Guiding Conservation for Mountain Tree Species in Lebanon

Rachid Cheddadi, Carla Khater

forests

Article

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Rachid Cheddadi [1,*] and Carla Khater [2]

[1] ISEM, University of Montpellier, CNRS, IRD, 34095 Montpellier, France
[2] Center for Remote Sensing, National Council for Scientific Research, Beyrouth 362060, Lebanon; ckhater@gmail.com
* Correspondence: rachid.cheddadi@umontpellier.fr

Abstract: The objective of this study is to contribute to the conservation of upland tree species in the face of climate change. We used a conservation index to prioritize the areas and populations of three conifer species in the mountains of Lebanon. This conservation index integrates (1) mountain topography to identify areas that could provide a suitable microclimate, (2) genetic diversity to assess the adaptive capacity of populations in these mountain areas, and (3) a hypothetical climate change scenario that could affect this Mediterranean region. The idea of this index is to prioritize protected areas based on a match between the relevance of the area to be protected and the populations that need local and long-term protection. The stronger the match, the higher the priority of the area to be protected. We applied this conservation index to 36 populations of 15 fir, 15 cedar, and 6 juniper. These populations were genotyped by different authors whose published data we used. The results show that 10 populations of the 3 species have a very high index and 9 others have a lower but still high index, indicating a high conservation priority. These 19 populations occur in 5 different areas that we delineated and that form a network along the Lebanon Mountains. We hypothesize that the conservation of these 19 populations across the Lebanon Mountains could contribute to the long-term sustainability of the 3 species in the face of a 2 °C increase in mean seasonal temperature and a 20% decrease in seasonal precipitation compared to the current climate.

Keywords: protected areas; biodiversity conservation; mountains; climate change; conservation index; Lebanon

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1. Introduction

The forests of Lebanon have been exploited for the last 5000 years, since the time of the Pharaohs [1,2] and later by Phoenicians, Assyrians, Babylonians, Kings of Israel, Romans, and more recently, by the Turkish Ottoman Empire until World War I [1]. At that time, forests covered up to 70% of Lebanon, but today they are highly fragmented due to urban expansion, sustainable timber use, grazing, and tourism [3,4] and have shrunk to 13.6% [5].

Since 2011, more than 1.2 million seedlings have been planted throughout Lebanon under the Lebanon Reforestation Initiative (www.lri-lb.org, accessed on 1 January 2020), including Lebanon cedar (Cedrus libani A. Rich.) and other native species. Many of Lebanon's mountain forests are national parks or nature reserves, including the largest, the Shouf Cedar Nature Reserve, established in 1996, which covers 550 km^2, about 5% of the country's total area, and includes 620 hectares of cedar forest (www.shoufcedar.org, accessed on 30 November 2021). Livestock has been banned from the Shouf Reserve, contributing to the successful regeneration of the Lebanon cedar. Thus, despite the decline and fragmentation of its forests, Lebanon's mountains are still more heavily forested than most surrounding countries in the region, with scattered stands of several endemic tree species such as pine, oak, fir, beech, cypress, cedar, and juniper [6].

The national symbol of the country is the Lebanon cedar, which still grows naturally in the mountains of the country. This tree has been heavily exploited, and only a limited number of mature trees remain in the wild, while thousands of Lebanon cedars have been planted in many reserves (www.lri-lb.org). The Lebanon cedar is classified as an endangered species by the IUCN Red List, with declining populations [7]. In addition to this emblematic tree, there is another long-lived and endemic tree species, the Cilician fir (*Abies cilicica* (Antoine and Kotschy) Carrière), whose few remaining small forests in the north of the country are not well protected. Cilician fir forests in Lebanon represent the lowest rear edge of temperate European firs, and the species is near extinction according to IUCN criteria [7].

The response of these long-lived mountain tree species to future climate change, particularly in a semi-arid Middle Eastern region, remains an open question. Several global climate models predict a temperature increase of about 4 °C and a decrease in precipitation of about 20% by the end of the 21st century [8,9]. Under such a climate scenario, the range of Lebanon cedar is expected to be severely affected [10], and Cilician fir will also experience a significant reduction in its range [11]. Climate change in the northern part of the country, a region prone to desertification, is causing a bioclimatic shift from subhumid to semi-arid [11,12]. At the same altitude, local conditions related to the topographic ruggedness of the terrain and its orientation can create microclimatic conditions favorable to the survival of tree species [13,14]. The microclimate of these upland areas may differ from a regional or global climate that is unfavorable to the species, allowing their local survival [13,15]. This was the case in the past when mountain regions served as a refuge for species during the last ice age [16], which lasted several millennia, and served as source areas for recolonization of climatically wider areas during global warming in the Holocene.

During the last ice age, the mountains of Lebanon provided a refuge for Lebanon cedar [17] and certainly for other endemic tree species. Threatened tree species living under an unfavorable regional climate may well be saved from extinction in future microrefugia with suitable microhabitat conditions [18]. The challenge is to map these microrefugia with suitable populations in the wild. Local conservation of populations in suitable microrefugia may be a viable option [19–22] that should be considered for the long-term conservation of Lebanese tree species, especially when resources allocated for conservation are limited.

In the context of the ongoing climate change, the local adaptive capacity of the Lebanese conifer species will also be affected by ongoing human activities [23] and the progressive reduction in the effective size of their populations [24,25]. The genetic diversity, high interbreeding rates, and great plasticity of trees in general [26] give them a great capacity to adapt to climatic variation [27,28]. It is therefore important to consider the genetic capacity of the focal species to adapt for their long-term conservation.

Several approaches have been proposed to anticipate the potential extinction of threatened species and conserve them in the face of ongoing climate change. Among these approaches, a greater number of protected areas than those already established by local governments, and especially their effective management [29], would increase the chances of conserving threatened species. Climate-change refugia as areas for species conservation have been identified through simulation models that integrate topographic and ecological complexities at different spatial and temporal scales [30,31] or based on species-specific information [32].

In northern America, authors have created a hierarchy of these protected areas based on different environmental diversity metrics and concluded that managers should consider different theoretical and field data to optimize their conservation efforts [33]. In Lebanon, scientists have used a database of species richness across the country to prioritize plant conservation to optimize the management of threatened species [34]. However, there remains great uncertainty about whether or not designated protected areas will be adequate in the long term [35,36]. Furthermore, protecting all potentially suitable areas could be a difficult task if local resources are limited.

Today, there is an urgent need to identify both potential refugial areas and populations with high adaptive capacity and to prioritize these areas for effective protection in the long term. In this study, we developed a new conservation index combining mountain topography, genetic diversity of three mountain tree species, and a climate scenario for the Mediterranean region. The objective of this conservation index is to (1) identify potentially suitable microrefugial areas in the mountains, (2) assess the adaptive capacity of populations within or near these areas, and (3) consider the effects of climate change on the populations studied in the areas where they occur. The overall goal of this index is to prioritize areas for a cost-effective, long-term conservation plan.

2. Species and Methods

2.1. Studied species

In the present study, we focused on three mountain conifer species in Lebanon: *A. cilicica* (Cicilian fir), *C. libani* (Lebanon cedar), and *Juniperus excelsa* (Greek juniper) (Figure 1). *Abies cilicica*, *Cerus libani*, and *Juniperus excelsa* are slow-growing species that can live an average of 100 to 300 years [37]. They are very tolerant of summer drought and receive winter precipitation mainly as snow [38]. They reproduce in spring, with the male and female cones growing on separate branches of the same tree. By late fall or early winter of the following year, the seeds have matured, are shed, and are dispersed by wind up to 60 m from the parent tree or occasionally by squirrels over greater distances [39]. Cedar pollen grains fall within approximately 800 m, with less than 1% up to 1 km from the source tree [17,40], and fir pollen grains also decline sharply with increasing distance, with most deposited within 50 m to 100 m of the source population [41].

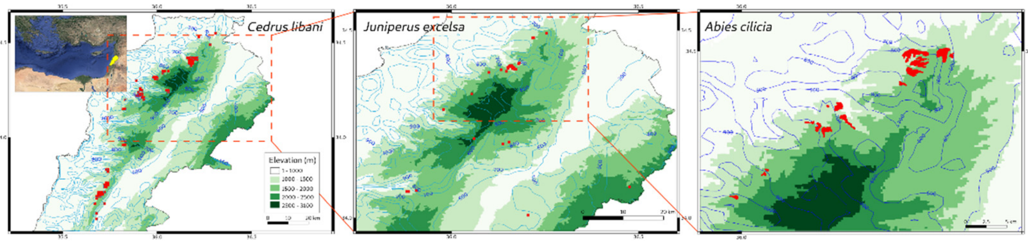

Figure 1. Maps showing current distribution of *Abies cilicica*, *Cedrus libani*, and *Juniperus excelsa* in the mountains of Lebanon with isohyets of current annual precipitation.

2.2. Conservation index

To contribute to the conservation of these three species in the wild, we considered (1) the topography of the area in which they occur based on mountain ruggedness (Figure 2), (2) their potential adaptability to ongoing climate change based on their genetic diversity (Figure 2), and (3) the question whether the populations that comprise them will remain within a suitable local climate, analyzed by the calculated distance between their current climatic niche and an expected hypothetical future climate (Figure 3 and Table 1). These variables were integrated into a conservation index (CI) as follows:

$$CI = Gd * Tr / max\,(Di)$$

Gd is a genetic diversity variable. In this study, it was taken from the literature [42–46] (Figure 2). We integrated different measures of genetic diversity for Gd because the three species were genotyped using different techniques (AFLP, RFLP, RAPD) and with different primers (nuclear and chloroplast microsatellites) to obtain different measures of genetic diversity (allelic richness, expected heterozygosity). To make the CI comparable between the 3 species and among populations of the same species that have been studied by different authors, we scaled the different measures of genetic diversity between 0.1 and 1 (Figure 2, Table 1). The goal of scaling the different measures of genetic diversity is to obtain comparable measures of genetic diversity between species and populations of the same species. In the latter case, different populations of *Cedrus libani* in Lebanon were genotyped by two different groups of authors; Fady [45] used Nei's index, and [46] used a Bayesian approach to estimate heterozygosity to assess the genetic diversity of Cedrus libani. These two approaches provided different values that can be compared after rescaling to a similar range.

Tr is the terrain ruggedness (Figure 2). Mountains with highly heterogeneous topography may host local microclimates that differ from regional climates [13,14,47]. Mountain topography, quantitatively measured using various indices, helps predict suitable habitats for species [48]. Other local factors such as soil temperature [49] and water [50] may contribute to the maintenance of a local microclimate. In this study, we used the Terrain Ruggedness Index (TRI) to identify areas likely to provide suitable long-term habitat. The TRI is derived from a GTOPO30 digital elevation model [51] with a spatial resolution of 30 arc seconds (approximately 1 km) and is based on the elevation difference between a grid cell and its 8 neighboring cells [52]. We used a geographic information system [53] to calculate TRI. The TRI varies from 0 (flat) to over 1000 (extremely rugged) [52].

Table 1. Location with latitude and longitude of populations (Pop) of *Abies cilicica* (Species A), *Cedrus libani* (Species C), and *Juniperus excelsa* (Species J) with their site name, genetic diversity (Gd), terrain ruggedness (Tr) in the area where they occur and the distance (Di) between the mean of their current climate range and a hypothetical expected warmer (+2 °C) and drier (−20% precipitation) climate. Colors correspond to quantiles of the conservation index (Ci) for each species, which represents a gradation of conservation priority from very high (red) to low (green, see Figure 4).

Pop	Spot	Species	Site Name	Longitude	Latitude	Gd	Tr	Di	Ci
1	3	A	Jaïroun	36.12559	34.42586	0.71	431	103	2.97
2	3	A	Kfarbnine	36.10355	34.40200	0.75	347	95	2.75
3	3	A	Kfarbnine	36.10797	34.39806	0.74	320	96	2.47
6	2	A	Ehden	35.99223	34.30729	0.34	364	55	2.24
5	3	A	Kfarbnine	36.09566	34.40533	0.56	347	94	2.05
4	4	A	Kobayat	36.26463	34.49820	1.00	288	151	1.91
7	4	A	Qammouaa	36.24337	34.49640	0.80	303	147	1.66
8	3	A	Wadi Jhanam	36.13486	34.41423	0.68	232	106	1.49
9	4	A	Hermel	36.27785	34.49399	0.72	288	153	1.35
10	4	A	Qammouaa	36.22776	34.48551	0.80	176	142	1.00
15	2	A	Bqaa_Safrine	36.03345	34.34325	0.10	584	69	0.85
13	2	A	Karm El Mohr	36.03026	34.33841	0.22	232	68	0.76
11	4	A	Qammouaa	36.22445	34.47012	0.67	148	141	0.71
12	4	A	Qammouaa	36.21097	34.45737	0.52	154	137	0.58
14	3	A	Qarsita	36.11414	34.42744	0.11	382	102	0.41
16	1	C	Bcharre/Hadeth el Jebbe	35.83333	34.20000	1.00	388	13	29.85
17	5	C	Barouk	35.68333	33.60000	0.99	360	23	15.47
24	5	C	Chouf	35.68333	33.56667	0.67	292	23	8.52
30	5	C	Ain Zhalta	35.71667	33.65000	0.57	318	26	6.91
21	1	C	Jaj	35.82884	34.14986	0.11	245	10	2.62
23	1	C	Bcharre	35.83333	34.20000	0.11	307	13	2.53
25	4	C	Akkar/Quammoua	36.21667	34.53333	0.98	303	138	2.14
19	1	C	Tannourine	35.88660	34.20318	0.11	353	21	1.90
18	5	C	Arz El Chouf	35.69391	33.68814	0.14	302	23	1.88
20	2	C	Jord Njas	36.03081	34.34111	0.14	350	68	0.73
29	2	C	Ehden	35.99223	34.30729	0.10	387	55	0.70
22	2	C	Karm El Mohr	36.03026	34.33841	0.13	350	68	0.69
27	3	C	Jabal Illy	36.16951	34.39775	0.11	584	120	0.56
26	4	C	Kharm Chbat	36.31379	34.55227	0.15	265	162	0.24
28	4	C	Hermel	36.27785	34.49399	0.11	288	153	0.22
31	2	J	Wadi El Njass	36.05444	34.33028	0.68	350	79	3.00
32	3	J	Donniyeh	36.10000	34.38806	0.34	584	93	2.15
33	6	J	Barqa	36.13750	34.19667	0.83	282	114	2.06
34	4	J	Qammouaa	36.25389	34.49278	0.80	302	149	1.63
35	6	J	Aarsal	36.47611	34.08250	1.00	202	212	0.95
36	1	J	Afqa	35.90550	34.07361	0.10	361	45	0.80

Di is the Euclidean distance between a hypothetical future temperature and precipitation at the population location and the current climate. Climate variables and their values were obtained from the CHELSA climate dataset [54] and then interpolated to the species' georeferenced locations. The geographic range of *A. cilicica* and *C. libani* was first georeferenced in [10,42], and that of *J. excelsa* was derived from [6] (Figure 1). The current climatic niche (temperature versus precipitation) of each species is represented by its seasonal average temperature and seasonal precipitation sum (Figure 3A). The hypothetical future climate scenario corresponds to a 2 °C increase in the current mean seasonal temperature and a 20% seasonal decrease in precipitation (Figure 3B). We used this uniform climate change scenario for the entire study area and for each season because of the coarser spatial resolution (between 9 and 50 km) of the available model simulations for the Mediterranean [55] than the size of the studied populations, which is often less than 1 km^2, and the fact that there are some discrepancies between climate models. However, our hypothetical climate scenario is consistent with the overall predicted climate change in the Mediterranean region [9]. Di is calculated for each season and species between their mean current seasonal temperature and precipitation values of each species and the future temperature and precipitation values at the population location. We used the mean values of each seasonal climate variable because the most frequent populations occur in a narrow climatic range around the mean value of their climatic envelope and these central populations are able to withstand a wider temperature range than they currently experience [56].

The objective of this CI is to prioritize areas where the 3 species can potentially survive as separate species (sector 5) or where they coexist (sector 2 and 4) for long-term conservation. The CI was originally developed and applied to Atlas cedar (*Cedrus atlantica*) in Morocco [57].

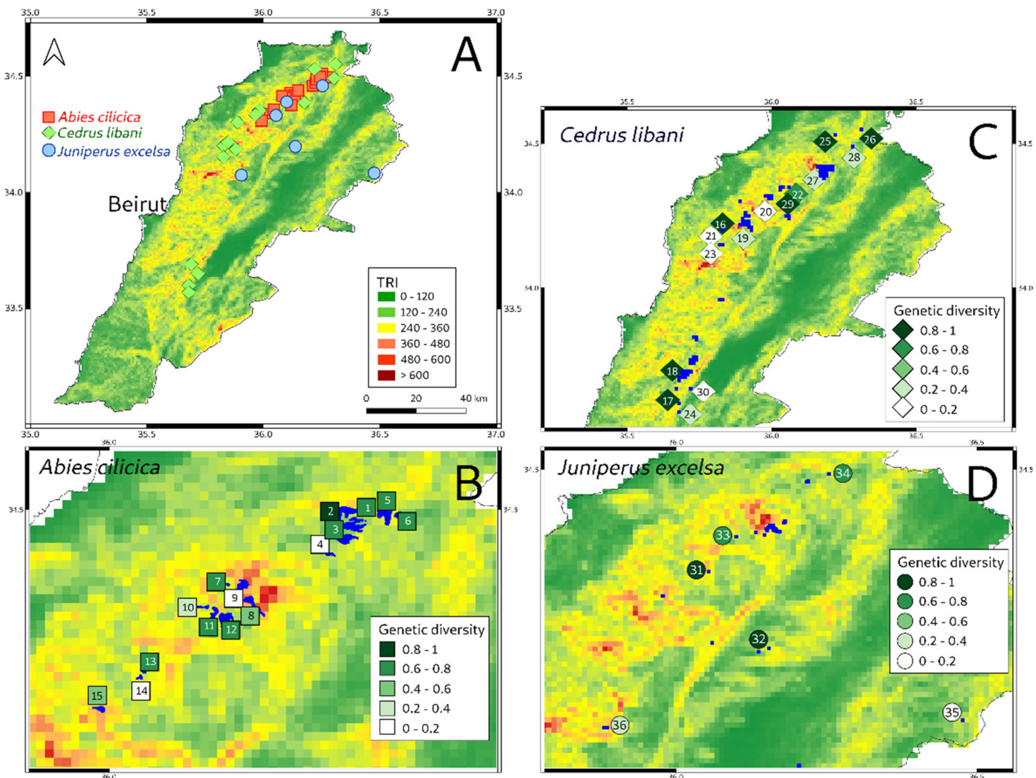

Figure 2. Terrain Ruggedness Index (TRI) of Lebanon showing the location of the studied populations of *Abies cilicica*, *Cedrus libani*, and *Juniperus excelsa* (**A**) and their genetic diversity from Awad [42] (**B**), Fady [45], Bou Dagher-Kharrat [43] and Semaan & Dodd [46] (**C**), and Douaihy [44,58] (**D**). [42]. For comparison purposes, we scaled the different genetic diversity markers used by the authors between 0.1 and 1.

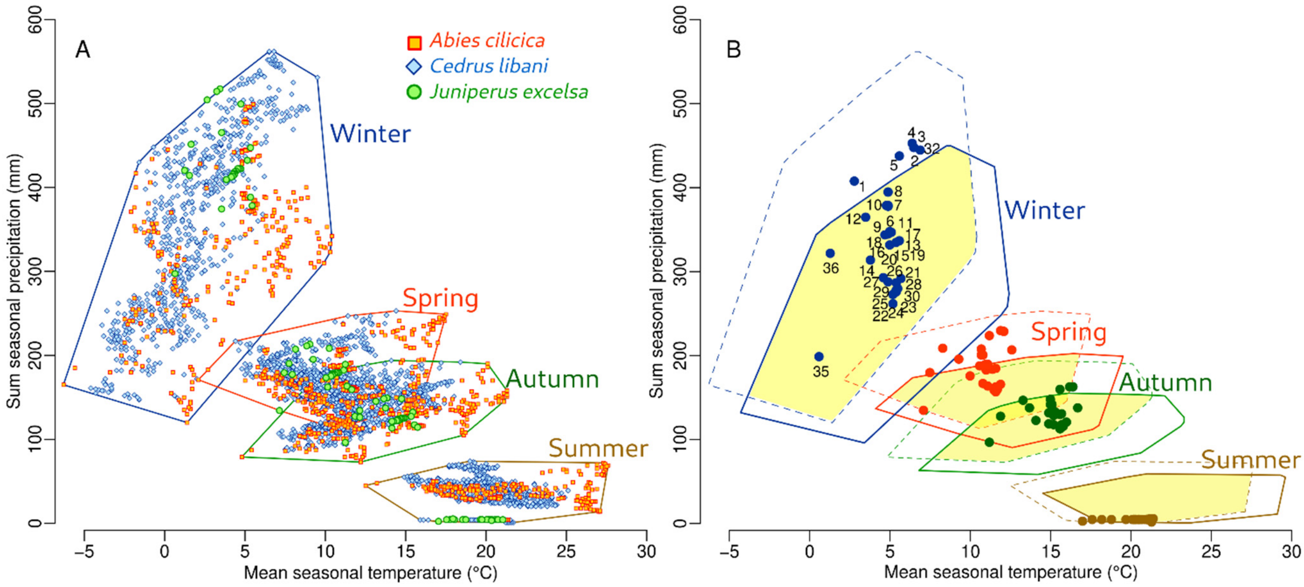

Figure 3. (**A**) Climate range of *Abies cilicica* (green dots), *Cedrus libani* (blue dots), and *Juniperus excelsa* (red dots) based on mean seasonal temperature and sum of seasonal precipitation. (**B**) The shifted climatic range overlaps with current values (yellow area) for a 2 °C increase in mean seasonal temperature and a 20% loss in seasonal precipitation sum. Populations studied (1 to 36, see Table 1) are plotted for each season (blue = winter, red = spring, green = fall, and maroon = summer).

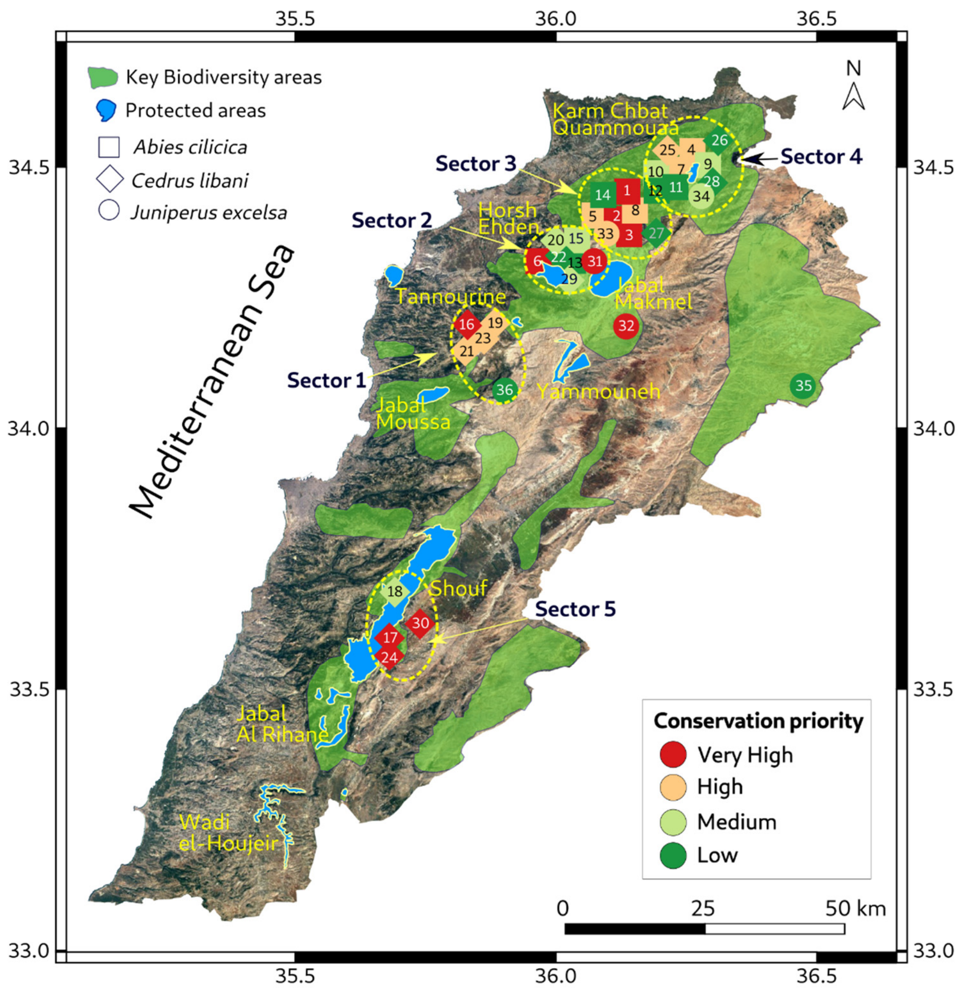

Figure 4. Conservation priority from very high to low (red to green) for 15 populations of *Abies cilicica* (squares), 15 populations of *Cedrus libani* (diamonds), and 6 populations of *Juniperus excelsa* (circles), based on the conservation index developed in Table 1. National protected areas (blue areas) and Key Biodiversity Areas (green areas) were digitized from [34] and https://www.keybiodiversityareas.org/ (accessed on 1 April 2022), respectively.

3. Results

Based on the conservation index, we identified 5 main forest sectors in Lebanon (Figure 4). The ecosystems of 3 of them (sectors 2, 3, and 4), the northernmost, contain the three species of this study. A fourth (sector 1) is predominantly cedar with some sparse juniper populations, and the last (sector 5), the southernmost, is a cedar forest.

Using quantiles of the CI, we classified each species into four groups to rank their conservation priority from very high to low (Table 1 and Figure 4). The populations with the highest CI are those that should be given the highest priority. These populations are located in or close to rugged areas, and their genetic diversity is higher than average. In terms of climate, the hypothetical future climate shows an overlap with their climatic envelope (Figure 3). Among the 36 populations studied, there are 10 populations, including 4 cedar forests in sectors 1 and 5 (populations 16, 17, 24, and 30, Figure 4), 4 fir forests in sectors 3 and 4 (populations 1, 2, 3, and 5), and 1 juniper population in sector 2 (31) that have a very high CI. There is 1 isolated juniper population (32) that also has a very high CI. If we were to evaluate the conservation status of the populations of the 3 conifers studied based on our conservation index, these 10 populations could be considered the best positioned climatically and genetically to survive locally.

We found that 4 fir populations (4, 5, 7, 8), 4 cedar populations (19, 21, 23, 25), and 1 juniper population (33) also have high CI (Figure 4). These populations are located in sectors 1, 3, and 4. Populations in these 5 sectors constitute a network of areas along Mount Lebanon that should be given a higher priority for protection from human inferences. The remaining 16 populations in the 5 sectors have lower CI. However, their lower CI should not be interpreted as suggesting that they should not receive protection measures but rather that they may be more vulnerable to the expected climate change than the populations with higher CI.

4. Discussion

Palynological studies have shown that Cilician fir, Lebanon cedar, and Greek juniper have been continuously present in Lebanon during the last 15 millennia [10,17,56,59]. The mountains of Lebanon are the lowest latitude forests where these coniferous species occur today, but the number and size of their populations are decreasing dramatically in some areas and are less than 20 individuals, such as some Cilician fir (field observations). Although protected areas have proven to be very useful in Lebanon, the low dispersal capacity of these species and the small size of the protected areas (Figure 4) will limit their ability to track ongoing climate changes [60]. Moreover, management plans adopted to date may prove inadequate in the longer term, given the current rapid climate change [4,61]. Protection of all forests or all populations in Lebanon would be extremely difficult to implement, especially in the context of limited resources. These problems force planners to select areas for protection in a cost-effective manner. The approach we propose in this study is complementary to other conservation approaches that aim to either create new protected areas [62], make existing ones more effective [29], or prioritize new or existing protected areas [34] based on different and more or less complex ecological, botanical, geographic, or model-based criteria. Now we need to communicate our academic findings to local conservation planners in a comprehensive and efficient way.

Our approach in this study aims to optimize the conservation process of species by prioritizing populations for local conservation based on their genetic adaptability (Figure 2), the adequacy of the uplands where they currently occur, and expected climate change relative to their current range (Figure 3B). This approach is not intended to discard lower-priority populations but rather to optimize conservation efforts in the face of limited resources. In addition to our prioritization approach, planting new populations at higher elevations in areas that might be suitable under future climatic conditions could be an additional conservation measure to be explored in future studies. For example, this measure should be taken for the Greek juniper populations, which are considered a genetic resource for reforestation projects on Mount Lebanon above 2000 m elevation.

Scientists have prioritized plant biodiversity conservation in Lebanon based on species richness and have provided valuable guidance to conservation managers to avoid the threat of extinction [34]. Our conservation index is a contribution to such conservation efforts in Lebanon with other environmental, genetic, and climatic data to assess the potential persistence of three conifer species in their current natural habitat.

Based on this conservation index, we defined five mountain sectors where Cilician fir, Lebanon cedar, and Greek juniper occur and where populations of each species would be worth protecting. Action is needed in all five areas (Figure 4), with a focus on the most genetically diverse populations in the most likely suitable upland areas.

In Afqa and Jaj (Sector 1, Figure 4), the cedar populations (16, 19, 21, and 23) (Figure 4) have the highest conservation index because they are genetically diverse and the landscape in which they occur is rugged (up to 500 m). Thus, they have a good potential to survive in this area. The forests of Afqa and Jaj are already considered areas of natural and/or ecological importance worthy of protection and were declared Cedar Nature Reserves (lb.test.chm-cbd.net/biodiversity/protected-areas/Nature-Reserves, accessed on 1 April 2022) by Law 257 in 2014 and are Key Biodiversity Areas (KBA, keybiodiversityareas.org/kba-data, accessed on 1 April 2022) (Figure 4).

In the forests of Horsh Ehden (Sector 2, Figure 4), we observe populations of *C. libani* and *A. cilicica*, as well as *J. excelsa*. Ehden is a biodiversity hotspot that was declared a nature reserve and KBA by law 121 in 1992 (Figure 4). Ehden is the southernmost limit of the range of *A. cilicica* and thus one of the two critical biogeographic sites for this species. This sector also includes the Qadisha Valley in Bcharré, a natural area protected by the Ministry of Environment, a UNESCO World Heritage Site, and a KBA (Figure 4).

Further north, the forests of Jairoune, Quemmamine, and Hrar (sector 3, Figure 4) are located in the most rugged mountains of Lebanon (up to 600 m) with genetically very diverse populations of fir, cedar, and juniper. Three populations of Cilician fir (1, 2, and 3) have very high CI, while 2 other populations of juniper (33) and fir (5 and 8) have high CI. This area, which is not a protected area and does not have a management plan, should be given a high conservation priority because it may provide suitable habitat for populations with potential adaptive capacity in the future.

The forests in the far north of Qobayat, Qammouaa, Mishmish, Akroum, Andqet, and Akkar Al Atiqa in sector 4 are the most species-rich in Lebanon [34]. They host about 70% of the plant species in Lebanon. These forests harbor both mixed tree species and pure cedar or fir stands. The mixed forests are mainly composed of *A. cilicica*, *C. libani*, and *J. excelsa*, but the dominant species is *A. cilicica*. Qammouaa is a protected area with cedar and fir forests. In this sector, there are 2 fir populations (populations 4 and 7) and 1 cedar population (25) that have a high CI. The overall low CI is due to the low ruggedness (less than 300 m) of this area with a more hilly landscape. This could be a barrier to providing suitable microclimates for in situ conservation.

The last sector is the southernmost Shouf cedar forest, which was declared a nature reserve by Law 532 in 1996 and is the largest reserve in Lebanon, covering about 5% of the country (Figure 4). Shouf hosts four cedar forests: Maaser el Shouf, Barouk, Ain Zhalta, and Dalhoun. The latter was declared a protected natural area by Decision 22/2002 of the Ministry of Environment. Maaser el Shouf is a protected forest by Decision 127/1991 of the Minister of Agriculture. Mount Barouk is recognized as a KBA (Figure 4) and ranks third in Lebanon with 20 endemic species. Shouf Cedar Nature Reserve is a biosphere reserve (Biosphere Reserves UNESCO-MAB). It hosts the largest strand of *C. libani* in the region. The predominant species is *C. libani*, but *J. excelsa* is also found on the southeastern slopes.

However, these juniper populations have not been genetically studied. The biosphere reserve hosts 25 threatened species, 48 species endemic to Lebanon, 14 rare species, and 214 eastern Mediterranean species. In this sector, 3 populations studied (17, 24, and 30) have a very high CI. These populations have a high genetic diversity and are located in a place that could potentially be a climatic microrefugium in the future, as the area is very rugged (up to 400 m). Moreover, under our scenario of a 2 °C warming and a 20% decrease in seasonal precipitation, the location of the studied populations could well remain within the species' current climatic niche (Figure 3).

When we overlay these five sectors with the simulated future potential range of *C. libani* under different climate scenarios ([10], Figure 5), we see that parts of sectors 1, 2, 3, and 4 correspond to the appropriate simulated future ranges. The model simulations were only run for Lebanon cedar, but the co-occurrence of this species with the other conifers and the overlap of their climatic niches (Figure 3) suggests that these areas may also be suitable for them.

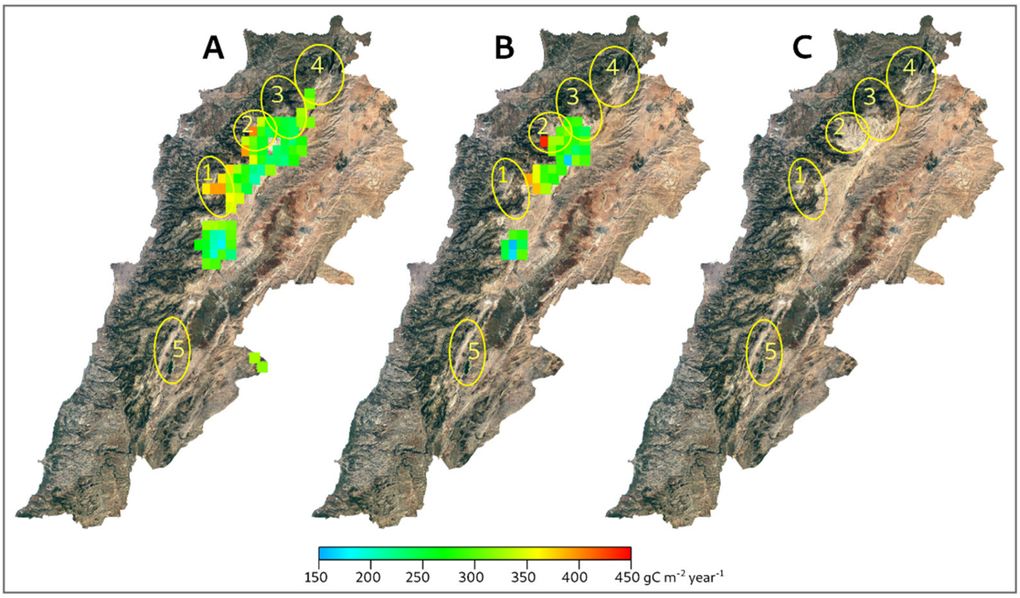

Figure 5. Five sectors (1 to 5) of priority populations for conservation with predicted potential occurrence of *Cedrus libani* (in terms of predicted net primary productivity in grams of carbon per meter square and per year (gC$m^{-2}$$year^{-1}$)) simulated under three different IPCC climate scenarios of atmospheric CO_2 concentration [10] (**A**) B1 with 500 ppmv, (**B**) A1B with 660 ppmv (**B**) and A2 with 750 ppmv (**C**).

In all five sectors, our conservation index suggests that there are populations of the three species that should be prioritized for protection, either because they are located in rugged mountainous regions that provide a favorable microclimate for their long-term survival or because their genetic diversity is higher than that of other populations, indicating a better potential adaptive capacity to anticipated climate change, or because the current climate in their geographic area may remain within their climatic niche.

These 5 sectors represent a network of endemic *Abies cilicica*, *Cedrus libani*, and *Juniperus excelsa* populations along the Mount Lebanon range, which extends across the entire country for about 170 km to the highest peak in the Middle East (>3000 m a.s.l.). The long-term persistence of endemic mountain needle species in Lebanon ([10,17] may well be related to the existence of a large number of microrefugia along the Mount Lebanon range, which provided suitable microhabitats and were maintained due to their proximity to the Mediterranean coast, which provides them with persistent and considerable rainfall (today up to 4000 mm/year) and snow with low winter temperatures. These mountain microrefugia are considered particularly important because they can provide a microclimate that is more suitable for local and long-term survival of plant species than the regional/global climate [13,19–21]. Hannah [19] suggested that effective conservation plans should incorporate a network of these microrefugia because they can facilitate seed dispersal and species migration, which should allow gene flow between populations and thus higher genetic diversity.

Today, this network of five sectors where populations of different species have a high conservation index needs to be protected, and special efforts should be made to protect the populations and areas with the highest conservation index. Our eco-evolutionary conservation index could be of great interest in prioritizing specific populations for long-term and cost-effective conservation action. However, this does not preclude the protection of other populations within the network of five identified sectors.

5. Conclusions

This study is a contribution to the current thinking on the conservation of biodiversity and, in particular, species threatened by global warming in the mountainous areas of Lebanon. We developed a conservation index to prioritize areas for conservation, which could be very useful when funds invested in conservation are limited. Ideally, if resources are unlimited, the conservation of all species could be addressed. However, even in the latter case of unlimited resources, conservation efforts may fail if the protected area is not suitable for the future climate or if the population or species to be protected cannot survive in the long term. There are other conservation approaches that rely on the use of predictive models to predict suitable areas for threatened species. However, these predictions are often based on statistical relationships rather than field data.

There are also initiatives, often at the government level, that call for the establishment of protected areas and reserves where human disturbance is controlled to a greater or lesser degree. In some cases, studies suggest that these areas, which are now very effective in addressing biodiversity loss, may prove unsuitable in the near future, either because the chosen area is no longer climatically suitable or because the local population(s) are no longer adapted.

With this study, we aim to provide managers with an additional tool to consider both the topography of mountain areas where threatened species currently occur and their genetic diversity in order to predict, as far as possible, their adaptive capacity in potential microrefugia to emerging climate change.

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References

1. Mikesell, M.W. The Deforestation of Mount Lebanon. *Geogr. Rev.* **1969**, *59*, 1–28. https://doi.org/10.2307/213080.
2. Khuri, S.; Shmoury, M.; Baalbaki, R.; Maunder, M.; Talhouk, S. Conservation of the Cedrus libani populations in Lebanon: History, current status and experimental application of somatic embryogenesis. *Biodivers. Conserv.* **2000**, *9*, 1261–1273. https://doi.org/10.1023/a:1008936104581.
3. Jomaa, I.; Auda, Y.; Khater, C. Contribution of the Charaterization of Forest Fragmentation on the Eastern Flank of Mount Lebanon Over 33 years. *Leban. Sci. J.* **2007**, *8*, 59–74.
4. Jomaa, I.; Auda, Y.; Saleh, B.A.; Hamzé, M.; Safi, S. Landscape spatial dynamics over 38 years under natural and anthropogenic pressures in Mount Lebanon. *Landsc. Urban Plan.* **2008**, *87*, 67–75. https://doi.org/10.1016/j.landurbplan.2008.04.007.
5. Haroutunian, G.; Chojnacky, D.C.; El Riachy, R.; Chojnacky, C.C. Reducing Reforestation Costs in Lebanon: Adaptive Field Trials. *Forests* **2017**, *8*, 169. https://doi.org/10.3390/f8050169.
6. Jomaa, I.; Khater, C. Mapping Glitches of Juniper Forests in Lebanon under Natural Conditions and Anthropogenic Activities. *Open Journal of Forestry*, **2019**, *9*, 168181. https://DOI: 10.4236/ojf.2019.92008

7. Gardner, M.; Knees, S. Abies Cilicica. The IUCN Red List of Threatened Species 2013: E.T42275A2968944. 2013. Available online: https://doi.org/10.2305/IUCN.UK.2013-1.RLTS.T42275A2968944.en. (accessed on 18 January 2022).
8. Evans, J.P. 21st century climate change in the Middle East. *Clim. Chang.* **2008**, *92*, 417–432. https://doi.org/10.1007/s10584-008-9438-5.
9. Gao, X.; Pal, J.S.; Giorgi, F. Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation. *Geophys. Res. Lett.* **2006**, *33(3)*, 14. https://doi.org/10.1029/2005gl024954.
10. Hajar, L.; François, L.; Khater, C.; Jomaa, I.; Déqué, M.; Cheddadi, R. *Cedrus libani* (A. Rich) distribution in Lebanon: Past, present and future. *Comptes Rendus. Biol.* **2010**, *333*, 622–630. https://doi.org/10.1016/j.crvi.2010.05.003.
11. MOA. *National Action Programme to Combat Desertification*; Ministry of Agriculture, Beyrout, Lebanon, 2003; 198p.
12. MOE/UNDP. Climate change vulnerability and adaptation: climate risks, vulnerability & adaptation assessment; 2011; 44p. Publisher: Ministry of Environment, Beyrouth, Lebanon.
13. Dobrowski, S.Z. A climatic basis for microrefugia: The influence of terrain on climate. *Glob. Chang. Biol.* **2011**, *17*, 1022–1035. https://doi.org/10.1111/j.1365-2486.2010.02263.x.
14. Valencia, B.G.; Matthews-Bird, F.; Urrego, D.H.; Williams, J.; Gosling, W.D.; Bush, M. Andean microrefugia: Testing the Holocene to predict the Anthropocene. *New Phytol.* **2016**, *212*, 510–522. https://doi.org/10.1111/nph.14042.
15. Keppel, G.; Van Niel, K.P.; Wardell-Johnson, G.W.; Yates, C.J.; Byrne, M.; Mucina, L.; Schut, A.G.T.; Hopper, S.D.; Franklin, S.E. Refugia: Identifying and understanding safe havens for biodiversity under climate change. *Glob. Ecol. Biogeogr.* **2012**, *21*, 393–404. https://doi.org/10.1111/j.1466-8238.2011.00686.x.
16. Bennett, K.D.; Provan, J. What do we mean by 'refugia'? *Quat. Sci. Rev.* **2008**, *27*, 2449–2455.
17. Hajar, L.; Khater, C.; Cheddadi, R. Vegetation changes during the late Pleistocene and Holocene in Lebanon: A pollen record from the Bekaa Valley. *Holocene* **2008**, *18*, 1089–1099. https://doi.org/10.1177/0959683608095580.
18. Pearson, R.G. Climate change and the migration capacity of species. *Trends Ecol. Evol.* **2006**, *21*, 111–113. https://doi.org/10.1016/j.tree.2005.11.022.
19. Hannah, L.; Flint, L.; Syphard, A.; Moritz, M.A.; Buckley, L.B.; McCullough, I.M. Fine-grain modeling of species’ response to climate change: Holdouts, stepping-stones, and microrefugia. *Trends Ecol. Evol.* **2014**, *29*, 390–397. https://doi.org/10.1016/j.tree.2014.04.006.
20. Keppel, G.; Mokany, K.; Wardell-Johnson, G.W.; Phillips, B.; Welbergen, J.; Reside, A. The capacity of refugia for conservation planning under climate change. *Front. Ecol. Environ.* **2015**, *13*, 106–112. https://doi.org/10.1890/140055.
21. Rull, V. Microrefugia. *J. Biogeogr.* **2009**, *36*, 481–484. https://doi.org/10.1111/j.1365-2699.2008.02023.x.
22. Barrows, C.W.; Ramirez, A.R.; Sweet, L.C.; Morelli, T.L.; Millar, C.I.; Frakes, N.; Rodgers, J.; Mahalovich, M.F. Validating climate-change refugia: Empirical bottom-up approaches to support management actions. *Front. Ecol. Environ.* **2020**, *18*, 298–306. https://doi.org/10.1002/fee.2205.
23. Dubois, J.; Cheptou, P.-O. Effects of fragmentation on plant adaptation to urban environments. *Philos. Trans. R. Soc. B Biol. Sci.* **2017**, *372*, 20160038. https://doi.org/10.1098/rstb.2016.0038.
24. Leimu, R.; Fischer, M. A Meta-Analysis of Local Adaptation in Plants. *PLoS ONE* **2008**, *3*, e4010. https://doi.org/10.1371/journal.pone.0004010.
25. Young, A.; Boyle, T.; Brown, T. The population genetic consequences of habitat fragmentation for plants. *Trends Ecol. Evol.* **1996**, *11*, 413–418. https://doi.org/10.1002/cphc.201000986.
26. Petit, R.J.; Hampe, A. Some Evolutionary Consequences of Being a Tree. *Annu. Rev. Ecol. Evol. Syst.* **2006**, *37*, 187–214. https://doi.org/10.1146/annurev.ecolsys.37.091305.110215.
27. Davis, M.B.; Shaw, R.G. Range Shifts and Adaptive Responses to Quaternary Climate Change. *Science* **2001**, *292*, 673–679. https://doi.org/10.1126/science.292.5517.673.
28. Christmas, M.J.; Breed, M.F.; Lowe, A.J. Constraints to and conservation implications for climate change adaptation in plants. *Conserv. Genet.* **2016**, *17*, 305–320. https://doi.org/10.1007/s10592-015-0782-5.
29. Watson, J.; Dudley, N.; Segan, D.B.; Hockings, M. The performance and potential of protected areas. *Nature* **2014**, *515*, 67–73. https://doi.org/10.1038/nature13947.
30. Albrich, K.; Rammer, W.; Seidl, R. Climate change causes critical transitions and irreversible alterations of mountain forests. *Glob. Chang. Biol.* **2020**, *26*, 4013–4027. https://doi.org/10.1111/gcb.15118.
31. Morelli, T.L.; Barrows, C.W.; Ramirez, A.R.; Cartwright, J.M.; Ackerly, D.D.; Eaves, T.D.; Ebersole, J.L.; Krawchuk, M.A.; Letcher, B.H.; Mahalovich, M.F.; et al. Climate-change refugia: Biodiversity in the slow lane. *Front. Ecol. Environ.* **2020**, *18*, 228–234. https://doi.org/10.1002/fee.2189.
32. Michalak, J.L.; Stralberg, D.; Cartwright, J.M.; Lawler, J.J. Combining physical and species-based approaches improves refugia identification. *Front. Ecol. Environ.* **2020**, *18*, 254–260. https://doi.org/10.1002/fee.2207.
33. Carroll, C.; Roberts, D.R.; Michalak, J.; Lawler, J.J.; Nielsen, S.E.; Stralberg, D.; Hamann, A.; McRae, B.H.; Wang, T. Scale-dependent complementarity of climatic velocity and environmental diversity for identifying priority areas for conservation under climate change. *Glob. Chang. Biol.* **2017**, *23*, 4508–4520. https://doi.org/10.1111/gcb.13679.
34. Dagher-Kharrat, M.B.; El Zein, H.; Rouhan, G. Setting conservation priorities for Lebanese flora—Identification of important plant areas. *J. Nat. Conserv.* **2018**, *43*, 85–94. https://doi.org/10.1016/j.jnc.2017.11.004.
35. Hannah, L.; Midgley, G.; Andelman, S.; Araújo, M.B.; Hughes, G.; Martinez-Meyer, E.; Pearson, R.; Williams, P. Protected area needs in a changing climate. *Front. Ecol. Environ.* **2007**, *5*, 131–138. https://doi.org/10.1890/1540-9295(2007)5[131:paniac]2.0.co;2.

36. Lawler, J.J.; Rinnan, D.S.; Michalak, J.L.; Withey, J.C.; Randels, C.R.; Possingham, H.P. Planning for climate change through additions to a national protected area network: Implications for cost and configuration. *Philos. Trans. R. Soc. B Biol. Sci.* **2020**, *375*, 20190117. https://doi.org/10.1098/rstb.2019.0117.
37. Wolf, H. TEMPERATE ECOSYSTEMS | Spruces, Firs and Larches. *Encycl. For. Sci.* **2004**, 1449–1458. https://doi.org/10.1016/B0-12-145160-7/00187-3.
38. Farjon, A. Pinaceae. Drawings and Descriptions of the Genera. In *Koeltz Scientific Books*; 1990; ISBN 3-87429-298-3.
39. Miller, R.O. *Ecology and Managemnet of white Cedar. In Proceedings of the Workshop on Northern White Cedar in Michigan;* Department of Forestry, Michigan State University: Escanaba, MI, USA, 1990, 114. Available online: https://www.canr.msu.edu/uploads/files/Research_Center/FBIC/Northern_White_Cedar/Ecology_and_Mgmt_of_Northern_White_Cedar.pdf. (accessed on 5 December 1990).
40. Wright, J. Pollen dispersion of some forest trees. In *Station Paper 46*; United States Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: Upper Darby, PA, USA, 1952; p. 42.
41. Poska, A.; Pidek, I.A. Pollen dispersal and deposition characteristics of Abies alba, Fagus sylvatica and Pinus sylvestris, Roztocze region (SE Poland). *Veg. Hist. Archaeobotany* **2010**, *19*, 91–101. https://doi.org/10.1007/s00334-009-0230-x.
42. Awad, L.; Fady, B.; Khater, C.; Roig, A.; Cheddadi, R. Genetic Structure and Diversity of the Endangered Fir Tree of Lebanon (Abies cilicica Carr.): Implications for Conservation. *PLoS ONE* **2014**, *9*, e90086. https://doi.org/10.1371/journal.pone.0090086.
43. Dagher-Kharrat, M.B.; Mariette, S.; Lefèvre, F.; Fady, B.; March, G.G.-D.; Plomion, C.; Savouré, A. Geographical diversity and genetic relationships among Cedrus species estimated by AFLP. *Tree Genet. Genomes* **2006**, *3*, 275–285. https://doi.org/10.1007/s11295-006-0065-x.
44. Douaihy, B.; Restoux, G.; Machon, N.; Bou Dagher-kharrat, M. Ecological characterization of the Juniperus ex-celsa stands in Lebanon. *Ecol. Mediterr.* **2013**, *39*, 169–180.
45. Fady, B.; Lefèvre, F.; Vendramin, G.G.; Ambert, A.; Régnier, C.; Bariteau, M. Genetic consequences of past climate and human impact on eastern Mediterranean Cedrus libani forests. Implications for their conservation. *Conserv. Genet.* **2008**, *9*, 85–95. https://doi.org/10.1007/s10592-007-9310-6.
46. Semaan, M.T.; Dodd, R.S. Genetic variability and structure of the remnant natural populations of *Cedrus libani* (Pinaceae) of Lebanon. *Tree Genet. Genomes* **2008**, *4*, 757–766. https://doi.org/10.1007/s11295-008-0148-y.
47. El Hasnaoui, Y.; Mhammdi, N.; Bajolle, L.; Nourelbait, M.; Bouimetarhan, I.; Cheddadi, R. Locating North African microrefugia for mountain tree species from landscape ruggedness and fossil records. *J. Afr. Earth Sci.* **2020**, *172*, 103996. https://doi.org/10.1016/j.jafrearsci.2020.103996.
48. Kübler, D.; Hildebrandt, P.; Günter, S.; Stimm, B.; Weber, M.; Mosandl, R.; Muñoz, J.; Cabrera, O.; Zeilinger, J.; Silva, B. Assessing the importance of topographic variables for the spatial distribution of tree species in a tropical mountain forest. *Erdkunde* **2015**, *70*, 19–47. https://doi.org/10.3112/erdkunde.2016.01.03.
49. Lembrechts, J.J.; Hoogen, J.; Aalto, J.; Ashcroft, M.B.; De Frenne, P.; Kemppinen, J.; Kopecký, M.; Luoto, M.; Maclean, I.M.D.; Crowther, T.W.; et al. Global maps of soil temperature. *Glob. Chang. Biol.* **2021**, *28*, 3110–3144. https://doi.org/10.1111/gcb.16060.
50. Zhang, Y.; Schaap, M. G.; Zha, Y. A high-resolution global map of soil hydraulic properties produced by a hierarchical parameteri-zation of a physically based water retention model. *Water Resour. Res.* **2018**, *54*, 9774–9790.
51. USGS EROS Archive-Digital Elevation-Global 30 Arc-Second Elevation (GTOPO30). Available online: https://doi.org/10.5066/F7DF6PQS. (accessed on 11 July 2018).
52. Riley, S. A terrain ruggedness Index that quantifies topographic heterogeneity. *Intermt. J. Sci.* **1999**, *5*, 23–27.
53. QGIS Development Team. QGIS Geographic Information System. Open Source Geospatial Foundation Project. 2018. Available online: http://qgis.osgeo.org (accessed on 11 March 2022).
54. Karger, D.N.; Conrad, O.; Böhner, J.; Kawohl, T.; Kreft, H.; Soria-Auza, R.W.; Zimmermann, N.E.; Linder, H.P.; Kessler, M. Climatologies at high resolution for the earth's land surface areas. *Sci. Data* **2017**, *4*, 170122. https://doi.org/10.1038/sdata.2017.122.
55. Akhtar, N.; Brauch, J.; Ahrens, B. Climate modeling over the Mediterranean Sea: Impact of resolution and ocean coupling. *Clim. Dyn.* **2018**, *51*, 933–948. https://doi.org/10.1007/s00382-017-3570-8.
56. Cheddadi, R.; Khater, C. Climate change since the last glacial period in Lebanon and the persistence of Mediterranean species. *Quat. Sci. Rev.* **2016**, *150*, 146–157. https://doi.org/10.1016/j.quascirev.2016.08.010.
57. Cheddadi, R.; Taberlet, P.; Boyer, F.; Coissac, E.; Rhoujjati, A.; Urbach, D.; Remy, C.; Khater, C.; Antry, S.; Aoujdad, J.; et al. Priority conservation areas for *Cedrus atlantica* in the Atlas Mountains, Morocco. *Conserv. Sci. Pract*. **2022**, *E12680*, 1–15. https://doi.org/10.1111/csp2.12680.
58. Douaihy, B.; Vendramin, G.G.; Boratyński, A.; Machon, N.; Dagher-Kharrat, M.B. High genetic diversity with moderate differentiation in Juniperus excelsa from Lebanon and the eastern Mediterranean region. *AoB PLANTS* **2011**, *2011*, plr003. https://doi.org/10.1093/aobpla/plr003.
59. Douaihy, B.; Sobierajska, K.; Jasińska, A.K.; Boratyńska, K.; Ok, T.; Romo, A.; Machon, N.; Didukh, Y.; Dagher-Kharrat, M.B.; Boratyński, A. Morphological versus molecular markers to describe variability in *Juniperus excelsa* subsp. *excelsa* (Cupressaceae). *AoB PLANTS* **2012**, *2012*, pls013. https://doi.org/10.1093/aobpla/pls013.
60. Loarie, S.R.; Duffy, P.B.; Hamilton, H.; Asner, G.P.; Field, C.B.; Ackerly, D.D. The velocity of climate change. *Nature* **2009**, *462*, 1052–1055. https://doi.org/10.1038/nature08649.

61. Sattout, E.J.; Nemer, N. Managing climate change effects on relic forest ecosystems: A program for Lebanese Cedar. *Biodiversity* **2008**, *9*, 122–130. https://doi.org/10.1080/14888386.2008.9712917.
62. Klausmeyer, K.R.; Shaw, M.R. Climate Change, Habitat Loss, Protected Areas and the Climate Adaptation Potential of Species in Mediterranean Ecosystems Worldwide. *PLoS ONE* **2009**, *4*, e6392. https://doi.org/10.1371/journal.pone.0006392.