replaced by forests dominated by more xeric species. According to Sun *et al.* (2020), climate change affects the richness distribution pattern of oaks (*Q. suber*L.), and these species may migrate to higher altitudes or higher latitudes. The high percentage of species lost is the reason for the higher turnover values in the mountainous areas, while other regions are mostly influenced by the high percentage of species gained associated with the northward shift of species. Predicting changes in the richness distribution pattern of *Q. suber*L. as a result of climate change can help to understand the biogeography of *Q. suber*L. and enact conservation strategies to minimize the impacts of climate change (Sun *et al.*, 2020).

The cork production of *Quercus suber*L.

Climate-growth relationships

Cork oaks are well-known for cork production (Figure 3), a non-wood forest product of high industrial value that economically strengthens the otherwise fragile production regions (Oliveira *et al.*, 2016). Cork is a biological material with a rather unique set of properties that gave it worldwide recognition as a wine sealant and insulator (Fortes *et al.*, 2004; Pereira 2007, 2015). During summer droughts, Mediterranean oak transpiration is mainly supplied by direct groundwater and subsoil water uptake through deep roots (David *et al.*, 2007, 2013). On the other hand, Besson *et al.* (2014) reported that the accumulated tree transpiration matched the precipitation in spring at the stand level and suggested that the cork oak trees rely on water sources

from precipitation during the peak of the growing season that is made available to the many superficial roots. Temperature directly influences atmospheric evaporative demand and should affect cork productivity (Rambal *et al.*, 2003). Cork growth recorded a high climate signal, with highly significant and coherent responses to the yearly climate-related sources of variation (Costa *et al.*, 2016). The authors concluded that the high mean sensitivities and inter-series correlations found for cork ring chronologies combined with the significant variance explained by climate variables suggest that climate is likely one dominant signal that affects cork growth, but local environmental stresses can decisively affect this climate signal.

Oliveira *et al.* (2016) showed that precipitation is the main factor positively influencing cork growth in the Coruche region, one of the major cork production areas in Portugal. Temperature had a positive influence on growth at the beginning of post-dormancy phellogen activity (until April) but exerted a negative influence during the growth period (from May to August). The authors suggest that cork growth is strongly hindered by drought conditions related to spring precipitation. Precipitation and temperature have been recently found to be clearly imprinted in cork rings (Oliveira *et al.*, 1994; Caritat *et al.*, 1996, 2000; Costa *et al.*, 2003, 2015). Unlike the wood rings, which are often faint and indistinct (Natividade, 1950; Sousa *et al.*, 2009), cork rings have clear boundaries and climate seems to be the dominant signal. Ghalem *et al.* (2018) suggested that cork growth encodes a climatic signal and drought-driven cork growth reduction is a threshold function of the precipitation–temperature ratio, and with an expected increase in drought occurrence under changing climate conditions, cork growth is likely to be similarly affected in Mediterranean regions. Lack of precipitation effectively reduces soil water availability and lowers groundwater levels and, thus, directly constrains the cork-ring widths that are formed in each growing season, with important implications for cork yield (Mendes *et al.*, 2016).

Leite *et al.* (2019) confirmed the outcomes of several studies on the negative effects of drought on cork growth (Caritat *et al.*, 1996; Costa *et al.*, 2016; Oliveira *et al.*, 2016), reinforcing that spring and winter rain strongly influence phellogen activity. Ghalem *et al.* (2018) found precipitation–temperature index thresholds below which cork growth should be constrained in drier climatic conditions. The climate/growth relationships are remarkably strong in young trees (< 30 years) of *Q. suber* (Leal *et al.*, 2008). A strong direct cork growth response has been found to be connected to the previous year's winter precipitation (Caritat *et al.*, 1996, 2000; Costa *et al.*, 2001), together with a generally inverse relationship with monthly (summer) temperature (Caritat *et al.*, 2000). Costa *et al.* (2016) showed that climate is likely the dominant signal affecting cork growth in mature trees under cork exploitation. However, a similar direct effect of precipitation on cork growth across Mediterranean environments may not be straightforward, because limiting local environmental stresses, related to (soil) water availability, would affect the strength of climate signals on cork rings. Most of the studies carried out on oak decline in Italy and Spain reported drought as the main driving factor (Gentilesca *et al.*, 2017). The authors concluded that although this phenomenon seems generalized and strictly related to site-specific conditions, drought, and in general, ongoing climate warming is identified as the main threat to declining oak stands. Declining oak trees are often characterized by a reduction in ring width, mostly due to the absence or low production of late-wood in ring-porous species (Gentilesca *et al.*, 2017).

Cork-ring growth

The average cork-ring widths are between 2.2 and 4.8 mm yr⁻¹ in southwestern Portugal reported at the national (Portugal) level (Ferreira *et al.*, 2000). In Algeria growth is between 0.8 mm yr⁻¹ and 3.2 mm yr⁻¹ (Dehane, 2012) (Table 1). In Spain, the cork ring width averages are between 2.2 and 4.8 mm yr⁻¹ and ranged between 1.85 and 5.25 mm yr⁻¹ (Costa *et al.*, 2016; Caritat *et al.*, 2000). The annual average cork growth (2.43 mm) was in line with that mentioned in the European Research Project (CORKASSESS, 2001). In Spain (Andalusia and Catalonia), the annual growth was an average of 3.1 mm, ranging between 2.0 and 4.8 mm (Table 1). In Sardinia (Italy) and Corsica (France), the averages were 2.6 and 3.4 mm, respectively, ranging between values of 2.3 and 2.8 mm and 2.8 and 4.4 mm, accordingly (Chorana *et al.*, 2019). Considering only the growth of cork, the accumulated radial increment of cork during the 10 years of the production cycle ranged

between 18 and 42 mm among individual trees, with an average of 26.50 mm Chorana *et al.* (2019). This value was lower than the values shown in previous studies (Ferreira *et al.*, 2000; Aloui *et al.*, 2006): in Portugal (33.8 mm), Spain (31.7 mm), Morocco (31.5 mm), and Tunisia (28.9 mm). In addition, it was also noted that in Algeria, the thicknesses of cork in the northwest were much lower than those of the center (32.85 mm), and East (32.21 mm) of the country (Dehane and Ghifar, 2017). In a study of the average annual cork-ring width, Leite *et al.* (2019) showed that the mean value of the entire sample was 3.30 ± 1.44 mm. The values found for cork ring width by different authors are in the range of 2.8 to 3.6 mm (3.30 mm and 3.56 mm by Caritat *et al.* (2000); 3.8 mm by Costa *et al.* (2002); 3.5 mm by Pereira (2007); 3.3 mm by Oliveira *et al.* (2016); 3.6 mm, 3.1 mm, and 2.8 mm by Costa *et al.* (2016)). In a large cork sampling covering all the production regions in Portugal, a mean value of cork ring width of 3.6 mm was reported ranging from site means of 1.6 mm to 4.6 mm (Lauw *et al.*, 2018).



Figure 3. Cork production in North Africa (Tunisia)

Table 1. The annual average cork ring widths

Countries	The annual average cork ring widths	Authors
Algeria	Between 0.8 mm yr ⁻¹ and 3.2 mm yr ⁻¹	Dehane (2012)
	Between 1.9 and 2.6 mm yr ⁻¹	Ghalem <i>et al.</i> (2018).
	2.6 mm mm yr ⁻¹	Chorana <i>et al.</i> (2019)
Spain	Between 2.2 and 4.8 mm yr ⁻¹	Ferreira <i>et al.</i> (2000)
	Between 1.85 and 5.25 mm yr ⁻¹	Caritat <i>et al.</i> (2000)
	Between 2.0 and 4.8 mm yr ⁻¹	European Research Project (CORKASSESS, 2001)
	Between 3.30 mm and 3.56 mm yr ⁻¹	Caritat <i>et al.</i> (2000)
	Between 1.85 and 5.25 mm yr ⁻¹	Costa <i>et al.</i> (2016)
Portugal	Between 2.2 and 4.8 mm yr ⁻¹	Ferreira <i>et al.</i> (2000)
	The mean is 3.5 mm yr ⁻¹	Pereira (2007)
	The annual average of 1.6 and 2.3 mm yr ⁻¹	Dehane (2012)
	The means is 3.3 mm yr ⁻¹	Oliveira <i>et al.</i> (2016)
	Between 1.6 mm to 4.6 mm yr ⁻¹	Lauw <i>et al.</i> (2018).
	Between 3.8 and 4.3 mm yr ⁻¹	Chorana <i>et al.</i> (2019).
	Average 3.30 mm yr ⁻¹	Leite <i>et al.</i> (2019)
Italy	Between 2.6 and 3.4 mm yr ⁻¹	Chorana <i>et al.</i> (2019).
France	Between 2.8 and 4.4 mm yr ⁻¹	Chorana <i>et al.</i> (2019).
The accumulated radial increment of cork during the 10 years		

Algeria	32.21 mm	Dehane and Ghefar, 2017
Portugal	33.8 mm	Ferreira <i>et al.</i> (2000); Aloui <i>et al.</i> (2006)
Spain	31.7 mm	
Morocco	31.5 mm	
Tunisia	28.9 mm	

Potential impact of climate change on the spatial distribution of Aleppo pine

In one study, the potential distribution of three Mediterranean pine species (*Pinus pinea* L., *Pinus halepensis* Mill., and *Pinus pinaster* Aiton) in southern Spain in response to the forecasted increase in aridity was explored. Lopez-Tirado and Hidalgo (2016b) showed that the results predict a wider distribution of stone pine, which could expand its potential area in southern Spain. In contrast, Aleppo pine, especially cluster pine, would reduce their present distribution, with cluster pine occupying sites at higher altitudes. Pine forests are mainly concentrated in sites with poorly developed soils and under harsh climatic conditions (Cabezudo Artero and Perez Latorre, 2004). Largescale reforestation, however, has led to the introduction of pines in potential areas for oaks (Lopez-Tirado and Hidalgo, 2016b). The thermophilous nature of Aleppo pine will probably hinder migration to higher altitude sites (Lopez Gonzalez, 2007). Similar poleward and upward migration trends have also been projected by other authors (Parmesan and Yohen, 2003; Lenoir *et al.*, 2008; Bertrand *et al.*, 2012; Rabasa *et al.*, 2013) and in addition, Aleppo pine is reported as the most suitable species for the most desertification prone zones (Lopez-Tirado and Hidalgo 2016b; Fons-Esteve and Paramo, 2003). Garah and Bentouati (2019) showed that the annual thermal amplitude followed by altitude appears to be the main factor affecting the spatiotemporal distribution of Aleppo pine in the study area. The authors showed that future predictions expect an extension of the areas classified as "moderately favorable" to the Aleppo pine. The authors concluded that in response to climate change, the Aleppo pine may display two contrasting tendencies: a progressive evolution in the north, and a regressive evolution in the south of the Aurès region (Algeria), as well as a displacement of suitable areas for Aleppo pine to the north. In this context, this result coincides with the findings of Vennetier *et al.* (2011), who predicted that current and future global warming will have a positive influence on Aleppo pine growth in wet sites and negative effects in dry sites. In such cases, the Aleppo pine would reduce its present distribution in the lowest altitude areas (Garah and Bentouati, 2019). This was also predicted by Vennetier *et al.* (2005) and observed by Tirado and Hidalgo (2016) for pine species located in the southern shore of the Mediterranean.

Aleppo pine expansion in cork oak habitat

Biological invasions are dynamic processes whose extent and impact commonly increase over time, while the chances of effective intervention are reduced. The invasion of plants in mountainous areas is a particular challenge that has been increasing due to climate change and their use for tourism, among other reasons (Becker and Bugmann, 2001). Invasive species are recognized as one of the main causes of erosion of global biodiversity, and also threaten economies and human health (Millennium Ecosystem Assessment, 2005). Invasive species can profoundly affect ecological communities and processes, potentially leading to rapid or irreversible changes in trophic complexity and structure (Rodewald and Arcese, 2016). Historically, human activities have caused the accidental or planned dispersal of many species beyond their original distribution ranges, and this process is presently at its highest expression (Zalba *et al.*, 2008). Invasion changes the diversity of ecosystems and affects the provision of certain services (Simberloff *et al.*, 2010). In general, environmental factors that prevent or facilitate invasions are predictable, but other factors may be present that ultimately determine the success or failure of Pinaceae invasion, such as biotic interactions (Nunez *et al.*, 2017). Mechanical control of pine trees requires a high level of diligence to be successful. All invasive pines need to be cleared from a site and all green

foliage (when trees are felled or cut) must be removed, or trees need to be completely removed from the soil (when hand pulled) to avoid regrowth (Ledgard, 2009). Understanding the dispersal ability of an invasive species is a major challenge in attempting to predict its future potential spread (Munzbergova *et al.*, 2010).

The impacts of pine invasions have been widely recognized (Langdon *et al.*, 2010). Pines show similar invasion processes throughout the world, involving two main stages: (a) immigration and establishment and (b) population growth/expansion (Richardson *et al.*, 1994). Other impacts related to pine invasions include the reduction of structural diversity, the increase in biomass, the disruption of prevailing vegetation dynamics, and changes in nutrient cycling (Mack *et al.*, 2000; Peterken, 2001; Richardson, 2001). The successful establishment of pines and their ability to invade natural ecosystems are influenced by climate, topography, and disturbance regimes such as fires and herbivory (de Villalobos *et al.*, 2011). By definition, expansive species are species that increase their distribution and colonize new habitats in a geographical area where they are native (Prach and Wade, 1992; Pyšek *et al.*, 2004). Although the effects of alien invasive plants on ecosystems and biodiversity lead to economic losses (Didham *et al.*, 2005) and have a strong negative effect on global biodiversity (Woziwoda *et al.*, 2014; Van der Meersch *et al.*, 2020), expansion by indigenous species can have detrimental consequences on biodiversity through the reduction in ecosystem productivity, leading to a loss of various ecological goods and services, loss of genetic diversity, and decline in the abundance of populations of affected species (Pyšek *et al.*, 2004; Simberloff, 2010; Kelbel and Adamcikova, 2011).

In Tunisia, we observed the phenomenon of Aleppo pine expansion in cork oak forests in several habitats (Figures 4 and 5). Intensive regeneration of Aleppo pine under cork oak was also observed (Figures 6 and 7). According to Nathan *et al.* (1999) and Nathan and Ne'eman (2004), mean relative humidity and maximum temperature are good predictors of the release of *P. halepensis* seeds in the Mediterranean basin. The earlier release of seeds in the high areas could result in higher growth rates in this habitat, at least during the initial stages of colonization of new sites (Lavi *et al.*, 2005) and in greater risks of long-distance dispersal, considering that the peaks act as take-off sites for seeds (Ledgard, 1988; Buckley *et al.*, 2005). de Villalobos and Schwerdt (2020) showed that the effects of grazing of feral horses promote the invasion of *P. halepensis* and have provided some key information that allow the elaboration of management recommendations to avoid the propagation of *P. halepensis*. *Q. suber* is a Mediterranean species, and while it is widespread around the world, these areas are within the natural distribution of *P. halepensis*, and thus, the danger for the species replacement from *P. halepensis* invasion is high. This is the same case for the invasion of *P. pinea* by *P. halepensis* mentioned by several authors (Athanasiadis and Gerasimidis, 1986; Barbero *et al.*, 1998; Tapias *et al.*, 2004). Richardson and Higgins (1998) showed that Aleppo pine invasion can result in substantial changes in the invaded ecosystems, a decrease in biodiversity and complexity of ecosystems (Higgins and Richardson 1998; Higgins *et al.*, 1999; Richardson and Higgins, 1998), increased biomass and consequently in fire events (Richardson and Higgins, 1998), negative impact on water resources (le Maitre *et al.*, 1996), changes in soil properties, and the availability and flow of nutrients in the ecosystem (Richardson and Higgins, 1998).



Figure 4. Expansion of Aleppo pine in cork oak habitat in upstream of the mountain: North Africa (Tunisia)



Figure 5. Expansion of Aleppo pine in cork oak ecosystem in downstream of the mountain: North Africa (Tunisia)



Figure 6. Regeneration of Aleppo pine under cork oak in Tunisia

Management practices to limit the effects of climate change and the expansion effect into cork oak habitat

Management practices to limit the effect of climate change

Unlike early successional species, oaks might show considerable time lags in adjusting their ranges due to extremely slow migration rates (Delzon *et al.*, 2013; Gerber *et al.*, 2014). Current cork oak populations will therefore mostly rely on existing phenotypic plasticity, genetic diversity, and adaptation to respond to the expected scenario (Ghalambor *et al.*, 2007; Aitken *et al.*, 2008; Crispo, 2008; Alberto *et al.*, 2013; Kremer *et al.*, 2014; Bussotti *et al.*, 2015). Several provenance tests demonstrated the occurrence of the species local variability at several phenotypic and ecophysiological traits (Varela, 2001; Aranda *et al.*, 2005, 2007; Gandour *et al.*, 2007; Ramirez-Valiente *et al.*, 2010, 2011). A sustainable forest management strategy may reduce the potential impact of climate change on forest ecosystems (Pecchi *et al.*, 2020). Silvicultural practices should be aimed at increasing species richness and favoring hardwoods currently growing as dominant species under conifer canopy, stimulating natural regeneration, gene flow, and supporting (spatial) migration processes (Pecchi *et al.*, 2020). The models indicate that climate change will cause major shifts in the global distribution of cork oak woodlands. It is necessary to start addressing such shifts with appropriate mitigation and adaptation measures, as this ecosystem is particularly important for the rural economy and conservation of biodiversity in much of the western Mediterranean Basin (Bugalho *et al.*, 2011). The following practices proposed by Gentilesca *et al.* (2017) could enhance the resilience of susceptible oak stands in drought-prone Mediterranean areas: (i) controlling the understory vegetation through targeted cuts and controlled grazing; (ii) reducing aboveground biomass through selective thinning; (iii) anticipating regeneration cuts to stimulate seed dispersal and promote sexual regeneration; and (iv) shortening the rotation period of coppice stands.



Figure 7. Concurrency between cork oak and Aleppo pine in Tunisia

Management practices to limit Aleppo pine expansion into cork oak habitat

Since the habitat of *Q. suber* is of high socio-ecological importance, several authors propose that appropriate silvicultural measures should aim to conserve species habitat. These measures should include : (i) gradual transformation of even-aged *Q. suber* stands to more diversified structures (uneven, multi-aged, and multistorey stands) in order to favor the natural regeneration of the species; (ii) grazing control; (iii) careful control of the understory maquis species through the improvement of the moisture conditions in order to favor seedling establishment and growth (Ciancio *et al.*, 1986); and (vi) removal of *P. halepensis* trees in the *Q. suber* stands where the species has invaded, as early as possible, and preferably at the age before the trees reach full-reproduction. To limit the Aleppo pine expansion into cork oak habitat, it is necessary to integrate programs of development in the forest for sustainable development, and for territories and people and to introduce thinning to adapt to climate change to help reduce water competition in the forest, by controlling the understory vegetation, anticipating the regeneration cuts to stimulate seed dispersal, and promote sexual regeneration.

Conclusions

Climate change represents an important challenge for researchers studying forest silviculture and management. Several studies have shown that, under the effect of climate change, cork oak will disappear from a large area in the future and the rest will migrate to wet areas. In addition, the Aleppo pine is a plastic species and will move into areas that are projected to have a humid climate. Other authors have shown that current cork oak habitat has been colonized in several places mainly by the Aleppo pine. In the future, it is possible that Aleppo pine will colonize cork oak habitat under the effect of climate change in North Africa and the Mediterranean basin, and thus, it is necessary to implement management and silviculture practices that help to alleviate the effects of climate change and thus the expansion of Aleppo pine into cork oak habitat as well.

Authors' Contributions

KM did the field work, wrote and authored almost of the manuscript; WJ did field work authored part of manuscript and reviewed drafts of the paper; ASA, SN and YA reviewed drafts of the paper. All authors read and approved the final manuscript.

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Conflicts of Interest

The authors declare that there are no conflicts of interest related to this article.

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