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Cedrus libani (A. Rich) distribution in Lebanon: Past, present and future

Distribution de Cedrus libani (A. Rich) au Liban : passé, présent et futur

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ABSTRACT

Long-term vegetation studies are needed to better predict the impact of future climate change on vegetation structure and distribution. According to the IPCC scenario, the Mediterranean region is expected to undergo significant climatic variability over the course of this century. *Cedrus libani* (A. Rich), in particular, is currently distributed in limited areas in the Eastern Mediterranean region, which are expected to be affected by such climate change. In order to predict the impact of future global warming, we have used fossil pollen data and model simulations. Palaeobotanical data show that *C. libani* has been affected by both climate change and human activities. Populations of *C. libani* survived in refugial zones when climatic conditions were less favourable and its range extended during periods of more suitable climate conditions. Simulations of its future geographical distribution for the year 2100 using a dynamic vegetation model show that only three areas from Mount Lebanon may allow its survival. These results extrapolated for cedar forests for the entire Eastern Mediterranean region show that forests in Syria are also threatened by future global warming. In southern Turkey, cedar forests seem to be less threatened. These results are expected to help in the long-term conservation of cedar forests in the Near East.

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Abbreviations

C. libani	*Cedrus libani*
GCM	General Circulation Models
gC m^{-2} $year^{-1}$	Gram of carbon per m^2 per year
IPCC	Intergovernmental Panel On Climate Change

1. Introduction

The Mediterranean region is a hot spot of biodiversity [1] that has been under continuous anthropogenic pressure for millennia [2]. Today, it faces the consequences of ongoing climate change and human pressure. During the next century, the Mediterranean is expected to undergo stronger warming and water stress which might affect all ecosystems. Most of the forests and woodlands located in the southern and Eastern Mediterranean regions are threatened by decreased moisture availability that may be related to the global warming. Among these, cedar forests constitute an emblematic ecosystem, still relatively extensive but rapidly declining.

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Previous research studies, mainly in Turkey and Lebanon, have aimed to: define the bioclimatic limits of *C. libani* [3]; evaluate its economic value and justify its conservation status [4]; determine the cause(s) of its current regression [5]; highlight and protect new potential areas [6] and define new methods to preserve the more resistant populations [5,6]. Taberlet and Cheddadi (2002) [7] underline the importance of past vegetation dynamics in conservation studies and suggest that lessons from the past might improve the long-term efficiency of our conservation efforts. These authors [7] also outline the fact that species respond independently to climate change and not identically from one cycle to another, which requires the study of individual species dynamics. Petit et al. (2008) [8] also highlight the value of palaeoclimate data, fossils records and genealogical analyses in helping to interpret simulations of future species distribution and understanding their adaptive response to climate change.

The history of *C. libani* is only partially known in the Eastern Mediterranean through palynological studies performed in Lebanon, Syria and Turkey [9–17]. These studies show that the range of *C. libani* forests has changed since the Late Glacial.

Currently, in Lebanon, cedar forests are restricted to small mountain areas also due to increasing human activities since the beginning of the Neolithic [17,18]. Consequently, there presently remain only 12 scattered *C. libani* forests in Lebanon. These forests are currently shelters for high diversity and home to flora species (Convention on International Trade in Endangered Species [CITES]), and harbor a range of endemic plant species [19–21]. In Lebanon, *C. libani* forests require a better management strategy. Today, despite strict conservation policies, the decline of the forest is still significant and ongoing [22,23].

Model simulations [24] show that the predicted future decrease of precipitation will lead to a high probability of desertification throughout the Mediterranean region. The increases of atmospheric CO_2 and temperature, and the water stress predicted by several GCM outputs [25] within the next century, may lead to an expansion of xeric vegetation in the Eastern Mediterranean region. However, the resolution of climate data used as input by Cheddadi et al. [24] does not allow a precise analysis of future changes at the scale of Lebanon. Here, we downscaled a climate dataset to simulate the future potential distribution of *C. libani* using a dynamic vegetation model at the scale of Lebanon.

2. Regional setting

Lebanon is situated in the Eastern Mediterranean region between Israel, Syria and the Mediterranean Sea (Fig. 1). The landscape is shaped by four parallel structures: the littoral zone, Mount Lebanon, the Bekaa valley and the Anti-Lebanon Mountains (Fig. 1). Mountain elevations range from more than 3000 m.a.s.l. for Mount Lebanon to c. 2680 m.a.s.l. for the Anti-Lebanon Mountains. These two mountain ranges are separated by the Bekaa valley (elevation c. 800 m.a.s.l.).

A Mediterranean climate prevails in Lebanon with hot and dry summers [26]. Most of the precipitation falls during autumn and winter [27]. Precipitation falls mostly on the western part of Mount Lebanon because of a foehn effect, while the major part of the Bekaa valley and the northern part of the Anti-Lebanon Mountains are arid [28].

An important herbaceous and arboreal diversity is observed in Lebanon [28]. Forests and wooded lands are mainly located on the slopes of Mount Lebanon and the southern part of the Anti-Lebanon Mountains [28]. In summary, along the littoral zone and on the western slope of Mount Lebanon, several coniferous (cedar, cypress, fir, juniper and pine), deciduous (carob tree, European hop-hornbeam, manna ash, oaks, pistachio tree), semi-deciduous (Aleppo oak) and evergreen (Palestine oak) forests and wooded lands have developed (for details, see Abi-Saleh [28] and Ministry of Agriculture and FAO [29]). The eastern slopes of the Mount Lebanon range are characterised by drier vegetation units with the development of forests and wooded lands of conifers (cypress, junipers), evergreen (Palestine oak) and semi-deciduous (Aleppo oak) populations. The Bekaa valley is presently a cultivated area producing vegetables, fruit trees and industrial crops (e.g. beetroot, cereals, potato and grains). The northern part of the Anti-Lebanon mountain range is characterised by the development of herbaceous species and junipers. Finally, on the southern part of the Anti-Lebanon Mountains, semi-deciduous (Aleppo oak), evergreen (Palestine oak) and conifers (cypress, pine) populations are found.

3. Material and methods

3.1. Palaeodata

In this article, we review the palynological data available in the Eastern Mediterranean region (Fig. 2)

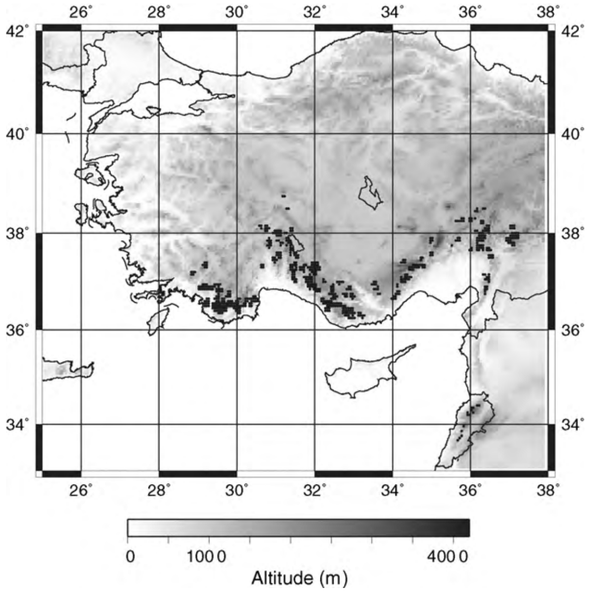

Fig. 1. *Cedrus libani* geographical distribution in Turkey [62], Syria [63] and Lebanon [45] and topography of the Eastern Mediterranean region in meters.

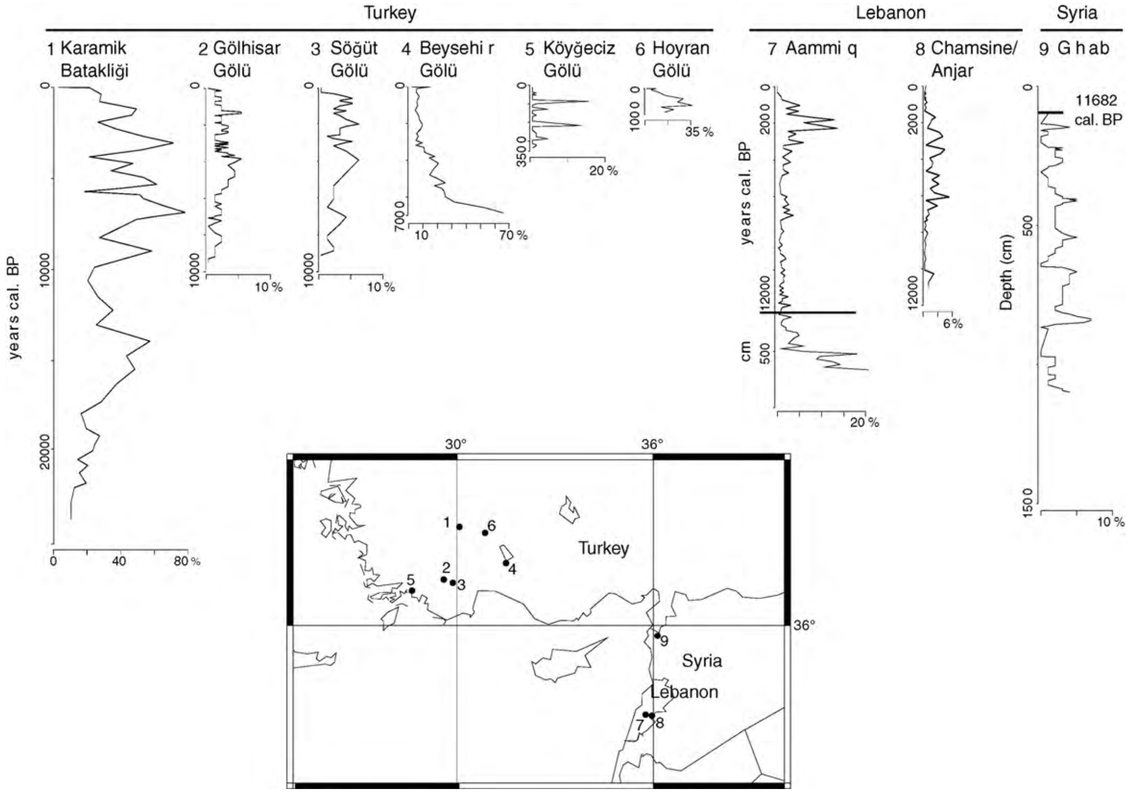

Fig. 2. Synthesis of *Cedrus libani* percentages from Eastern Mediterranean region main pollen records. Scales are in years cal. BP when an age-depth model is available and otherwise in cm. Pollen sequences are from Lebanon [16,17], Syria [9,14] and Turkey [11,12].

and synthesise them to provide an overview of past *C. libani* distribution (Fig. 2). All ages used in this article have been calibrated in years before present (cal. years BP) (Fig. 2), whenever possible, using CALIB 5.0 program ([30], using atmospheric data from [31]) to allow comparison between the sites. When the pollen record was poorly dated, which prevents the application of a reliable age-depth model, we decided to provide only the calibrated radiocarbon dates (i.e. the palynological sequence from Ghab valley in Syria [9,14]).

3.2. Model simulations

Simulations have been performed for both modern and future geographical distribution of *C. libani* using the CARAIB model. CARAIB simulates carbon cycle in the continental biosphere [32,33], biomass growth and vegetation carbon storage [34,35]. It is composed of five modules [36], which are: the hydrological cycle, photosynthesis and stomatal regulation, carbon allocation and biomass growth, heterotrophic respiration and litter/soil carbon, and biogeography. CARAIB requires climate, soil and vegetation data as input [37].

CARAIB can simulate the geographical distribution of *C. libani* using its modern climate boundaries. For the climate data, a local climate dataset was interpolated from meteorological stations (50 for temperature and 90 for precipitation) in Lebanon, (1930–1970) [27] with a 2' $\times$ 2' resolution (Fig. 3). Kriging with the R statistical software and gstat library [38] was used to spatially interpolate climate variables. Monthly mean temperatures were interpolated using universal kriging over altitude, longitude and latitude (Fig. 3a). For precipitation, ordinary kriging provided more robust interpolated data (Fig. 3b). Residuals (Table 1), which permit the evaluation of discrepancies between observed and interpolated data, are low for temperature values and slightly higher for precipitation values. Other climate data (wind speed, relative humidity, temperature amplitude, and sunshine hours) were obtained using bilinear interpolation over the same grid [39]. To obtain daily climatic data as input, CARAIB was coupled with a stochastic generator [40]. The soil texture class is taken from a data set originally at 1 $\times$ 1 resolution [41].

The climatic boundaries of *C. libani* (Table 2) used for its simulation are based on the largest populations from southern Turkey and western Lebanon (Fig. 1). The small patches of *C. libani* found in northern Turkey and western Syria (Fig. 1) were not used in this computation because of the low accuracy of the forests map. These climatic boundaries were computed from monthly climatic data [42] and present-day distribution using GRASS GIS (http://grass.itc.it/). These values differ from those of Khouzami and Nahal (1983) [3] where *C. libani* climatic boundaries were computed using 30 meteorological stations located in forests in Lebanon, Syria and Turkey; these differences can

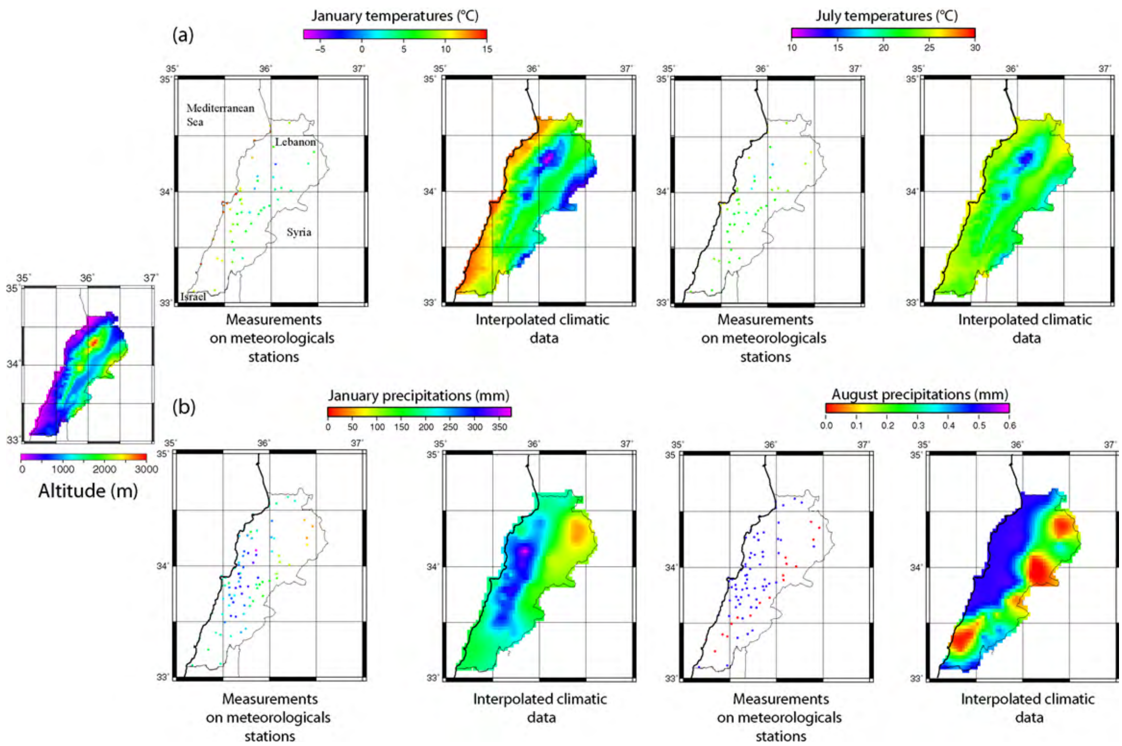

Fig. 3. Elevation, instrumental and interpolated climate data in Lebanon. a. Instrumental and interpolated (universal kriging) January and August temperatures in Lebanon. b. Instrumental and interpolated (ordinary kriging) January and August precipitations in Lebanon.

Table 1
Residuals (absolute dissimilarity) temperatures (°C) and precipitations (mm) between interpolated data and measurements made in meteorological stations in Lebanon.

	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Temp.												
Res. min	−1.58	−1.64	−1.31	−2.55	−2.38	−2.28	−2.43	−2.65	−3.02	−2.56	−1.83	−1.52
Res. max	1.77	1.38	1.49	1.26	1.91	2.08	2.44	1.86	1.93	3.46	1.57	1.48
Prec.												
Res. min	−73	−58	−58	−36	−20	−1.5	−0.5	−0.5	−5.5	−23	−53	−67
Res. max	88	95	69	29	16	2.4	0.5	0.4	5.7	43	50	82

Temp.: Temperatures; Res.: Residual; Prec.: Precipitations; Jan.: January; Feb.: February; Aug.: August; Sep.: September; Oct.: October; Nov.: November; Dec.: December.

be attributed to the fewer meteorological stations in Khouzami and Nahal's study (1983) [3].

The output of the CARAIB model used to predict the distribution of the species is net primary productivity (npp). The npp corresponds to photosynthesis minus autotrophic respiration and allows an accurate representation of potential distribution of a species; the presence of the species being proportional. The presence of these species is proportional to the npp values. The calibration of the model is based on the comparison of the npp values and the current geographical distribution of *C. libani* (Fig. 4a, b). The climate scenarios from the ARPEGE-Climat GCM [43] were interpolated on a 2' × 2' grid [34].

Table 2
Climatic boundaries used as input for *Cedrus libani* simulations.

Climatic boundaries	Tmin	Tmaxg	Wmaxg	Sw	Gdd
Cedrus libani	−16	4	0.5	0.03	1700

Tmin: Minimum absolute temperature threshold by the species (temperature threshold below which "cold" stress occurs); Tmaxg: Maximum mean temperature of the coldest month and tolerated by the species; Wmaxg: Maximum soil water content during the driest month allowing germination of the species; Sw: Minimum soil water content; Gdd5: Minimum values of growing degrees days above 5 °C (i.e., mean of the temperature exceeding 5 °C over the year, for the species to complete their vegetation cycle). Those parameters are obtained by overlapping the species distribution with climatic and soil data ([64] for details).

3.3. Model calibration

To calibrate the model, simulations of the present-day distribution of *C. libani* were performed. In order to obtain the most accurate output which best reflects the present-day distribution of *C. libani* as possible, we computed and tested different quantiles of current climatic boundaries of *C. libani*. The most suitable predicted current distribution

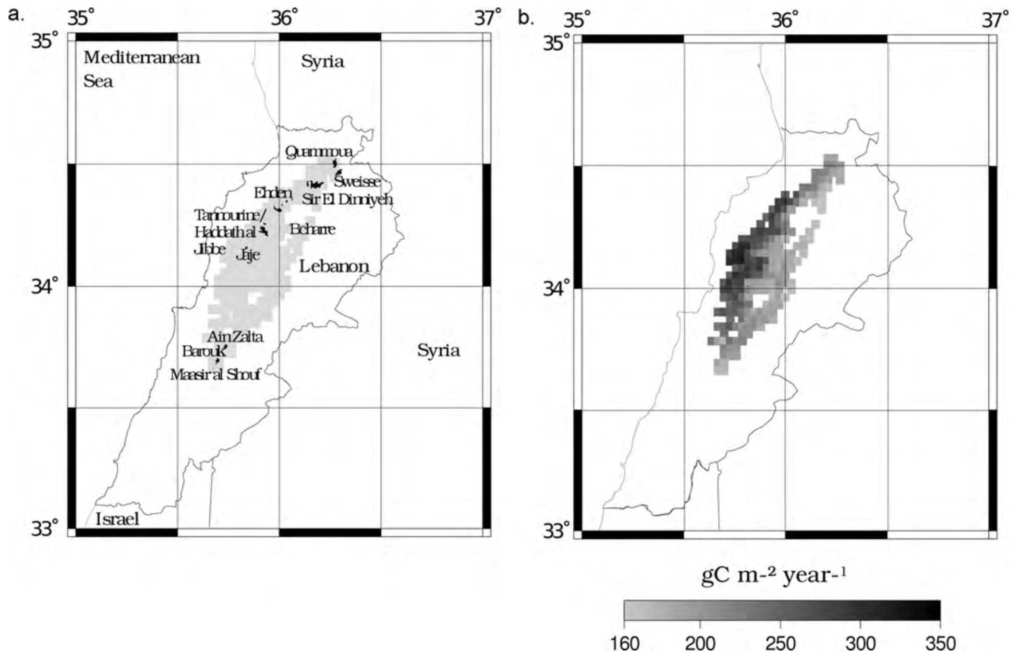

Fig. 4. a. In black: current distribution of *Cedrus libani* in Lebanon [45]. In gray: simulated net primary productivity above 160 gC m^{-2} year^{-1} b. Simulated present-day distribution of *Cedrus libani* in Lebanon using CARAIB model.

was simulated with the 0.05 and 0.95 quantiles (Fig. 4b, Table 2). The lowest npp value for which all *C. libani* forests in Lebanon are predicted is around 160 gC m^{-2} year^{-1} (Fig. 4a). Thus, we considered that all values of npp equal or higher than c. 160 gC m^{-2} year^{-1} correspond to a potential presence of *C. libani* (Fig. 4b). This threshold is coherent with that computed by Evrendilek et al. [44]. Based on this npp threshold, the CARAIB model predicts an expanded and continuous potential forest on Mount Lebanon (Fig. 4b). However, it should be noted that human activity has not been taken into account in the vegetation model and that the forest map of Lebanon [45] has a much finer spatial resolution than the climate dataset used here (2' $\times$ 2'). In Lebanon, *C. libani* trees are gathered into small patches (sometimes a stand comprising just a few trees) which does not allow satellite images of medium resolution to detect patch edges. None of the available maps in Lebanon depict all the extant occurrences of *C. libani* spots altogether either because of the map scale or because of the resolution of the satellite image used to derive the map.

4. Past distribution – review

Palynological records from the Eastern Mediterranean region providing percentages of *C. libani* are from Lebanon [16,17], Syria [9,14] and Turkey [11,12]. In order to interpret these palynological data accurately, modern pollen data obtained in/near cedar forests [16] have been used. The latter data show that *C. libani* pollen grains are not transported over long distances and that percentages above 5% indicate its presence near the site [16]. Using these results and palynological records from the Eastern Mediterranean region, we attempted to interpret past distributions of cedars since the Late Glacial.

Only three sequences have samples dated from the Late Pleistocene: Aammiq [16], Ghab [9,14] and Karamik Batakliği [11] (Fig. 2). The Aammiq and Karamik Batakliğı records have reliable age-depth models that can be used to reconstruct past vegetation dynamics. The Ghab record has no age-depth model because the dates are not reliable [9,14].

Reconstructing *C. libani* expansion and development since the Late Glacial with such few pollen data is difficult. Nevertheless, the available sequences show that *C. libani* percentages from the Aammiq (Lebanon) and Ghab (Syria) cores decrease during the Holocene in comparison to the Bølling/Allerød period. In the Karamik Batakliği core (Turkey), we observe an opposite trend.

These results suggest that cedar forests from Lebanon and Syria were better adapted to the climate prevailing near the Bekaa and the Ghab valleys during the Bølling/Allerød than during the Holocene (Fig. 2). Probably, in order to survive the warmer climate prevailing during the Holocene, *C. libani* forests migrated to more adapted areas at a higher elevations on Mount Lebanon and Jabal an-Nusayriya [9,14,16], where they occur nowadays (Fig. 1).

However, during the second part of the Holocene, human interference might have affected cedar forests [18] and exaggerated the limited expansion of these populations in Lebanon and Syria. Pollen records from the Holocene in these regions do not only reflect the impact of climate change on past vegetations. In spite of human interferences, cedar forests seem to have less developed during the Holocene in the southern part of the Eastern Mediterranean region than during the Late Pleistocene.

Conversely, in Turkey, the palynological records show rather a major development of cedar forests during the

Holocene (Fig. 2) which may suggest that climate was more favourable than in Lebanon and Syria.

5. Present-day distribution

Today, *C. libani* forests are present naturally in Lebanon, Syria and Turkey between 800 and 2100 m a.s.l. [5,6] (Fig. 1). More than 90% of the total distribution area is located in Turkey [46]. In Lebanon there are 12 scattered forests situated on the western slope of Mount Lebanon [28] (Fig. 1). The Ministry of Environment and the Ministry of Agriculture in Lebanon have designated some of these cedars forests as protected areas [47]. Thus, three forests are natural forest reserves (Barouk, Ehden and Tannourine); Al Quammoua area is designated as a protected natural site and the following forests: Barouk, Tannourine, Jaje, Quammoua, Sir El Dinniyeh and Sweisse are now protected forests. Most of the cedar forests in Turkey are located in the Taurus mountains but there are scattered populations in other parts of Anatolia [48] (Fig. 1). In Syria, as a consequence of increasing human impact, *C. libani* populations are currently located in an extremely restricted area in the Jabal an-Nusayriya in the northwestern part of the country [6,49–51] (Fig. 1).

6. Future distribution

Three simulations with different climate scenarios from the IPCC [25] were performed using the ARPEGE-Climat climate dataset as input to the CARAIB model. The A2 scenario projects an increase in global CO_2 emissions till the year 2100. The A1B scenario predicts an increase of global CO_2 values until c. 2050 then a decrease towards the year 2100. Lastly, the B1 scenario is more optimistic than the two previous ones, with a slight increase in CO_2 emissions until the year c. 2040 and a decrease by the year 2100. The simulations performed using these three scenarios predict higher npp values of *C. libani* on the most elevated regions on Mount Lebanon (Fig. 5). However, for each scenario, major geographical differences are observed. For scenario B1, the simulated area encompasses only the Bcharre, Ehden, Jaje and Tannourine/Haddath al Jibbe cedar forests and a small area on the southern part of the Anti-Lebanon mountain range. For scenario A1B, only Ehden and Bcharre forests are simulated. For the A2 scenario, all cedar forests, except for Bcharre forest, are simulated to expand into areas where a *Juniperus excelsa*-dominated forest-steppe vegetation unit is currently present.

7. Discussion

7.1. Future of Cedrus libani in Lebanon

Palaeobotanical records in the Eastern Mediterranean region show that the distribution of *C. libani* forests changed since the Late Glacial (Fig. 2). In Lebanon, palynological records suggest that cedars were more adapted to the Bølling/Allerød climate, which is assumed to be colder than the climate prevailing during the mid-Holocene [52,53]. The same observations have already been made for *Cedrus atlantica* forests in North Africa, where cedar forests were more expanded during the Late Pleistocene than at present [54]. The currently reduced development of cedar forests in the southern Mediterranean region is also attributable to human interferences such as the use of wood for construction by a succession of civilizations [18]. Consequently, cedar forests in the southern Mediterranean region are threatened not only by the climate warming during the Holocene but also by different human activities.

As the current climate in the Eastern Mediterranean region is warmer and drier than during the Bølling/Allerød [52,53], *C. libani* forests are becoming even more threatened nowadays in Lebanon. Consequently, the modern populations are already surviving in refugium areas. For future conservation strategies, the identification of new areas with suitable climate is crucial as *C. libani* may be able to survive in these locations under drier climatic conditions predicted by the various GCMs [55]. Climate during the next century is expected to be even more arid in Lebanon which will undoubtedly affect the distribution of *C. libani*. The available network of fossil data does not allow the evaluation of its migration rate, but a migration to higher altitudes should be expected.

Three climate scenarios allowed us to simulate areas where cedars could potentially be preserved until the year 2100. These simulations show that only a few of the existing *C. libani* forests will be able to survive in the northern part of Mount Lebanon (Fig. 5). The three scenarios show that cedars may be preserved near their present-day geographical distribution at higher elevations (Fig. 5). However, it is important to consider the rate of climate change during the next century and the ongoing strong human impact versus the migrational capacity of the species. Propagation of cedar seeds is accomplished by wind, gravity or animals [56]. Of these, wind is the most important agent that can carry seeds over varying distances, depending on wind velocity and plant location [56]. This natural dispersal ability allows forests to expand from their borders at several distances, depending on abiotic (i.e. wind velocity, topography, climate) and biotic influences (i.e. plant competition, grazing, deforestation) [56]. Today in Lebanon, most of *C. libani* forests cannot expand any higher because they are already located at the summit of mountains. Only Bcharre, Ehden and Tannourine/Haddath al Jibbe have higher altitudes. Fady et al. [57] show that cedars from Tannourine/Haddath al Jibbe forest (Fig. 4) have a high genetic diversity. As suggested by Cheddadi et al. [54] for *Cedrus atlantica,* by combining model simulations and genetic data, it would be appropriate to rely on populations with high genetic diversity for eventual reforestation projects. Consequently, in order to preserve *C. libani* forests in Lebanon efficiently, conservation efforts should focus on protecting forests where cedars present high genetic diversity, such as the Tannourine/Haddath al Jibbe forest and where high elevations are available.

Importantly, the ARPEGE-Climat climate dataset has a resolution between 0.5° (30’) and 1° (60’) in the Eastern Mediterranean region. The downscaling of such GCM

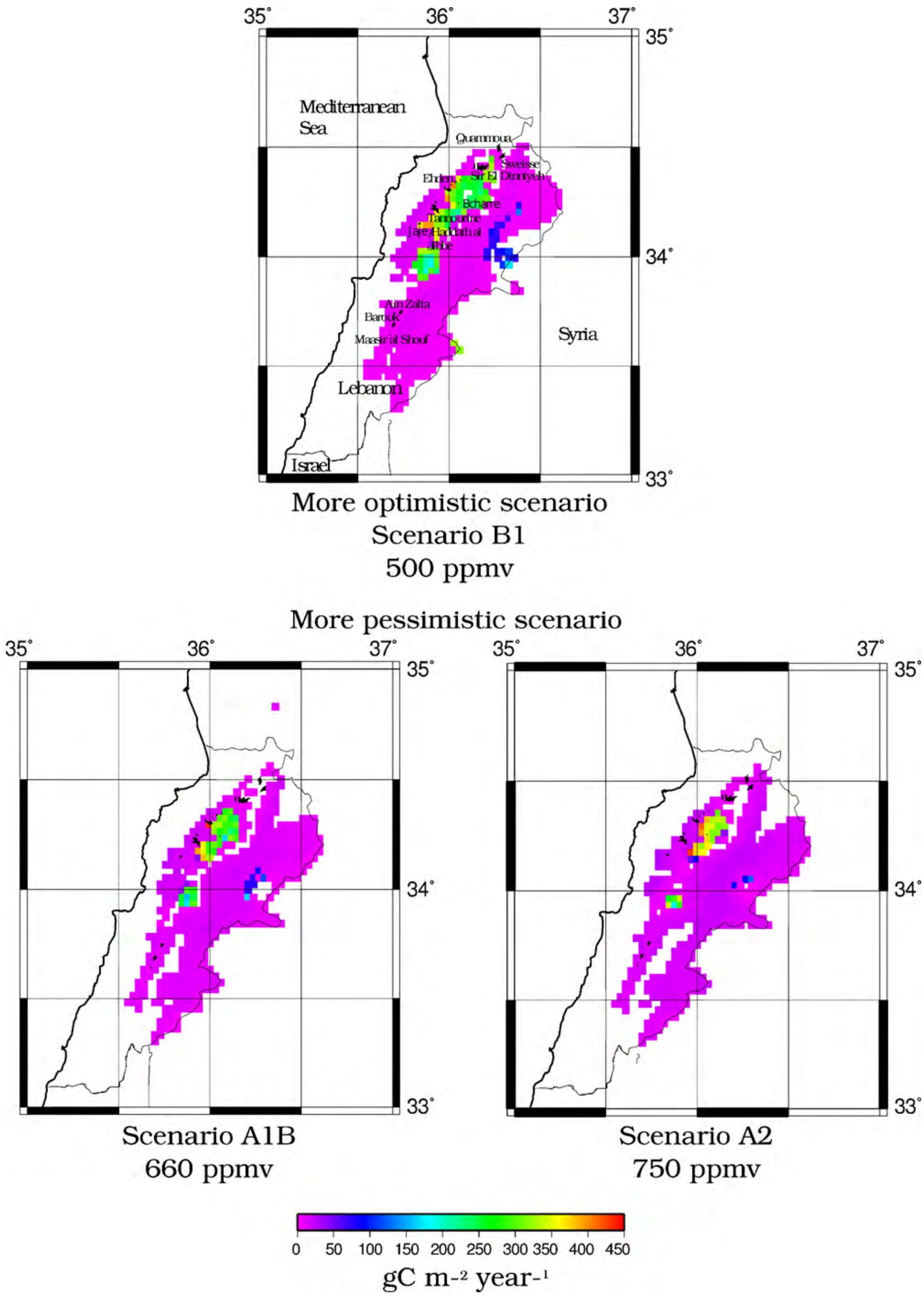

Fig. 5. Simulations of future potential areas for *Cedrus libani* in Lebanon using different IPCC climate scenarios.

resolution will be necessary in order to produce more accurate model simulations that portray the potential distribution at local scales in mountainous areas.

7.2. Future of Cedrus libani in the Eastern Mediterranean region

Palynological studies show that *C. libani* dynamics depend upon a range of natural and human-induced forcing mechanisms in the entire Eastern Mediterranean region. Our simulations allowed us to identify suitable areas for *C. libani*. In Turkey, most cedar populations have not yet reached the highest elevation in the Taurus mountain and are currently well expanded (Fig. 1). In these areas, there exist higher elevations where cedars could migrate and adapt. In the northern part of Turkey, there are small remnant populations [58] which are under threat because of the low mountain elevations. In Syria, scattered *C. libani* populations have also already reached the highest elevations (Fig. 1). Cedar populations in Turkey and Syria have high genetic diversity [57,59]. Therefore, there is less threat of loss of genetic diversity if these populations are preserved. However, it should be noted that Bou Dagher-Kharrat et al. (2007) [59] reported that genetic erosion has occurred in some *Cedrus* populations in the Eastern Mediterranean. Thus, maintaining population dynamics and regeneration of *C. libani* populations should be a priority matter for conservation managers [60]. Our simulations allow the identification of areas where cedars could potentially be preserved. Future studies need to take into account migrational processes. A network of well-dated fossil data may help to estimate these migrational rates.

7.3. Implications for conservation strategies

Previous studies [7,8,60,61] have shown that increased knowledge and understanding of long-term plant dynamics studies is needed for better evaluation of the predicted impacts of future global warming. The integration of palaeoecology, model simulations and genetics is necessary for conservation issues [7,8]. However, very few studies dealing with conservation do include long-term palaeoecological data [4–6,23,58], thus many conservation strategies are ill-informed regarding long-term trajectories of individual species. The results of this study aim at evaluating the impact of future global warming on *C. libani* and proposing where long-term conservation efforts should be applied:

1. The threats on Mediterranean species should be re-evaluated at different temporal scales, taking into account the long-term effect of future climate change based on palaeobotanical data and model simulations.
2. In order to preserve a species or a population, we need to identify and protect potential distribution areas and migrational corridors through a long-term conservation policy.

Potential migration areas for the survival of *C. libani* populations from Bcharre, Ehden and Tannourine/Haddah-al-Jibbé have been identified but these are not currently protected areas. If human activities (such as grazing) are allowed to continue over the future decades, then this will be a serious threat to the preservation of *C. libani* populations.

8. Conclusion

Studies on the long-term dynamics of *C. libani* are necessary, as the current distribution of this species is restricted to mountainous areas. Model simulations show that *C. libani* could be preserved around its current distribution area or/and on more elevated areas over Mount Lebanon. Such prospective is coherent with the simulated velocity of temperature change at the global scale [65]. In south Turkey, potential areas have also been identified. In Syria, the only remaining *C. libani* population has already reached the highest elevations. More importantly, the conservation of *C. libani* will depend on its ability to migrate across a predominantly cultivated landscape. The available palaeobotanical data are not sufficient to evaluate its migration rates. In order to better interpret our model simulations, we have investigated the long-term dynamics of *C. libani* using palaeobotanical data.

Our study shows that the threats on Mediterranean species should be re-evaluated considering the long-term effect of future global warming and that highlighting future potential areas for the survival of *C. libani* (or others species) is necessary to protect these areas against future human activities.

Conflict of interest statement

No conflict of interest.

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