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Dendrochronological studies in North Africa: reality and prospects

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The southern Mediterranean region, particularly North Africa, is a crucial area for biodiversity conservation. However, the impacts of climate change on plant species in this region are not well understood. Dendroecology, the study of tree rings, is a valuable technique for analyzing the effects of environmental changes on woody plants over time. In this study, we intend to assess the state of the art in dendrochronological research in North Africa and identify knowledge gaps and limitations in the field. The period of analysis spans from 1979 to 2023. We used all the available literature in Dendrobox and Google Scholar during this period. Our study revealed several research gaps in the region, including the need for more studies on the history of forest fires and their relationship to climate conditions in Morocco, Algeria, and Tunisia, the impact of climate on the anatomical characteristics of growth rings, and the effects of climate change on tree species diversity and forest health. Applying this technique in the future would allow for detailed insights into the effect of climate on the internal structure and growth of forest trees. The findings of this study will help guide future research and contribute to a better understanding of the climate-growth relationship of woody plants in North Africa.

KEYWORDS

dendrochronology, climate reconstructions, drought, wildfires, Southern Mediterranean

1 Introduction

The Mediterranean basin (Figure 1) is known to be one of the most sensitive regions in the world to be affected by global warming (IPCC, 2021). It can be seen as a global warming hotspot where aridification trends have become worse since the 1980s and are having a detrimental effect on the productivity of forests and the radial growth of tree species (Touchan et al., 2008a; Sarris et al., 2011). The climate of the Mediterranean Basin is distinguished by a change from dry and semi-arid conditions in southern and low-elevation regions to more continental or temperate conditions in northern and high-elevation sites (Xoplaki, 2002). With a projected 40 percent less precipitation during the winter rainy season, the climate of the Mediterranean basin will be drier than any landmass on Earth

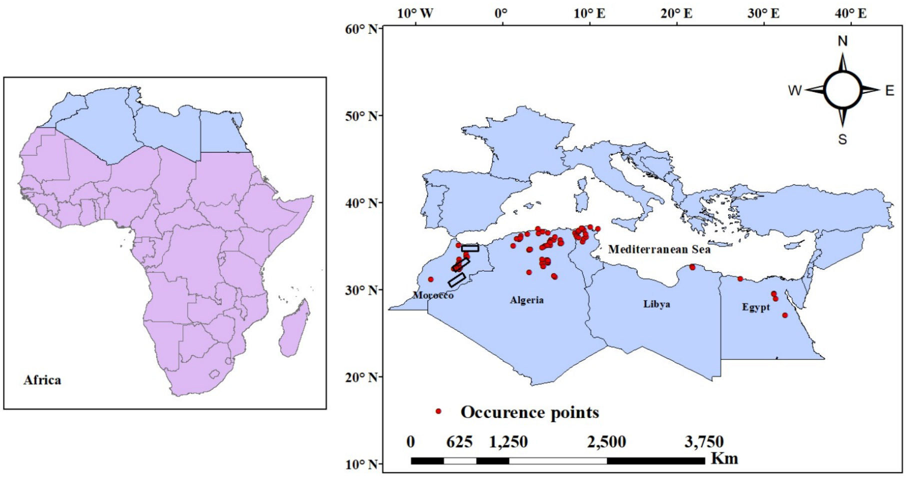

FIGURE 1
Location map of the studied sites for dendrochronological research. Some sites could not be represented due to the wide area they represent. Rectangles represent a wide area of sites in Morocco that could not be easily represented.

(Tuel et al., 2021). This decline in rainfall will eventually influence the growth responses of tree species to climate warming. The growing water demand of the atmosphere causes an increase in evapotranspiration resulting in decreasing soil moisture over the Mediterranean and some tropic and subtropical regions (IPCC, 2021). Furthermore, there is high confidence that aridification will exceed the magnitude of what already happened in the last millennium (IPCC, 2021), corresponding to observed trends towards increased hydrological droughts in the Mediterranean. The fact that the climate of the Mediterranean basin is drier compared to other regions will most likely influence the growth responses of tree species to climate warming. The extreme heat waves experienced at the start of the century may soon become the norm (Molina et al., 2020). In 2023, the world, including the Mediterranean basin, witnessed unprecedented temperature records.

According to Dai et al. (2004), the Mediterranean basin's southern and northeastern regions had already undergone severe drying in the latter half of the 20th century (PDSI = 3 to 5). The regional rainfall patterns in the Mediterranean basin also differ along a longitudinal gradient, with more autumn precipitation eastwards and more winter-spring precipitation westwards (Camarero, 2011). This gradient in precipitation has been linked to a gradient in forest productivity, which has been defined as an east-west dipole in the Mediterranean Basin due to various weather patterns. In North Africa, the forest productivity and net primary production of vegetation in general decrease remarkably from Morocco to Egypt, with a higher frequency of drought events (Vieira et al., 2022).

Extreme weather in North Africa can have a significant impact on the region. One of the most prominent weather phenomena in North Africa is the occurrence of heat waves (Varela et al., 2020). During the summer months, temperatures can soar to unbearable levels, sometimes reaching over 50° C (122° F). These extreme temperatures can lead to heat-related illnesses and even deaths (Palinkas, 2020). Another extreme weather event that affects North Africa is drought. The region is known for its arid and semi-arid climates, making it prone to periods of prolonged dryness (Bazza et al., 2018). Droughts can have severe consequences for agriculture, leading to crop failures and food shortages (Devkota et al., 2022). North Africa is also prone to flash floods during the rainy season (Sumi et al., 2022). When heavy rains occur, especially in areas with poor drainage systems, flash floods can quickly develop, causing destruction to infrastructure and putting lives at risk. These floods can also lead to the spread of waterborne diseases and create additional hardships for vulnerable populations (Loudyi and Kantoush, 2020). Overall, extreme weather events in North Africa pose significant challenges to the region's population, economy, and infrastructure. Climate change is expected to exacerbate these conditions, making it crucial for governments and communities to implement effective adaptation and mitigation measures (Waha et al., 2017; Zittis et al., 2022). Climate affects the annual radial growth of trees, and the effect varies according to species and site characteristics. The climatic factors affecting tree growth commonly studied are temperature and precipitation.

To analyze the influence of a changing climate on the radial growth of trees in a certain region, we use dendrochronological techniques and specific software. Dendrochronology is a useful tool for the precise determination of the annual radial growth of trees (or woody plants in general) and their relationship with climate conditions. It also provides information on the timing of events and environmental change rates (Grissino-Mayer, 2016). By gaining a deep understanding of the growth performance of the tree species in a certain region, we can identify the key limiting factors that drive their existence. Consequently, considering these findings, we can tailor a conservation program for the management of these species in situ.

The wider objective of this review is to highlight the advances in dendrochronological research in North Africa, from Morocco to Egypt, during the period 1979-2023 and identify the knowledge gap or limitations in the discipline in this region. In the results and discussion section, we will review the dendrochronological research efforts in each country and their applications. Then we will focus on the knowledge gaps and recommendations on research investigations needed in North Africa.

2 Materials and methods

For this study, we gathered and evaluated all the available English-language scientific articles that included tree-ring data that were collected in North Africa, from Morocco to Egypt. We selected all dendrochronological studies that investigate the relationship between tree growth and climate variables in North Africa, dendrochronological applications, reconstruction of past climate and fire history, monitoring, and modeling growth. We collected the available articles from Google Scholar (http://scholar.google.com) and Dendrobox web pages (http://Dendrobox.org). Dendrobox is an interactive exploration tool for tree-ring data that shows detailed chronologies in each site, climate, and climate-tree growth relationships. Most of the collected papers from the two sites were already published in Web of Science and Scopus journals. Google Scholar gives more published materials than WOS, particularly the local scientific journals. In Google Scholar, we used the following keywords: "tree-ring" and "climate" and "Morocco"; "Algeria"; "Tunisia"; "Libya"; "Egypt"; "dendrochronology"; "Southern Mediterranean". After checking each article individually and removing duplications, we obtained a total of 69 studies from Google Scholar and Dendrobox relevant to the study area for the period 1979-2023. This period represents all the available English literature on dendrochronological research in North Africa. Furthermore, we described the characteristics of each published dendrochronological record used in our evaluation and their connections to climatic or environmental information. The listed characteristics (Supplementary Table S1) include information about the studied species, country, site name, site location (coordinates and elevation), the tree-ring parameters e.g., average inter-series correlation, mean sensitivity, average autocorrelation, number of dated series, expressed population signal (EPS), or the average correlation coefficients between trees, and Rbar (Fritts, 1976; Wigley et al., 1984). Mean sensitivity is an index of relative inter-annual variability of tree-ring chronologies, while the mean inter-series correlation is the mean correlation of each series with the master chronology that was derived by COFECHA from all other series. It is worth noting that not all the tree-ring parameters are available in all articles. Figure 1 shows the locations of the most studied sites in North African countries. In Morocco and Algeria, there are too many study sites in one location, and we cannot easily draw them on the map. Instead, we placed rectangles above these locations, which are mostly located in the Atlas Mountains.

3 Results and discussion

3.1 Variations in precipitation pattern and forest cover in N. Africa

The Atlas Mountains are located in western North Africa and separate the Sahara Desert from the Mediterranean Sea and the Atlantic Ocean. It extends around 2,500 km through Morocco, Algeria, and Tunisia, with the highest peak at Toubkal in central Morocco (Dunmire, 2009). The average annual precipitation along the Atlas Mountains decreases from Morocco to Tunisia. This is because the mountains rise from the coast and block the moisture-laden winds from the Atlantic Ocean. The highest average annual precipitation is found in the Rif Mountains in Morocco, where the mountains are highest and the moisture-laden winds are strongest. The lowest average annual precipitation is found in the Tell Atlas Mountains in Tunisia, where the mountains are lowest and the moisture-laden winds are weakest (https://earthobservatory.nasa.gov/). The range of the average annual precipitation is 1,000-2,000 mm, 600-1,500, and 400-800 mm in Morocco, Algeria, and Tunisia, respectively (ourworldindata.org). The Atlas Mountains represent a complex system where many factors affect precipitation, such as the strength of the moisture-laden winds, the air temperature, and the topography. The average total precipitation along Al Jebal al Akhder, the only forested area in Libya, is about 294.5 mm per year. The highest precipitation occurs in the winter months when the moisture-laden winds from the Mediterranean Sea are strongest, while the lowest precipitation occurs in the summer months when the winds are weaker.

Along the Mediterranean coast in Egypt, the average annual precipitation does not exceed 200 mm (https://earthobservatory.nasa.gov/). Nevertheless, the Mediterranean coastal land in Egypt is a region of relatively high precipitation compared to the rest of the country. The precipitation in this region is important for the environment as well as for the economy, as it provides drinking water and hydroelectric power generation and is also the source of irrigation, helping to support a huge variety of plant and animal life. The mountain forests of North Africa provide habitat for a variety of animals, including deer, boar, and birds. The mountains are also home to several endemic species found nowhere else in the world. The precipitation in this region frequently occurring as heavy rainfall events that cause flooding and landslides, which can damage property and infrastructure. The heavy precipitation events can also make it difficult to grow crops in some areas.

Precipitation and forest cover are intimately related. This elucidates the generally positive correlation between the amount of forest cover and the hydrologic cycle intensity (Ellison et al., 2012). Forest cover in the north African countries mirrors the decreasing precipitation amount from west to east, showing the natural distribution of vegetation in this region. Morocco has the highest forest cover area in North Africa, followed by Algeria, Tunisia, Libya, and Egypt (Table 1). According to the Food and

TABLE 1 Forest cover area (hectares) and forest cover as % of total land area in the North African countries.

Country	Forest cover area (hectares)	Forest cover as % of total land area
Morocco	11,800,000	11.10%
Algeria	10,800,000	10.20%
Tunisia	1,500,000	5.60%
Libya	1,300,000	1.70%
Egypt	2,800,000	0.60%

Agriculture Organization of the United Nations (FAO, https://www.fao.org/3/X5329E/x5329e06.htm) and the World Wildlife Fund (WWF, https://www.worldwildlife.org/ecoregions), Morocco has 11.8 million hectares of forest cover, which is about 11.1% of its total land area. Algeria has 10.8 million hectares (about 10.2%), Tunisia 1.5 million hectares (about 5.6%), Libya 1.3 million hectares (about 1.7%), and Egypt 2.8 million hectares (about 0.6%) (Table 1). The forest cover percentage listed in Table 1 is linked to the total amount of annual precipitation received in each country. The total forest cover area in North Africa has been declining in recent years due to several factors, including deforestation, overgrazing, and climate change. In the Atlas Mountains, higher elevations are dominated by *Cedrus atlantica* (Endl.) Manetti ex Carrière, *Quercus pyrenaica* Willd., and *Pinus pinaster* Aiton. The vegetation on the arid summits of the Saharan Atlas is limited to sporadic stands of juniper and green oak trees (Ajbilou et al., 2006).

3.2 Drought and wildfire events in N. Africa during the last 50 years

Figure 2 shows some of the dates of recent drought and wildfire events during the last 50 years in Morocco, Algeria, and Tunisia. No considerable events were recorded in Libya or Egypt. It is important to note that these are just a few examples of recent drought events in these countries since there have been many other droughts over the years (IPCC, 2013). Droughts can be caused by a variety of factors, including climate change, El Niño/La Niña, and the natural variability of the moisture content of the winds. It is important to monitor the risk of drought in Morocco, Algeria, and Tunisia because it has a devastating impact on agriculture, water resources, and the environment (McPhaden, 2002). This can be done by tracking weather patterns, rainfall, and other factors that can contribute to drought risk. In addition, the information gathered by tree-ring analyses and related reconstructions of past drought events will strengthen studies on the effect of drought events on the growth and distribution of trees in the affected areas (see also Section 3.5). By taking steps to mitigate the risk of drought, we can help to protect people and the environment in these countries.

Many wildfire events have occurred in North African countries due to high temperatures and drought events. Supplementary Table S2 also shows some examples of wildfire events and their consequences regarding the loss of human life and burned forest areas. It is important to note that these are just a few of the many wildfire events that have occurred in Morocco, Algeria, and Tunisia during the 1979-2023 period (https://www.statista.com/statistics/1322254/area-burned-by-wildfire-in-morocco/). The frequency and intensity of wildfires in the region are expected to increase in the future due to climate change. It is important to take steps to mitigate the risks of wildfires in North Africa, such as by reducing deforestation and improving fire management practices (San-Miguel-Ayanz et al., 2022). It is apparent from Figure 2 and Supplementary Table S2 that there is an association between drought in some years and the occurrence of wildfires. This gives a good chance for the potential use of this association in the reconstruction of drought and fire past events in North Africa and other dendrochronological purposes.

3.3 Characteristics of the reviewed dendrochronological research in North Africa

Since 1979, many efforts have been made to study the dendrochronological potentiality of woody species and their relationship with the local climate in North African countries. Supplementary Table S1 shows detailed information on the present reviewed dendrochronological studies in North Africa. The total number of studies (69) was distributed among the North African countries, with 25, 18, 16, 3, and 7 studies in Morocco, Algeria, Tunisia, Libya, and Egypt, respectively. The studied sites were located at elevations ranging from 2 m a.s.l. at the Mediterranean coast in Egypt to 3313 m a.s.l. at the Upper Dad`es valley in Morocco. Most of the studied sites were in the Atlas Mountains in Maghreb countries (Morocco, Algeria, and Tunisia), while fewer sites were located in Libya and Egypt. The number of dated trees/series per study ranged from 6 trees in Egypt (Farahat and Gärtner, 2019) to 1000 trees collected from 40 sites in Morocco (Till, 1987; Till and Guiot, 1990). The length of the developed chronologies varied among countries, with the longest being in Morocco (>1000 years; Chbouki, 1992; Touchan et al., 2017) and the shortest being in Egypt (12 years). The range of inter-series correlations, average mean sensitivity, and average autocorrelation for the studied tree species were 0.31-0.88, 0.19-0.57, and -0.30-8.6, respectively.

The most commonly studied species were *C. atlantica*, *Pinus nigra* J.F. Arnold, *Pinus pinea* L., *Pinus halepensis* Mill, *P. pinaster*, and *Quercus* spp. (e.g., Chbouki, 1992; Touchan et al., 2011; Camarero et al., 2020). Less commonly studied tree species were *Castanea sativa* Mill, *Pistacia atlantica* Desf., and *Tetraclinis articulata* (Vahl) Masters (Ifticene-Habani and Messaoudene, 2016; Rabhi and Messaoudène, 2018; Zemrani et al., 2023). Recently in Egypt, some trees, shrubs, and perennial herbs were tested for their ring formation (Farahat and Gärtner, 2021) and their relationship with climate conditions in the Egyptian deserts (Farahat and Gärtner, 2019; Farahat and Gärtner, 2023a). The main explored trees or shrubs were *Moringa peregrina* (Forssk.) Fiori, *Lycium europaeum* L., *L. shweinfurthii* Dammer and *Calligonum*

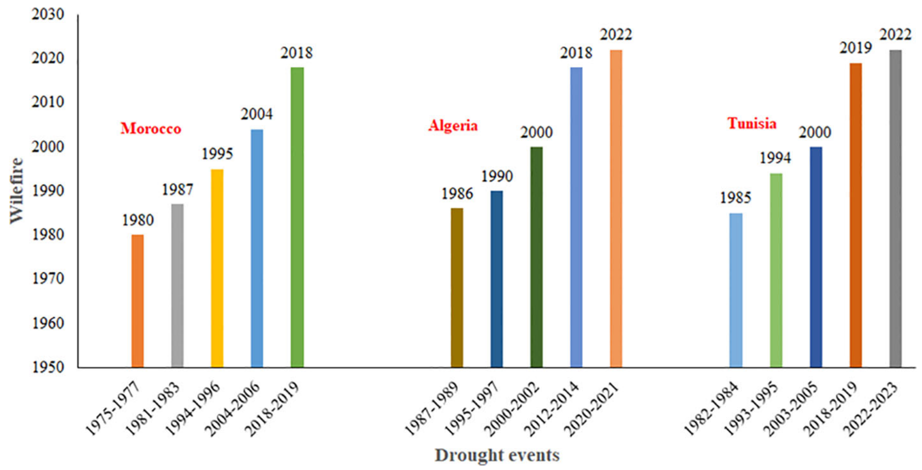

FIGURE 2
Occurrence of drought events and wildfires in the past 50 years in Morocco, Algeria, and Tunisia. (Source: https://www.statista.com/statistics/1322254/area-burned-by-wildfire-in-morocco/).

comosum L'Her. In these species, the ring boundaries were delimited by thick-walled flattened fibers or parenchyma bands in addition to the changes in the size of vessels (Figure 3).

3.4 Dendrochronological studies in North Africa

The dendrochronological studies vary dramatically from Morocco to Egypt in terms of the number of studies, sampled sites and studied species (Supplementary Table S1). Accordingly, in sections 3.4 and 3.5, we present published research work related to dendrochronology and the reconstruction of past events in each country, especially considering drought and precipitation.

3.4.1 Morocco

There is extensive and rich work in dendrochronological studies and its applications in the western countries of North Africa (Morocco, Algeria, and Tunisia). Morocco has been the main location for most of these studies since 1979. *Cedrus atlantica, P. nigra*, *P. pinea*, *P. halepensis*, *P. pinaster*, and *Quercus* spp. are commonly studied species in Morocco. Berger et al. (1979) studied the relationship between tree rings of Atlas cedar (*C. atlantica*) and climate in two sites located near Ketama at different altitudes (1280 m and 2100 m a.s.l.) in the Morocco Rif. They found that the radial growth of *C. atlantica* at low altitudes (1280 m) was more influenced by the mean temperature of January, April, and May of the current year, the mean temperature of October of the previous year, and total monthly precipitation for August. For the high-altitude site (2100 m), *C. atlantica* was more influenced by temperatures in January and May of the current year, total monthly precipitation in September, and precipitation in October of the previous year. Till (1987) found that *C. atlantica* in Morocco had a positive response to the autumn and winter precipitation and to January, April, and September temperatures. The reduction of the competitive ability of *C. atlantica* at low and high altitudes was explained by the unfavorable effects of April and September temperatures and winter cold, respectively. Dutilleul and Till (1992) found that there is a 7-year periodicity in a 120-year tree-ring chronology computed for *C. atlantica* from Rif and Atlas mountain sites in Morocco. These ring-width indices also exhibit periodicities of around 11 and 18.6 years, which have been attributed to sunspot activity and lunar nodal tide. The *C. atlantica* s tree ring data from Morocco, in addition to the δ18O annual series and GISP2 snow accumulation record, were used to study the North Atlantic Oscillation (NAO) (Glueck and Stockton, 2001). Their findings imply that the late 20th-century persistently high phase of the NAO is not remarkable in its occurrence or duration over the past 555 years, but that the magnitude of certain instrumental values may be unique.

In forests that have previously undergone extensive logging and grazing in the Middle Atlas Mountains, northern Morocco, Linares et al. (2011) studied the relative contributions of tree characteristics and stand structure to *C. atlantica* radial growth. They observed persistent growth decreases and increased drought sensitivity in *C. atlantica* across all sites. In the same region, Linares et al. (2013) attempted to separate the respective contributions of tree age to growth decline and growth-climate correlations in *C. atlantica* trees. They found that the recurrent droughts and the sharp temperature increase since the 1970s had a negative impact on the growth of the Atlas cedars. Additionally, low precipitation had a strong relationship with the decline in the radial growth of the trees, with a more negative impact on old trees (age ≥150 years). Ilmen et al. (2013) studied the effects of precipitation and temperature on tree growth in Morocco using 80 tree cores of *C. atlantica* from two sites located in the Middle Atlas region. They found that precipitation in March had a positive effect on tree growth at site 1 (1900 m a.s.l.), while high temperatures in autumn and spring in the current and previous years negatively affected tree growth at the second site (2078 m a.s.l.). Furthermore, Ilmen et al. (2014) studied the impacts of climate change on the productivity of *C. atlantica* in the Eastern Middle Atlas in Morocco. They developed a long

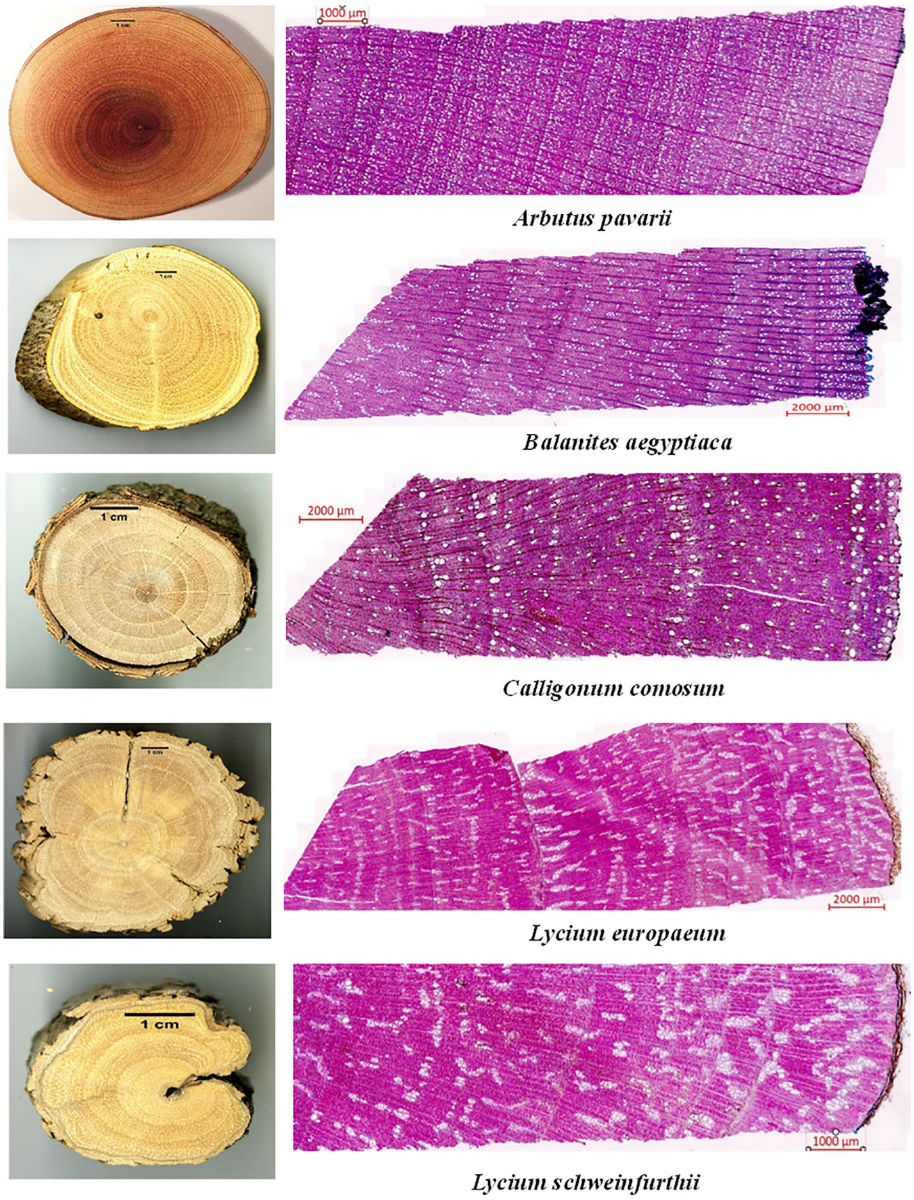

FIGURE 3
Macroscopic and microscopic views of wood in some North African trees/shrubs. Wood discs were collected, and permanent anatomical slides were prepared by the authors. *Lycium europaeum*, *L. shweinfurthii* and *Calligonum comosum* were collected from Egypt, while *Arbutus pavarii* was collected from Libya. All sections are available with the second author at WSL Institute, Zurich (Switzerland).

chronology (1498 -2011) that showed the sensitivity of the trees to climate conditions. The radial growth of *C. atlantica* correlated negatively with the monthly mean temperatures of June and October. In contrast, the cedar growth was positively correlated with precipitation in September. By comparing the natural stands of *C. atlantica* with plantations in Morocco, Camarero et al. (2021) reported negative impacts of summer temperature on the growth of *C. atlantica* plantations in Morocco. Drought reduced growth more severely in natural stands than in plantations of *C. atlantica*.

Copes-Gerbitz et al. (2019) assessed the long-term background for the current dieback of *C. atlantica* brought on by drought events and created a projection of its future growth by examining the periodic variability of its growth through time. Parallel analysis of historical climate data from 1901 to 2016 CE revealed that the multidecadal growth signal is mostly caused by variability in the precipitation throughout the growing season (spring and summer), which is exacerbated by slowly changing the summer and winter temperatures. Recently, Camarero et al. (2021) studied the dieback of *C. atlantica* in Moroccan forests after the 1970s. They found that the forest cover increased in the Middle Atlas and Rif (less xeric regions) by 20%, while it reduced by 18% in the xeric High Atlas due to massive dieback. Recent droughts in the Middle Atlas have caused cedars there to develop at a rate that was roughly 54% slower than in the Rif and High Atlas. There were few studies on the growth-climate relationships of other tree species in Morocco that could be compared to *C. atlantica*. Zribi et al. (2016) reported that the radial growth of *Quercus suber* L. is highly affected by autumnal precipitation before the growing season using the 1918–2008 time series. Additionally, deep soil water refill and the summer drought affected the growth phenology and carbon assimilation of this species. Navarro-Cerrillo et al. (2020) studied how secondary forests of *Abies pinsapo* var. *marocana* (Trab.) Ceballos & Bolaño at Rif in northern Morocco respond to climate change and analyzed their dynamics as a result of changes in stand structure and composition. They reported that *A. pinsapo*'s tolerance to subsequent droughts was weakened by drought events in both pure and mixed stands with *C. atlantica*. In pure and *A. pinsapo*-*C. atlantica* mixed forests, the competition reduced its growth. In the semi-arid High Atlas Mountains of Morocco, Malik et al. (2021) investigated how the growth of silver poplar trees (*Populus alba* L.) responded to a significant flood event in 2014. In 2015, the year following the flood, half of the trees in the study area had wider tree rings, while the other half had narrower rings. The study shows that trees impacted by floods in an arid high mountain region in Morocco can respond in two different ways, each leading to a dual opposite reaction. Using such tree cores for reconstruction purposes should be done with caution.

The effect of higher temperature and drought was studied by Vieira et al. (2022), who found that *P. halepensis* trees at their southern distribution limit in the High Atlas Mountains of Morocco exhibit decreased growth, low relative resilience, and more missing rings in response to these conditions. There was a negative relationship between tree-ring width, and maximum spring and summer temperatures, and previous winter and spring precipitation. Recently, the radial growth patterns and responses to the climate of *Tetraclinis articulata*, a Cupressaceae tree endemic to the western Mediterranean Basin, were characterized by Zemrani et al. (2023). They reported that the growth of *T. articulata* was favored by wet conditions from the prior autumn to the spring of the growth year. Growth in the two Moroccan sites was constrained by 6-to-18-month-long droughts peaking in summer, which account for the cumulative water deficit since the previous autumn. Winter and early spring precipitation were the main climate drivers of growth in the Moroccan *T. articulata* populations, and their year-to-year variability was linked to the NAO.

Data show that the radial growth of the studied species in Morocco was positively correlated with the total annual precipitation. In contrast, high temperatures, drought events, and extreme weather conditions had negative impacts on the growth of these species.

3.4.2 Algeria

The dendrochronological studies in Algeria were manifold, dealing with many topics. Tessier et al. (1994) reported a direct positive relationship between the entire *Quercus* genus (*Q. afares* Willd, *Q. canariensis* Pomel, *Q. pubescens* Willd, and *Q. robur* L.) in the western Mediterranean region and summer precipitation, but a negative response to temperature. Messaoudène and Tessier (1997) examined ring-width variations for 15 populations of *Q. afares* and *Q. canariensis* in Algeria. They showed that precipitation had a bigger impact on the two species than temperature, whose action only affected minor quantities. In contrast to *Q. canariensis*, which considerably responds to the interannual changes of climatic factors, precipitation in October-November-December and March-April for either P-T_{max} or P-T_{min} combinations has a significant negative relationship with *Q. afares*.

Choury (2015) found that low precipitation and high temperatures (in the autumn of the previous year, spring, and summer) were limiting factors for the growth of *P. halepensis* in the green barrier of Algeria. Sarmoum et al. (2016) studied the radial growth of *P. halepensis* in north-western Algeria. They found that the trees had variable growth at different sites according to their ages and local site conditions. According to their results, precipitation can affect the growth rings of *P. halepensis* before or during their formation. Meanwhile, high temperatures had a negative effect on the radial growth of the species. Choury et al. (2017) found that the basal area index for *P. halepensis* was found stable or slightly increased over time (1925–2013) at their southernmost distribution limits in Algeria. In contrast, the intrinsic water-use efficiency (WUEi) increased by about 39%. This suggests a high resilience of the species to climate change at their southernmost distribution limits. Camarero et al. (2020) found that prior wet winters and chilly, moist springs were favorable for the *P. halepensis* network's tree growth in dry continental sites located in southeastern and eastern inland Spain and Algeria, but warm summers were associated with reduced growth. As an application for dendrochronological data, Touchan et al. (2016) used climatic data and a reconstruction of January–June precipitation from ten *P. halepensis* tree-ring chronologies to examine the variability of wheat-growing conditions in Algeria. The results revealed that *P. halepensis* and wheat rely on monthly and seasonal precipitation similarly. They have a dissimilar pattern towards temperature. These findings confirm the positive effect of precipitation on the growth of *P. halepensis* compared to the high temperatures.

Slimani et al. (2014a) analyzed the response of *C. atlantica* to climate variability in Algeria. The results indicated that the second half of the 20th century had the largest growth uncertainity. The radial growth of the species was mostly influenced by precipitation variability. Sarmoum et al. (2018) investigated the radial growth of *C. atlantica* and *Quercus ilex* L. in pure and mixed stands located in northwestern Algeria. They found that there was a significant decline in the radial growth of *C. atlantica* from 1980 to the 2000s due to frequent drought conditions. Sarmoum et al. (2019) studied how site conditions and drought affect the vitality and radial growth of *C. atlantica* in Algeria. The results indicated that the annual variations in rainfall have a significant impact on *C. atlantica*. Populations situated at low altitudes, on incline slopes, and on marl or sandstone soils are more sensitive to these factors. This may be attributed to the inability of the soil at these sites to retain moisture necessary for the growth of *C. atlantica*. The effect of anthropogenic pressure and repeated drought events on the radial growth of *C. atlantica* in north-western Algeria during the period 1910-2006 was studied by Navarro-Cerrillo et al. (2019). They found that *C. atlantica* growth changed because of the warmer and drier climate of the 1980s. They found that *C. atlantica* growth is enhanced by cool and wet conditions in spring. Tafer et al. (2021) studied the climate-growth relationship in two southern Algerian cedar forests in the Saharan Atlas that were subjected to different climatic disturbances. *C. atlantica* responded differently at the two sampled sites. The age of the stand, along with its low altitude, poor soil, and even older structure, all seem to make the dieback of *C. atlantica* worse. The effects of a severe attack by *Thaumetopoea pityocampa* Schiff. on *C. atlantica* in Chréa National Park, Algeria were studied by Sbabdji et al. (2015). They found that the infection resulted in up to a 50% growth decline after complete defoliation. These findings reflect the sensitivity of *C. atlantica* to drought and infestation events in Algeria, which lead to the decline of their populations in many sites. In contrast, precipitation is the main limiting factor for the radial growth of cedar.

The radial growth and its relationship with climate were studied for some other tree species in Algeria. Ifticene-Habani and Messaoudene (2016) reported that precipitation was the main limiting factor for the radial growth of *Pistacia atlantica* Desf. (Mount Atlas mastic tree) in Algeria, while temperature was less important. It was found that *P. atlantica* is more vulnerable to extremes in warmer environments, particularly when these extremes impede growth. Average sensitivities on south-facing and north-facing slopes are comparable, albeit lower than those obtained for dry and semi-arid regions (Ifticene-Habani and Abdoun, 2018). In Western Algeria and southern Portugal, Ghalem et al. (2018) analyzed the climatic signal of cork oak (*Q. suber*) chronologies from the period from 1996-2010. Their findings suggested that cork oak growth reduction is driven by drought and a precipitation-temperature ratio. Recently, Rabhi and Messaoudène (2018) reported that the planted chestnut trees (*Castanea sativa* Mill.) in the mountains of Kabylia (Algeria) showed high adaptability, growth potential, and significant fruit production. Again, these findings emphasize the negative effects of drought and high temperatures on the radial growth of growing tree species in Algeria compared to precipitation.

3.4.3 Tunisia

In Tunisia, there are 14 studies dealing with tree growth and climate relationships, in addition to the reconstruction of past events. Simulation of *P. halepensis* tree-ring chronology from Tunisia using the Vaganov-Shashkin model showed that the growing season lasts 191 days on average, with obvious variation from year to year. Tree-ring growth was limited by soil moisture (for 128 days) and temperature (for 63 days) (Touchan et al., 2012). To find the seasonal climatic signal in indices of annual ring width, Touchan et al. (2017) examined the first extensive network of tree-ring chronologies from the western Mediterranean. *P. halepensis* and *C. atlantica* had overall positive relationships with winter (December–February) and spring (March–May) precipitation across this network. Results revealed that chronologies reflect soil moisture and the combined effects of precipitation and evapotranspiration signals in at least a portion of the network. The variety of climatic responses shown throughout this network shows a confluence of biotic and abiotic factors. The North Atlantic Oscillation is most strongly associated with Western Moroccan chronologies. It is revealed that the radial growth of *C. atlantica* and *P. halepensis* in Tunisia has the same climatic response as those in Algeria and Morocco.

The effect of distance from the coast on the variation in ring width of two pine species, *P. pinea* and *P. halepensis*, found in the Remel and Menzel Belgacem coastal forest region (Tunisia), was estimated by Bouachir et al. (2017). The mean growth of trees growing close to the shoreline for both species significantly decreased. Most stands exhibit a positive link with precipitation from October of the previous year to April of the current year. A low correlation with climate was detected for trees growing close to the shoreline compared with trees away from it. The decline in tree growth close to the shoreline was attributed to the combination of unfavorable factors such as drought, storms, and poor soil. This means that trees under stress conditions cannot respond similarly to the common climate signal at coastal sites.

For 19 provenances of black pine (*Pinus nigra*), the impacts of interannual climatic fluctuations on radial growth were evaluated by Fkiri et al. (2018). The findings showed a significant negative correlation with spring temperatures and a strong positive correlation with April precipitation. In contrast to a spring drought, a cool wet spring is beneficial to the growth of the species at the beginning of the growing season. However, black pine growth in the examined area was significantly hampered by winter snow and hail. It is revealed that the mild temperature and wet spring are limiting factors for the growth of black pine in Tunisia. Fkiri et al. (2019) studied how well two *P. pinaster* varieties —var. *renoui* from Tunisia and var. *maghrebiana* from Morocco— adapted to the ecological conditions of the Kroumirie Mountains in northwest Tunisia. In terms of survival and mean radial growth rates, they discovered that the *Maghrebiana* variety was superior and well-acclimated to the Kroumirie Mountains compared to the other variety.

Cork oak (*Q. suber*) forests in the Mediterranean basin, particularly in the Kroumirie region (northwest Tunisia), which is presently experiencing exceptional drought conditions, have been subject to vulnerability evaluations by Touhami et al. (2020). The study region has experienced numerous protracted drought spells, particularly between 1988 and 1995. It was found that droughts consistently had a worse effect on the rates of population growth and death for cork oaks. Touhami et al. (2021) found that the growth of cork oak was remarkably influenced by the drought episodes from 1988-1995. This simply means that the radial growth of cork oak is sensitive to drought events that may affect the future persistence of the species in the region.

3.4.4 Libya

There were limited dendrochronological studies in Libya. The dendroclimatology of *Cupressus dupreziana* A. Camus was tested by Cremaschi et al. (2006), using samples taken from the door beams of the ancient cities of Ghat and Barkat (southwestern Libya). Twenty samples' tree rings were measured and dated using twenty-four AMS ^{14}C dates. They developed a mean ring-width chronology that spans, albeit continuously, 5220 to 100 ^{14}C BP (5990-65 cal. BP). The mean ring-width chronology provides a decade-by-decade record of changes in rainfall during the middle and late Holocene in the central Sahara since the width of tree rings in arid regions is mostly determined by the availability of water. Due to the occurrence of false and missing rings, it was not possible to synchronize the single samples (on an annual basis) for the interval of practically regular growth.

Mohamed et al. (2019) studied the growth of the cultivated Aleppo pine trees (*P. halepensis*) growing in five different plantations in the Aljabal Al-Akhdar region, Libya. They found that there was a negative relationship between temperature and the width of earlywood or latewood or the thickness of the annual rings of the species. Another study has been conducted on the age structure of *P. halepensis* trees on the western side of the Sidi Alhumry plantation in the Aljabal Al-Akhdar region (Alsanousi and Ali, 2018). Currently, there is an ongoing research effort on the wood of *Arbutus pavarii* Pamp. and *Quercus coccifera* L. from Aljabal Al-Akhdar region, Libya, by the authors of this review and a researcher from Libya. The lack of dendrochronological research in Libya has hindered our ability to understand the mechanisms that restrict the radial growth of tree species there.

3.4.5 Egypt

In Egypt, Farahat and Gärtner (2019) studied the wood anatomy and dendrochronological potential of *M. peregrina* trees at two sites (Hurghada and St. Catherine). They reported that the tree growth at Hurghada had a significant positive relationship with January-March precipitation before the vegetation period and the April temperature of the previous year. In contrast, the radial growth of the species had a significant negative relationship with the April and May-August temperatures of the current growing season. Gärtner and Farahat (2021) studied the cambial activity in the wood of *M. peregrina* in Egypt. According to their findings, there was a clear correlation between the emergence of fresh green leaves at the start of vegetative growth in October and the cambial activity phase (November–January). The beginning of cambial activity appears to be connected to a dip in temperature in October and the arrival of flash floods in the area. The response of *M. peregrina* in the Egyptian desert to environmental conditions for the last 10 years using wood anatomy, δ13C, and δ18O isotope analyses was studied by Farahat et al. (2022). They found that the tree-ring widths (TRWs) of *M. peregrina* have largely decreased over the past ten years. The decreased stable δ13C isotope values indicated the effect of increased drought conditions on trees. The mean δ18O value (33.0 ‰ ± 0.85) showed a typical drought signal. The findings demonstrate that *M. peregrina* trees appear to chill their leaves and the surrounding air at the expense of water conservation. This water-use strategy and the correlation of wood formation in *M. peregrina* with the prevailing climate conditions demonstrate the adaptation and robust ecological performance of this species in arid environments.

To extend their research efforts in Egypt, Farahat and Gärtner (2021) surveyed the ring formation in about 300 desert plant species from Egypt. They found that there are 94 species out of the sampled plants that have distinct rings. These species are trees, shrubs, and perennial or short-lived herbs. Wood porosity, fibers, and marginal parenchyma were the main indicators for the ring boundaries. Farahat (2020) investigated the age structure of *J. phoenicea* L. populations from two mountains (Gabal (G.) El-Halal and G. El-Maghara) in the North Sinai, Egypt. The results indicated that the tree ages were 50-262 years and 96-431 years at G. El-Halal and G. El-Maghara, respectively. He found that the last seedling recruitment was about 50 years ago at both sites. Additionally, the dendrochronological potential of three Mediterranean desert shrubs in Egypt (*L. schweinfurthi*i var. *schweinfurthii*, *L. europaeum*, and *C. polygonoides* subsp. *comosum*), as well as their anatomical structure, were investigated by Farahat and Gärtner (2023a). Their findings demonstrated that both macroscopic and microscopic growth rings in the target species were unique. The characteristics of the vessels demonstrated each species' capacity to adapt to the prevailing arid environmental circumstances. They developed three short chronologies from the tree-ring widths of the studied species (2011-2022). There was a distinct variation between the earlywood and latewood densities for each species. The connections between the climate variables and the radial growth of the examined species were weak to moderate, but most of the time not significant. This was attributed to the low sample depth in this study. Salem et al. (2023) estimated the ages of four common species (*Vachellia tortilis* (Forssk.) Galasso & Banfi, *Acacia ehrenbergiana* Hayne, *Balanites aegyptiaca* (L.) Delile, and *Tamarix nilotica* Bunge) in Wadi Allaqi, in south-east Egypt. They reported that the ages of the trees varied according to their location in the wadi. The growth of the three species was dated back to 1648 (*V. tortilis* subsp. *raddiana*), 1608 and 1715 (*B. aegyptiaca)*, and the 1980s (*T. nilotica*).

3.5 Reconstruction of past events

Dendrochronologists have made important efforts to reconstruct historical climate occurrences in North Africa. Many of them tried to identify the frequency of drought in this sensitive region. Till and Guiot (1990) reconstructed the annual precipitation (October through September) for Morocco from 1100 A.D. to the present, using *C. atlantica*. They identified a sequence of dry and wet periods during the previous 1100 years, with a maximum length of 6 years for the dry period. Chbouki (1992) studied the characteristics of the historical drought events at 12 sites of *C. atlantica* in Morocco using runs theory. They found that the shortest drought duration was over the High Atlas, and the longest ones were recorded over the Central and Middle Atlas. 84% of drought occurrences have an average duration of one to two years. Chbouki et al. (1995) reconstructed the past climatic moisture anomalies from the tree-ring chronologies of *C. atlantica* in Morocco during the period 1845-1974. According to their findings, there was an alteration between favorable and unfavorable climatic regimes that lasted 20-25 years. In 2007, Esper et al. (2007) used ring-width data for *C. atlantica* in Morocco to reconstruct the long-term changes in the Palmer Drought Severity Index (PDSI) over the past 953 years. The majority of the 1450–1980 period showed PDSI values above average. The findings also showed that the typically drier conditions dating back to 1049 preceded this pluvial episode of the previous millennium. Ilmen et al. (2016) used *C. atlantica* samples (from four sites in Morocco) to reconstruct the effects of the North Atlantic Oscillation (NAO) on their growth rings. Results showed that for the period 1900-2000, the Moroccan winter precipitations were negatively correlated to the NAO.

In Algeria, Meko et al. (2020) used the TRW chronologies from drought-sensitive sites of *P. halepensis* and *C. atlantica* to reconstruct the discharge for the Chemora River in semi-arid northeastern Algeria. The results demonstrated the significance of snowmelt for river discharge and provided insight into the reasons why the discharge in the outlier high-flow year of 1996 was significantly underestimated. Slimani et al. (2021) used tree-ring data from *C. atlantica* at Mount Takoucht, northern Algeria, over the period 1830-2015 to reconstruct the precipitation from March to June. The late winter to early summer precipitation showed significant interannual to decadal volatility in the reconstructed data. While the final years were distinguished by a distinct shift toward rainy conditions, the decade 1993-2002 had the greatest drought frequency of the reconstruction, with the third most severe dry event (1999).

The only published article on the reconstruction of fire history in North Africa was conducted by Slimani et al. (2014b). They reconstructed the fire history of the *C. atlantica* forest in Chélia at two sites in northern Algeria. The time spans of the dated samples at the two sites were 1507-1977 and 1303-1991, respectively. They found that most of the fire events occurred in the summer with no significant relationship with October-June precipitation.

In Tunisia, Touchan et al. (2008a) reconstructed the Palmer Drought Severity Index (PDSI) for the period AD 1456–2002 in Tunisia and Algeria using a set of 13 C. *atlantica* and *P. halepensis* chronologies. According to their findings, it appears that the most recent drought (1999–2002) was the worst since the middle of the 15th century. Touchan et al. (2008b) used a *P. halepensis* regional tree-ring chronology (1771–2002) from Tunisia to reconstruct October–June precipitation. The 19th century showed a 2-year drought, which is the longest drought by this classification to be recreated in the 232-year reconstruction. Over Morocco, Algeria, and Tunisia, Touchan et al. (2011) reconstructed the PDSI data back to A.D. 1179. The reconstructions give a long-term context for the hydroclimatology of northwest Africa and show that there were significant regional droughts before the sixteenth century as well as more diverse patterns in the sixteenth, eighteenth, and twentieth centuries. Recent decades have seen a change in the region's weather toward drier conditions, which is in line with general circulation model estimates of increasing regional subtropical dryness caused by greenhouse gases. Based on the PDSI, the reconstruction of seasonal drought in the mountainous Mediterranean areas of Morocco, Algeria, and Tunisia revealed severe dry conditions since the 1980s compared to the last 600 years (Sarris et al., 2011).

3.6 Limitations and prospects

Due to the deficiency in laboratory equipment and the absence of funds in many North African countries, dendrochronological studies are limited in some countries, such as Egypt and Libya. In Tunisia, Algeria, and Morocco, there are still some research efforts. Most of the literature reviewed in this article dealt with the tree growth-climate relationship in North Africa, with few articles on the reconstruction of past events, particularly drought, fire history, and the cambial activity of trees. Most of the dendrochronological work in this region was led by experts from the USA and Europe (e.g., Touchan et al., 2011; Touchan et al., 2016; Copes-Gerbitz et al., 2019; Navarro-Cerrillo et al., 2019; Camarero et al., 2021), and a few were led by local experts (e.g., Zribi et al., 2016; Fkiri et al., 2019; Sarmoum et al., 2019; Slimani et al., 2021; Farahat and Gärtner, 2023b).

It is obvious from the reviewed studies that the number of species used for dendrochronological potentiality in North Africa is limited compared to other regions. This may be attributed to phytogeographical reasons and the low number of specialists in dendrochronology in North Africa. Understanding the tree-growth-climate relationships of these species is valuable for assessing the health and productivity of forests, developing forest management strategies, and identifying vulnerable tree species or habitats that may be at risk from changing climatic conditions. It is also important to predict how trees will respond to future climate change and past climate conditions. Researchers in this region should extend their efforts to explore and include more species in dendrochronological research. For instance, *Arbutus pavarii* Pamp., *Quercus coccinera* muenchh., and *A. pinsapo* var. *marocana* are some of the recommended species for dendrochronological research in this region. More techniques, such as wood anatomy, monitoring of cambial activity, the application of isotopes, and X-ray densitometry, should be used to facilitate the identification of ring boundaries in wood and the extraction of more dendroecological data. Due to the recent frequency of forest fires in Morocco, Algeria, and Tunisia, more research efforts for the reconstruction of fire history should be conducted in these countries. Moreover, linking fire frequency on the one hand with current climate conditions, soil physicochemical structure, and soil microbial content may be important.

As we noticed from the reviewed articles, many forest sites in North Africa are suffering from overgrazing, cutting, or natural dieback due to drought, fires, or pathogens. Accordingly, monitoring and management plans should be implemented to protect these sites from further deterioration. Transplanting forest trees in these areas should be a priority to replace the destroyed sites. Forest management will not only save the North African forests but also help in maximizing their economic resources (e.g., production of cork) and ecosystem services (e.g., as a habitat for birds and wild animals).

Another important remark is the absence of any published articles for any tree species in Maghrib countries and Libya on the impact of climate conditions on the anatomical characteristics of growth rings (e.g., vessel traits, tracheids, fibers. etc.). This research topic gives more insights into the direct effect of climate on the internal structure and growth of forest trees and their interaction with the surrounding environment.

Finally, the establishment of a network for dendrochronologists in North Africa will be a good contribution to the dendrochronological research efforts. Through this network, proper training and research collaboration can be conducted, which represents a strong start-up for more complementary work.

Author contributions

EF: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. HG: Conceptualization, Writing – review & editing.

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Conflict of interest

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Supplementary material

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