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Review

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Review

Carpathian Forests: Past and Recent Developments

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Abstract: Forests of the Carpathians are of increasing research interest, as they cover a large area (>9 Mha) within European forests and are influenced by diverse environmental conditions and contrasting historical developments. We reviewed 251 papers dealing with Carpathian forests, their history, and future perspectives. Over 70% of articles and reviews appeared in the last ten years, and 80% refer to the Western and Eastern Carpathians, while the Serbian Carpathians remain a gap in this research field. Forest expansion and species changes have occurred since Holocene deglaciation, influenced by timber use, settlements, cropland development, and, since the Bronze Age, pasture activities. At higher elevations, early conifer successors have been increasingly replaced by Norway spruce (*Picea abies*), silver fir (*Abies alba*), European beech (*Fagus sylvatica*), and hornbeam (*Carpinus betulus*), while oaks have been present in the Carpathian foothills throughout the whole of history. In the 19th and 20th centuries, Norway spruce afforestation was favored, and timber use peaked. Recent transitions from agriculture to forest land use have led to a further increase in forest cover (+1 to +14% in different countries), though past forest management practices and recent environmental changes have impaired forest vitality in many regions; climate warming already causes shifts in treelines and species distributions, and it triggers pest outbreaks and diseases and affects tree–water relations. The risk of forest damage is the highest in monodominant Norway spruce forests, which often experience dieback after cascade disturbances. European beech forests are more resilient unless affected by summer droughts. In the future, increasing dominance of broadleaves within Carpathian forests and forest management based on a mix of intensive management and ecological silviculture are expected. Maintenance and promotion of silver fir and mixed European beech forests should be encouraged with respect to forest stability, biodiversity, and economic sustainability. As supported by the Carpathian Convention and related institutions and initiatives, connectivity, management, and stakeholder cooperation across administrative borders will be crucial for the future adaptive potential of Carpathian forests.

Keywords: mountain forests; climate change effects; sustainable forest management; mixed forests; tree species; literature review

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1. Introduction

Forests are vital for human well-being, as they provide basic livelihood (e.g., food, timber, energy), recreational resources, and relevant cultural values [1–3]. They are also important in global carbon, water, and nutrient cycles, and they are biodiversity hotspots [4–6]. The prediction of the future development of these provisioning ecosystem services is often difficult given regional contrasts and uncertainties [7,8]. Additionally, forests fulfil ecosystem regulation services, among which are stabilizing soils and reducing natural hazards, and they provide many cultural services [9]. These ecosystem services are also expected to undergo changes in the future. They are especially important for forests in the mountains [10–12], such as the Carpathians, where natural hazards are key risks to people and infrastructure and increase under climate change conditions [13].

The Carpathians are the second largest mountain range in Europe and provide multiple ecosystem services of enormous regional importance [4]. The Carpathians belong to seven Central and Eastern European countries (Czech Republic, Slovakia, Poland, Hungary, Ukraine, Romania, and Serbia), whose share of forest land is among the lowest in Europe (27%). With a total area of 9.92 million hectares, Carpathian forests constitute over 70% of the total forested land in Slovakia and Romania, with Romania alone harboring more than 45% of all Carpathian forests [14]. Most of the Carpathian forests are dominated by European beech (*Fagus sylvatica*), Norway spruce (*Picea abies*), oak (*Quercus robur*, *Quercus petraea*), and silver fir (*Abies alba*) stands, covering over 70% of the altitudinal range (with the highest point being Gerlachovský štít, 2655 m a.s.l., in the Slovakian Tatra Mountains). The Tatra Mountains, along with the mid-altitude mountains Fatra Mountains, Slovenské Rudohorie, and Beskids, form the largest massifs in the Western Carpathians. The Beskids extend into the Eastern Carpathians, where the Chornohora, Călimani, and Rodna Mountains dominate, with the highest point being Pietrosul (2303 m a.s.l.). The biggest areas above the treeline, however, are in the second highest group of the Southern Carpathians, including Bucegi, Parâng, Retezat, and Făgăraș, with the highest peak being Moldoveanu (2544 m a.s.l.) Many areas within the forested Carpathians are strongholds of ecologically valuable forests within Europe; they show high diversity of species and habitat types, and well-structured forest sites, and the largest areas of old-growth forests in the temperate zone are found in the Carpathians [15–18].

The economic importance of Carpathian forests has developed since the Bronze Age and has recently manifested itself in an increase in the growing stock and timber production in the Carpathian countries [9]. At the same time, economic activities in the Carpathians have also caused substantial changes in this ecosystem in the last 500 years [19–21]; anthropogenic activities, such as agricultural expansion, mining, wood, and the related chemical industry, have led to deforestation, forest fragmentation, and degradation in some areas [22,23]. The current species composition (with European beech dominating in more than 53% of Carpathian forests; Norway spruce, in ca. 30%; silver fir, in only 2.4%; and oaks, in 15%; see Figure 1) is a result of these processes. In recent decades, new and contrasting developments have been observed, with the abandonment of mountain areas leading to the expansion of forests, intensification of logging activities [22–24] (Table 1), but also increasing efforts to protect forest areas [15,25].

Table 1. Forest management in the Carpathian countries. Area data from 2007 are from [14]; wood production data from 2020 are from [9,26] and apply to the countries' forests in general. No data regarding forest areas and growing stock for wood production are available for Serbia.

	Czech Republic	**Hungary**	**Poland**	**Romania**	**Serbia**	**Slovakia**	**Ukraine**
Portion of Carpathian forests in 2007 (% of total Carpathian forest area)	3.1	4.0	7.7	46.4	0.4	20.2	18.1
Proportion of Carpathian forests to national forests in 2007 (% of Carpathian forest out of total national forest area)	11.7	20.1	8.4	71.6	1.9	100.0	16.7
Wood production in 2020							
Forest area (10^3 ha)	2304	1871	8331	5586	-	1796	5016
Forest area, mean annual change (%, since 2010)	−0.0	−0.3	0.2	0.8	-	0.1	−0.2

Table 1. *Cont.*

	Czech Republic	Hungary	Poland	Romania	Serbia	Slovakia	Ukraine
Growing stock (10^6 m^3)	791	397	2730	2355	-	538	2280
Roundwood (10^6 m^3)	33.4	5.8	40.6	18.1	8.2	7.5	16.8
Roundwood, mean annual change (%, since 2010)	9.9	−1.3	1.4	3.8	0.1	−2.2	0.3

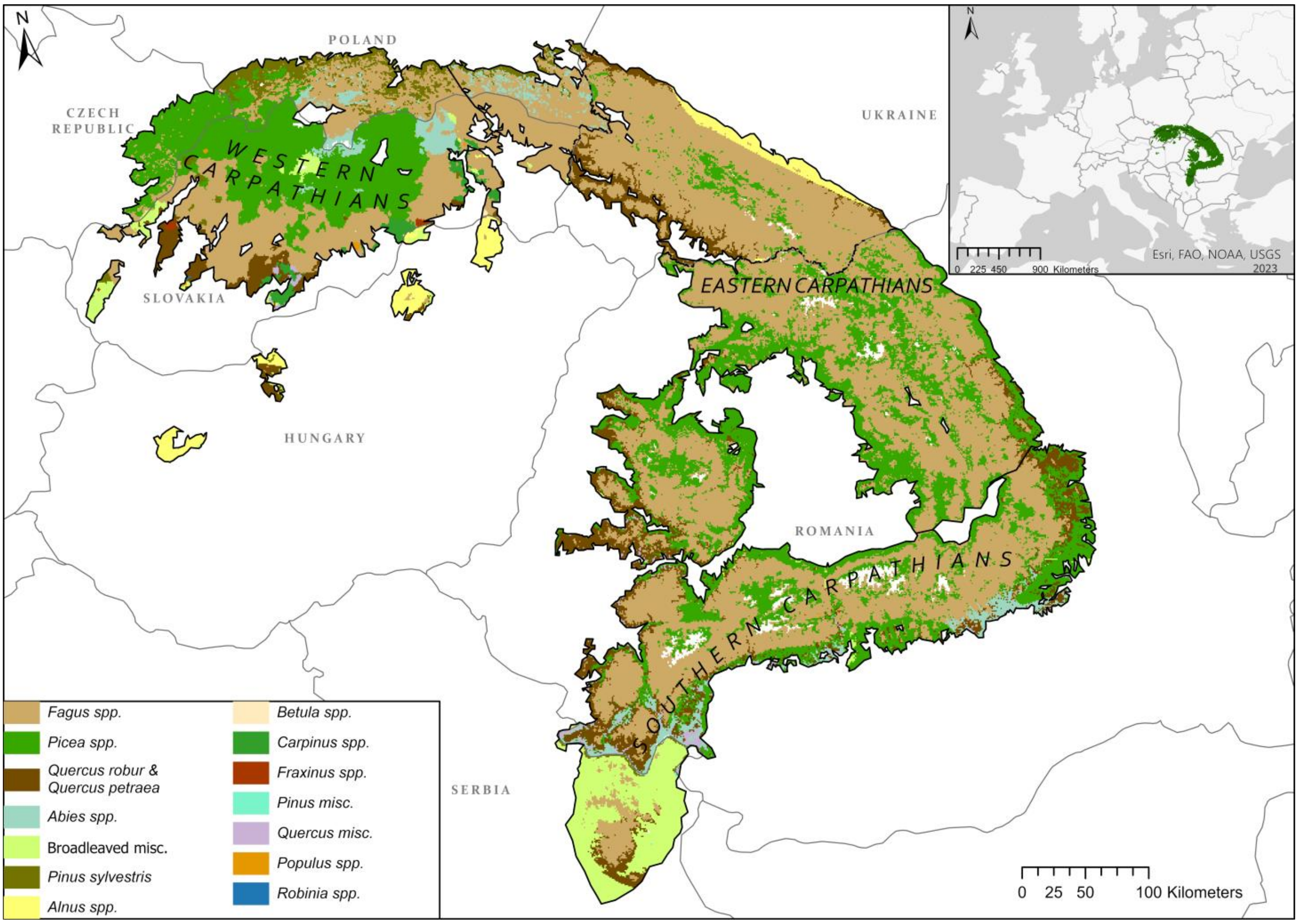


Figure 1. Dominant tree species (adapted from [27]) in Carpathian forests; delimitation of the Carpathians according to [25,28].

Carpathian forests are also increasingly influenced by climate change effects. Global warming is known to cause more frequent and more intense drought and heat events [29,30], while it may also prolong the vegetation period and contribute to an upward shift of tree-lines [31]. Higher temperatures are expected to increase the risks of pest outbreaks and wildfires, and temporal and spatial changes in precipitation patterns may affect the hydrology of forest areas [25]. These complex and interrelated changes will affect forests [32–35] and require adaptations in forest management [36,37].

There are numerous studies on various aspects of Carpathian forests, though they usually focus on specific regions or countries, while an overview of the general situation in the Carpathians is often missing. Based on a broad literature search, this review seeks to offer comprehensive overview and discussion of the past, current, and (potential) future developments of Carpathian forests with respect to their crucial ecological and socio-economic relevance. In the following chapters, we analyze (i) the evolution of forest cover and composition during the Holocene, (ii) developments in recent decades with a special focus on (iii) climate change responses and risks (treeline, vegetation period, and species resilience and health). Finally, we discuss (iv) recent and future management strategies.

2. Methods

The basis for the literature used in this study was the use of queries in the Web of Science (WoS) (Clarivate, London, UK) and Scopus (Elsevier, Amsterdam, The Netherlands) APIs with the search string "(Carpath* AND (Forest* OR Afforestation))", which should cover all relevant topics related to forests in the Carpathians (Table 2). We searched in titles, abstracts, and keywords and restricted the search to articles and reviews in English peer-reviewed journals. Given that the Scopus database is the larger one [38] and yielded more hits for our specific search (2112 for January 1900 to March 2023), we used these results. Then, we calculated the most frequent terms in the titles and abstracts. The results were used to formulate three thematic clusters: "Land cover or/and land use change", "Climate change", and "Forest management".

Table 2. Literature search procedure. The column Eligibility Criteria indicates filters applied for the search in each stage. The column Number of Articles indicates the total number of documents after the application of previous filters.

Steps	Description	Eligibility Criteria	Number of Articles
1	Scopus and WoS database search	Search terms: (Carpath* AND (Forest* OR Afforestation)) Language: English; dates: January 1900 to March 2023 Sources type: articles, review Search within title, abstract, keywords	1233 (WoS) 2112 (Scopus)
2	Database selection	Broader coverage	2112 (Scopus)
3	Detection of clusters	Most frequently used terms relevant for forests in titles and abstracts (number of articles including respective terms)	266 "Vegetation" 234 "Landscape" 229 "Climate" 225 "Management"
3	Abstract screening for thematic relevance	Thematic clusters: "Land cover or/and land use change", "Climate change", "Forest management"	689
4	Content examination for evidence of change	At least one massif of the Carpathians	276
5	Exclusion of redundant content	Removal of specific case studies or similar studies providing the same evidence by the same authors	251

Attempts were made to automatically sort out the articles according to thematic clusters; however, due to the interrelated nature of these topics, a clear division could not be achieved effectively. Consequently, all abstracts were thoroughly reviewed by the authors to identify information relevant to at least one of the thematic clusters.

In the subsequent phase, the whole content of the selected articles was scrutinized for evidence of changes occurring in at least one Carpathian massif. This stringent criterion ensured a focus on substantial and meaningful transformations in the region and resulted in the selection of 276 articles.

To enhance the coherence of the review, any redundant or overlapping content from very specific case studies or similar studies by the same authors were excluded during the manuscript generation process. Consequently, a total of 251 articles were utilized and cited in the review (Supplementary Materials, List S1). In the following bibliographical analysis, we calculated statistics for the selected 251 documents and geolocation of study areas in the documents. Additionally, we used VOS-viewer (version 1.6.9; Leiden University, Leiden, The Netherlands) to create network maps based on the weight of journals (number of articles) and links (bibliographic coupling) among each other (for the identification procedure, see [39]).

3. Results of the Bibliographical Analysis

The research interest in Carpathian forests has significantly grown in the last two decades, as the number of articles selected in our literature search raised from a few to about 30 per year (Figure 2). In total, 90% of the selected articles were published after 2008, and in the last ten years, 195 research papers (78%) were published. This increase was observed in all thematic clusters (see Supplementary Figure S1), with a remarkably high number of papers on forest management from 2017 onwards. Interestingly, the number of papers related to forest and climate change, although increasing, was relatively low (since 2003, less than 10 papers per year on average).

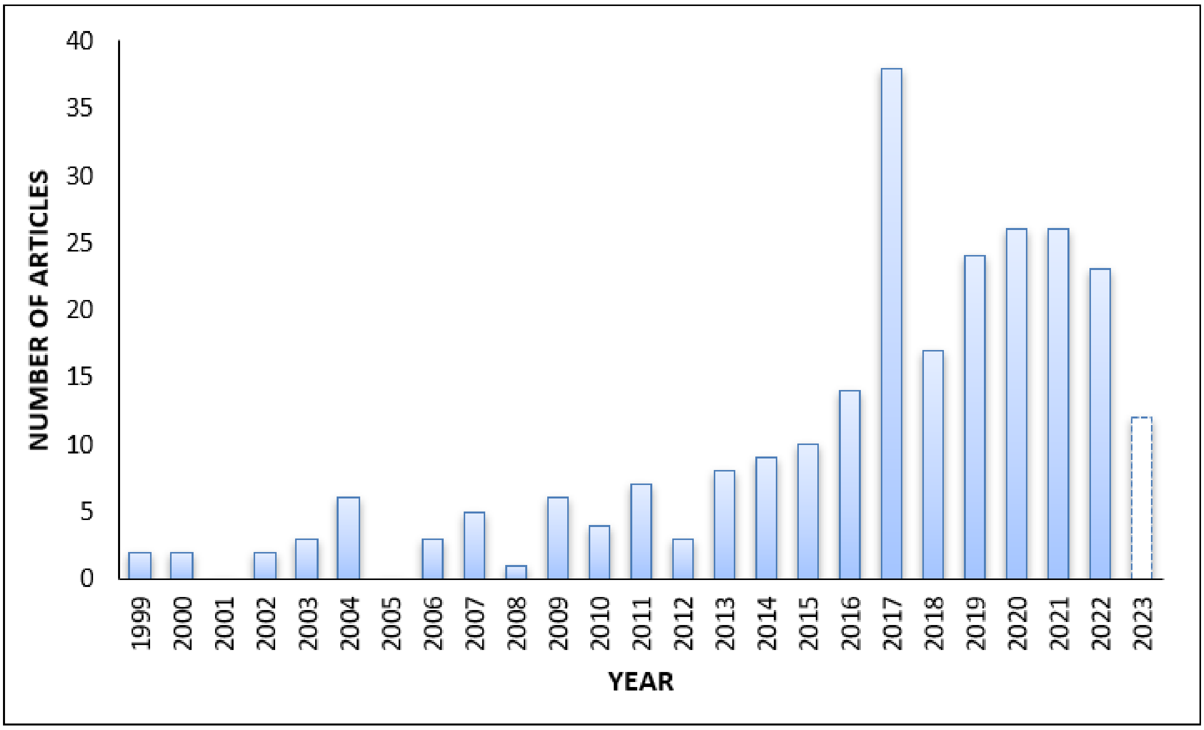
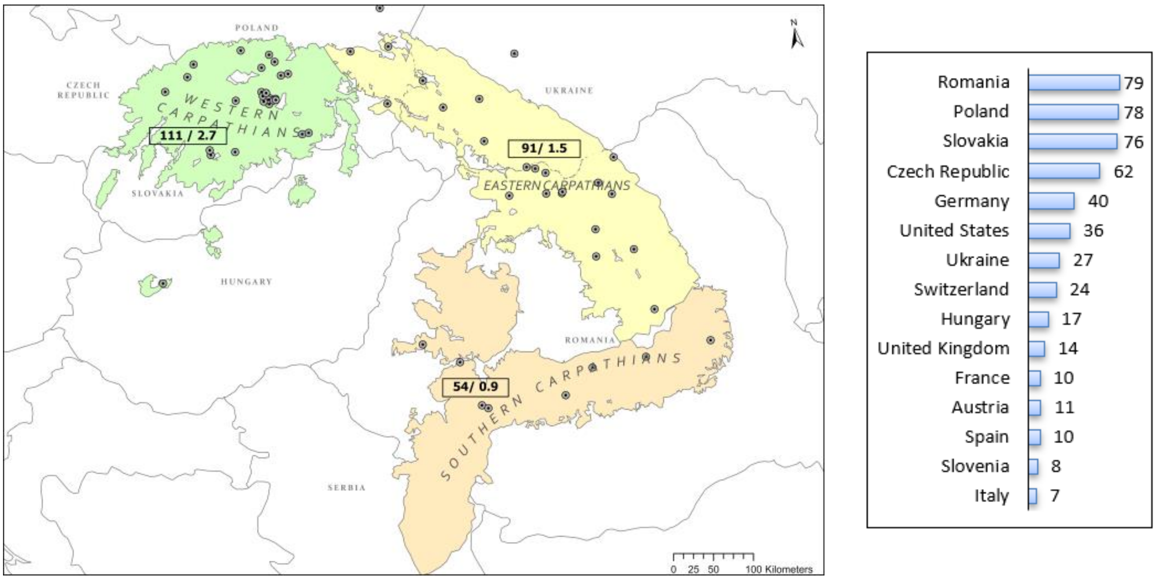


Figure 2. Number of scientific articles from 1999 to 2023 (for research query and selection criteria, see Section 2). The graph starts with 1999, as it is the year of publication of the oldest document selected for the review. The column for 2023 is hatched, as only the data for the first three months of the year were used.

As for scientific journals, most of the papers were published in journals on environmental sciences (169 studies; Supplementary Figure S2). Accordingly, the most frequent terms in titles and abstracts were region, tree, disturbance, temperature, growth, stand, response, structure, altitude, expansion. With respect to forest species, Norway spruce, European beech, and silver fir deserved the biggest attention, with the latter two being often addressed together (Supplementary Figure S3).

The studies covered different parts of the Carpathians, with the highest number of articles (43%) being related to the Western Carpathians (Poland, Slovakia, Hungary, and Czech Republic) (Figure 3a). In total, 36% of articles were on the Eastern Carpathians (Romania and Ukraine), with the majority being on Romania. A total of 20% of the studies were conducted in the Southern Carpathians, all of them in Romania, with no studies being found for the Serbian Carpathians. Case studies often dealt with the Tatra Mountains (Poland, Slovakia) in the Western Carpathians, while the Eastern and Southern Carpathians were represented by a variety of mountain ranges from north to south (Gorgany, Maramures, Rodna, Calimani, Curvature Mountains, Făgăraș, Retezat, and Apuseni Mountains). As for the countries represented by the authors, Romania had the highest research output on Carpathian forests, followed by Poland and Slovakia (Figure 3b). The available literature from different fields and sites enabled the multifaceted insight into past and future developments of Carpathian forests dealt with in the following chapters.



(**a**) (**b**)

Figure 3. Number of scientific articles dealing with Carpathian forest regions: (**a**) absolute number/number per region's area (1000 km^2) and case studies (gray points) dedicated to different Carpathian subregions (green—Western; blue—Eastern; yellow—Southern; numbers are given in black frames); (**b**) number of articles per country of publication (shown are the 15 countries with the highest publication output). In case of several subregions or publishing countries mentioned in the article, the count in both figures is made for each subregion or country.

4. Past Developments of Carpathian Forests

4.1. From the Holocene to the Anthropocene

In the Holocene, deglaciation was followed by substantial forest expansion in the Carpathians. Increasing temperatures (up to +10 °C at higher elevations) led to an upward shift of the treeline, with the glacial refugees Scots pine (*Pinus sylvestris*) and larch (*Larix decidua*) reaching more than 2000 m (present limit: 1200 to 1900 m [40,41]) in the Early Holocene (11,500–8000 years ago [42–45]). In the foothills, the warming enabled the spread of mixed oak stands [46]. In the Preboreal and the especially warm and humid Atlantic climatic phase, early coniferous and broadleaf successors were continuously replaced by Norway spruce (exceeding 60% in proportion), silver fir, European beech, and hornbeam (*Carpinus betulus*) [42,47,48] (Figure 4). Due to their higher shade tolerance, especially silver fir and beech were competitive compared with early conifer successors [49]. The competition in dense mixed stands also favored beech over Norway spruce, resulting in beech-dominated forests up to 1000 m. This transition started earlier (around 5200 years ago) in the Western and Eastern Carpathians and later (around 4000 years ago) in the Southern Carpathians [43,50,51].

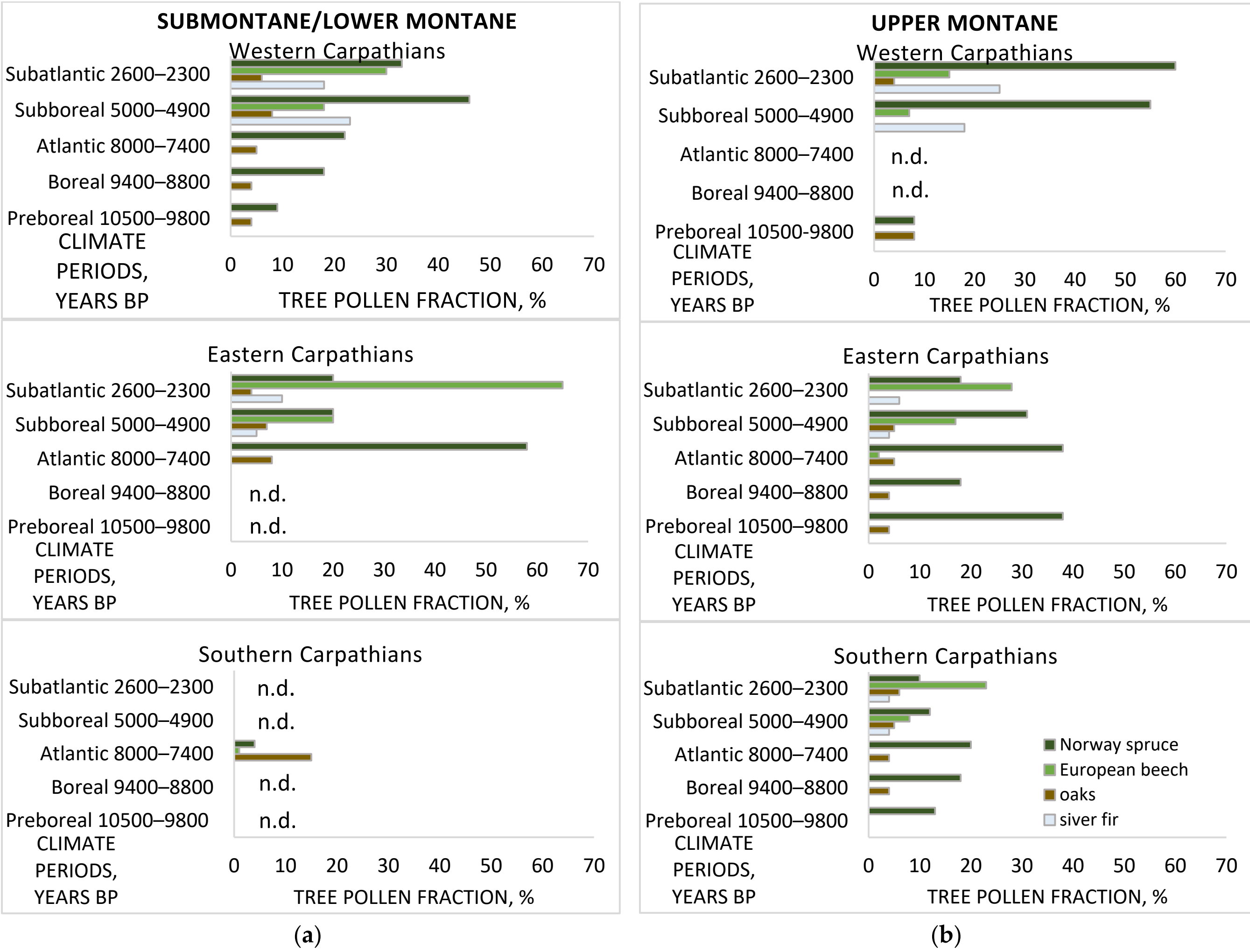
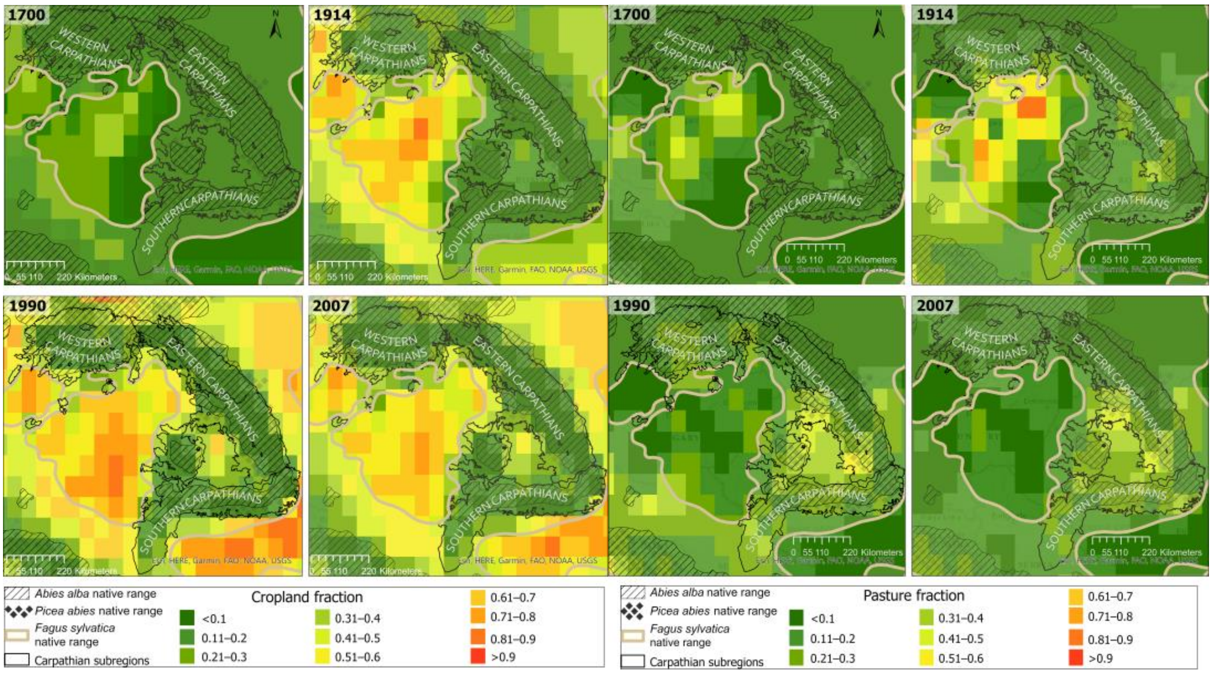


Figure 4. Holocene evolution of tree species which are dominant in present-day Carpathian forests: (**a**) submontane and lower montane zones; (**b**) upper montane zones. The pollen fraction is the averaged fraction of tree pollen (%) calculated from pollen analyses of 30 studies in total [19–21,43,44,48–72] (Supplementary List S2). The pollen fraction of forest tree species for the Subatlantic period is based on the time before the 16th century. For some periods, no data (n.d.) are available. The location of the case studies is given in Supplementary Figure S4.

In the Late Bronze and Early Iron Ages, human activity became the main factor for the further development of Carpathian forests. The use of timber led to the lowering of the treeline (amplified by declining summer temperatures [41]), and at lower elevations, oak was intensively logged due to settlement and agricultural expansion, though forest openings contributed to its regeneration [43]. European beech and silver fir populations expanded, whereas silver fir especially benefited from fire activities due to colonialization of burned areas [20,55]. Anthropogenic influence (e.g., fire, logging, grazing) continued to be the dominating factor of development in the Late Iron Age and the Roman Age. In the late Middle Ages, mining and the Walachian colonization led to a dramatic transformation of Carpathian forests by humans: it resulted in a massive decrease in forest areas in the 14th–15th centuries in the Western Carpathians [21,73,74] and the Eastern Carpathians [20,66,75,76] and in the 16th and 17th centuries in the Southern Carpathians [77]. Intensive use of wood for construction led to a decrease in the proportion of both deciduous (European beech, required, e.g., for potash production [78,79]) and coniferous (silver fir and Norway spruce) trees [20], while oak forests expanded [66]. However, silver fir stands also regenerated in many Carpathian forests, probably due to favorable conditions for this species' growth after grazing activities, the predominant logging of European beech in the times of intense colonization, and litter raking [63,80–82].

Intense forest exploitation continued into the times of the Austro-Hungarian Monarchy (from the late 18th to the beginning of the 20th century), when the biggest decrease in Carpathian forests cover was reported [83–87]. The Western Carpathians were at the forefront of changes caused by cropland expansion into the mountain areas of native ranges for European beech and Norway spruce (Figure 5). For the sake of increasing timber yields, Norway spruce was favored, as it allowed for shorter rotation periods and provided wood of good quality and manifold usability. This resulted in monodominant forests in many regions. Consequently, these forests were very vulnerable to severe disturbances (windstorms, bark beetle outbreaks), aggravated by extreme cold periods in the Late Little Ice Period [67,88], with the most pronounced effects in the 19th century [89] and peaks in the periods from 1830 to 1850 and from 1860 to 1880 in the Western and Eastern Carpathians [90–93] and from 1880 to 1910 in the Southern Carpathians [94]. As a result, the lowest point in forest cover occurred in the 1920s [95].



(**a**) (**b**)

Figure 5. Cropland (**a**) and pasture (**b**) dynamics (created using the data from [96]) and native ranges of dominant forest tree species (data from [97]) in the Carpathians between 1700 and 2007.

In the 20th century, climatic conditions stabilized, and the Carpathian forest area increased between the two World Wars [98,99]. The latter went together with chaotic reforestation following land abandonment because of diverse land use decisions due to ownership changes, and asynchronous political and socio-cultural developments throughout the Carpathian countries [100–102].

4.2. Recent Developments

The political situation after World War II led to major socio-economic changes in Central and Eastern Europe, also resulting in land use changes in the Carpathians. The land use regimes shifted from agriculturally dominated to forest-dominated structures, and accordingly, agricultural land abandonment has become the common driver of the recent forest cover increase in the Carpathians (e.g., an increase of 6% in the Polish Carpathians from

1990 to 2012 [103]). This process took place especially in depopulated regions [104,105], in areas less suitable for agriculture, and at higher and steeper elevations [106,107]. At the same time, the artificial increase in Norway spruce forests (by 46% in the Southern Carpathians [108]), a profound decrease in silver fir stands (by up to 39% in the Ukrainian Carpathians [109]), and the tendency towards European beech dominance were characteristic of the postwar period. After 1990, the social and economic conditions in the transition period toward market economies, such as decreasing profitability of agriculture and improved possibilities for employment in industrial centers or tourism and recreation services, fostered further land abandonment [110–113]. Accordingly, in Poland, Slovakia, and the Czech Republic, where post-socialist land reforms and support from the European Union were adopted early, the rate of agricultural land abandonment (cropland and pasture reduction) and the respective increase in forest area within the Carpathian Mountains were the most pronounced [86,111,114,115]. In contrast, the forest area in the Romanian Carpathians, even in the first decade of the 21st century, was still shaped by grazing (Figure 5).

Land abandonment is also the main driver of the recent altitudinal forest expansion [116–118], supported by a prolonged vegetation period due to global warming [119], as well as protection measures (see, e.g., [116,120]). The altitudinal forest expansion was the most pronounced in recent decades, with an average upward shift of 0.5–1 m per year [121,122].

In contrast to the quantitative increase (in terms of forest area or timber production) in Carpathian forests, their qualitative development (in terms of forest vitality or structure) was hindered by unfavorable forest practices, like large-area deforestation (e.g., a 6% decrease in afforested area in the period from 1990 to 2012 in the Romanian Carpathians [123]), fragmentation, decrease in core forests (i.e., increase in patch and perforated forest), and homogenization in species and age structures [85,124,125]. Rapid modification of regulations in the post-socialist period resulted in liberalized deforestation regulations across the region. As early as the transition years (1988–1994), harvesting almost doubled in Ukraine, Poland, and Slovakia [126]. The ownership recovery process and massive forest restitution to private owners contributed to both legal and illegal logging, mostly in the Eastern and Southern Carpathians [127–130]). In the Romanian Carpathians, deforestation intensified after the restitution laws of 1991, 2000, and 2005, resulting in a loss of 4.5% in the total forest area and in disturbances (windthrows, droughts, bark beetle outbreaks) occurring more often [124,131–133]. Significant forest disturbances after 2000, with almost 20% of forests being affected, were also found in the Polish, Slovakian, and Czech Carpathians [134]. For instance, this also caused a cascade of disturbances in High Tatra Mountain Norway spruce forests as a consequence: a severe drought in 2003, followed by bark beetle infestation; the Elisabeth windstorm in 2004, followed by deforestation, fragmentation, and bark beetle outbreak; Kyrill and Phillip windstorms (2007), followed by deforestation; bark beetle infestation peak (2009) and clear-cut logging (2009–2012). These events led to a 54% decrease in the national park forest area from 2002 to 2018 [135,136], with the biggest damage being caused to the treeline [137]. Forest disturbances were observed in all ownership types, although disturbance rates in private forests were about five times higher than on public lands, and these forests were more fragmented than state and national park forests [23]. Additionally, wind and snowstorm disturbances were particularly destructive in forests, whose composition was artificially changed towards monocultures through clear-cutting [130].

Air pollution (peaking in the 1980s and 1990s), causing acid rain and photochemical pollution (reaction of nitrogen oxides and volatile organic compounds induced by sunlight), directly affected trees (needle yellowing) and increased the susceptibility of trees to pests [138–141]. The pollution effect was aggravated by the elevated concentrations of ozone in large parts of the Carpathian Mountains [138–140,142,143]. Despite reduced industrial emissions in the late 1990s, high levels of tree defoliation in forests in Poland, the Czech Republic, Slovakia, and Hungary were observed for years [141,144–146], most probably hindering regeneration and upward expansion (e.g., of silver fir; [147]) and contributing to Norway spruce dieback [148]. Improved emission regulations and technical developments enabled a significant decrease in pollutant loads on forests by the end of the 20th century. However, other abiotic factors, such as droughts, wind, frost, and snow/ice damage, and biotic factors (e.g., insect invasions) are the main reasons for tree damage in Carpathian forests [149–153], and current and future developments related to climate change are the main challenges for forest management in the Carpathian Mountains.

5. Climate Change

5.1. Changes in Climate Variables

Climate change (since the 1960s) has led to the warming of the Carpathians, with the highest temperature increase being in the Western Carpathians (Low Tatra Mountains; on average, +2.1 °C in the period from 1961 to 2021) and a lower increase (approx. +1.2 °C) in the Southern and Eastern Carpathians (Supplementary Figure S5). Elevation-dependent warming, as also reported in other mountain regions [36], also takes place in the Carpathians.

Significant increases in maximum and minimum air temperatures were reported for the entire Carpathians, although there is some variability regarding regions and seasons. While summer maximum temperatures have generally increased, higher winter and spring maxima were observed only in the Western and Southern Carpathians, and no trend in autumn maxima was found [154,155]. Minimum temperatures were observed to generally increase throughout the seasons, although less pronounced in the Eastern and Southern Carpathians in spring and summer [156], and autumn minima in the Western Carpathians did not show changes (probably because of an intensified western atmospheric circulation [157]). In the Western Carpathians, a lower frequency of frost days in the warm season was reported [155]. The risk of heatwaves (in terms of frequency, severity, duration) has increased not only in the foothills [157] but also at higher altitudes, as observed for the Western Carpathians [158]. Higher temperatures have also increased the risk of wildfires [159].

Changes in the precipitation patterns are more complex, with increasing (see, e.g., Supplementary Figure S5) or decreasing regimes randomly distributed across areas in the Carpathians [154]. The only consistent trends are an increase in precipitation in September in the inner forelands and the Transylvanian depression, in October in the outer foreland area, and in July in the Western and Eastern Carpathians [154,160,161]. However, there is evidence that extreme hydroclimatic events do not only occur more often but also with higher severity [162,163]. The severity of droughts has increased mostly in spring and early summer months (while in late summer and autumn, the frequency of droughts has even decreased in the high-altitude areas of the Slovakian Tatra Mountains, and the Polish and Ukrainian Carpathians [163,164]). The highest probability for prolonged drought events was observed for inner mountain valleys, the northern foothills of the Western Carpathians, and the southeastern macroslopes of the Eastern Carpathians and the Southern Carpathians.

5.2. Impact of Climate Change on Forests

Climate change produces various effects on Carpathian forests. The increase in the mean temperature has led to a vegetation period up to two weeks longer [165–167] and respectively earlier bud break [168]. A longer vegetation period, in combination with higher nitrogen deposition and elevated carbon dioxide [37], is favorable for wood growth [169], particularly in temperature-limited mountain regions [170–172]. Consequently, the climatic suitability for forests has been extended, and the treeline in the Carpathians has shifted to higher altitudes [117,156,173]. However, it must be taken into consideration that the land use changes, disturbances (see Section 4.2), and ontogenetic differences in the species' environmental requirements interfere with the warming effects and may cause locally modified changes in the treeline [122,174] and tree range shifts [175]. Warming can also lead to bark beetle calamities, and these indirect, biotic effects may often be more relevant than direct temperature effects on trees. For instance, annual tree mortality has increased over the years, with high growing degree days (annual sum of temperatures above +10 °C) due to bark beetle activities [176–178].

Tree–water relations have also been increasingly affected by climate change. This is due to increasing vapor pressure deficits, as well as changes in precipitation patterns (see Section 5.1), and is especially evident under extreme drought at lower elevations [179,180]. Precipitation is the main limiting factor for tree growth on the southern slopes [181,182]. In addition, severe droughts, such as the one in 2003, have been observed to weaken trees and aggravate a bark beetle invasion (Western Carpathians [183]; Southern Carpathians [184]) regardless of the forest management status [185]. More frequent pathogenic fungi invasions have also been driven by increasing water deficits [186].

With respect to Carpathian tree species, Norway spruce showed the overall highest susceptibility to climate change. Trees growing near their natural distributional limits at low elevations exhibit increased variability in radial growth and a reduction in latewood proportion [187,188]. The increasing June and July temperatures have especially affected Norway spruce growth [168,189,190]. Extreme summer heatwaves (as in 2000 and 2003) have reduced the growth rates of Norway spruce trees by 10%–35% in the Southern Carpathians [191,192], which has been probably caused by a combined effect of high temperature and high soil water deficit [168,192,193]. Precipitation and waterlogging changes are the main limiting factors of Norway spruce dominance (in contrast to European beech and silver fir), vitality, and annual increment in the Western Carpathians [72,194], and even of extensive dieback of Norway spruce [195]. However, some studies demonstrated that Norway spruce can adapt [196] or even benefit from higher temperatures at higher elevations (above 700 m a.s.l. [180,197]); the growth rates of adult trees were observed to increase, especially in connection with higher temperatures in late summer [191], while recruitment (sapling ingrowth) rates increased with warmer winters [198] (though the latter may be limited by winter drought [199]). In the Eastern Carpathians, warming-related expansion of subalpine spruce forests was reported, although the risk of windthrows has increased at the same time [200].

Silver fir showed plastic responses to recent severe droughts [201,202]. Higher summer temperatures were reported to enable higher growth rates in the western (Apennine) lineage (located in the Western Carpathians), whereas summer drought was reported to affect silver fir populations located in the Eastern and Southern Carpathians [203]. For instance, the extreme drought of 2012 led to an increase in mortality in silver fir in the Southern Carpathians [204]. However, some studies indicated limited effects of hydrological changes on silver fir [193,203]. European beech forests were found to be more affected by drought than by heat. Accordingly, drought periods were associated with more mortality events [32,204], with droughts in June and July being more relevant than later in the growing season [205]. Decreasing summer precipitation affected European beech especially in forelands and low-mountain regions between 600 and 1200 m on the eastern borders [206–209]. Interestingly, drought effects were less pronounced in beech trees growing in mixed stands [210].

Oak trees have demonstrated comparably high capacities of adaptation to different climatic conditions, as described, e.g., for stands in the Eastern Carpathians [18]. Only severe and prolonged drought periods, which became more frequent only in the last century, have made oaks prone to fungal attacks and mistletoe hemiparasites [211]. Other tree species were also reported to show responses to climate change. For instance, Swiss stone pine (*Pinus cembra*) and larch stands tend to expand at high elevations, as they benefit from warmer temperatures [212,213], but they may be also negatively affected by precipitation changes [214] or other disturbances (e.g., wind [215]). Introduced conifer trees, like black pine and Scots pine, show even higher sensitivity to drought than native species. In the Eastern and Southern Carpathians, these two pine species were found to be strongly affected by limited spring and summer precipitation and overall increasing aridity coupled with invasion of moss species [32,179,216]. At the same time, the climate change responses of many tree species are yet unknown, and respective studies in the Carpathians are overall scarce.

In recent years, much effort has been made to project future development of forests, also for the Carpathians. Several studies focused on modelling regional forest system changes in response to climate change [34,194,203,206,217,218], considering representative concentration pathways (RCPs) and regional climate models (mainly CCSM3, ECHAM5, and HadCM3 [219,220]). Forest models are mainly represented by the Landis-II forest change model (sometimes coupled with the PnET ecophysiological process model [218]) and the Sibyla SILVA model [195,221], including the main drivers of forest development (climate, management, pests, windthrows). According to the model predictions, forest biomass will increase across the Carpathians up to the end of the century, with differences in response to climate scenarios and tree species [32,217,218]. In the Western Carpathians, biomass increases are expected for silver fir (by ca. 25%), European beech (ca. 10%), and oak [222], while Norway spruce is expected to decline (by up to 50% [195]). In the Southern Carpathians, a ca. 21% increase in oak-dominated forests and a ca. 51% increase in mixed European beech–broadleaved forests are expected under the most extreme warming conditions (RCP 8.5), though this may be limited by increasing drought stress [32,218,223].

As for species composition, no significant changes are expected in the next 10 to 15 years [32], but a gradual replacement of highly productive species by low-productive ones is expected towards the end of the century. After 2040, a decline in European beech share (e.g., of 4% in the Eastern Carpathians) and Norway spruce (e.g., of 5% in the Eastern Carpathians) and an increase in silver fir share (e.g., of 18% in the Eastern Carpathians) are expected to be the most pronounced according to the extreme climate change scenario in the Eastern and Southern Carpathians [32,224,225]. The decline in European beech and Norway spruce by 2100 is expected at low elevations and at the receding edges, primarily caused by limitations in tree–water relations [207,226,227] and the expansion of suitable habitats for invasive plants [228,229]. Moreover, the upslope expansion of other broadleaf trees like oak or maple sycamore (*Acer pseudoplatanus*) is expected [34,230]; these species, however, are exposed to the invasion of black locust and ambrosia beetle [231].

6. Recent and Future Forest Management

Climate change, as described in the previous chapters, is the main challenge for forest management in the Carpathians (as in forests worldwide), although other developments and risks, such as deforestation or competing land use interests, illegal logging, lack of forest law enforcement at all administration levels, and lack of long-term funding programs for forest non-use [22,232–235], should also be considered. Addressing these challenges, the Carpathian Convention protocol [15] has, since 2011, been pursuing sustainable forest development (SFM). In alignment with this objective, closer-to-nature approaches in forestry [236] are gaining prominence and being actively implemented in the region. These scale-specific tools are designed to enhance structural diversity and foster natural forest dynamics, encompass the protection of biodiversity, optimize wood production and retention of deadwood, and support natural tree regeneration and the complexity of forest structures.

More than half of the entire Carpathian area is under different forms of protection (Figure 6), though only 3% of forests are completely excluded from logging, and the effectiveness of forest protection efforts varies [237,238]. In recent decades, the effectiveness of protection (reduced deforestation and related disturbance) has increased in the Czech Republic, Slovakia, and Ukraine, whereas it has decreased in Romania [96,127]. Main forest restitutions after the 1990s in Romania may be the reason for the latter, contributing, in turn, to higher effectiveness (preserving forest habitats, reducing fragmentation [239,240] of older protection areas (where natural forests survived) than in Poland or the Czech Republic [184,241]. Large areas of protected virgin and quasi-virgin forests with ongoing efforts toward a strict protection status (e.g., additional 12,288 ha of Ukrainian forests since 2018) may serve as study areas for SFM research and practices [242,243]. The most protected areas (over 90% of case studies found for this review) are objects for the experimenting on and the promotion of innovative forest practices, for which there is a rising interest, as indicated by numerous applied research projects in the Carpathians (within the platforms "Science for Carpathians" S4C and Forum Carpaticum conferences [244]).

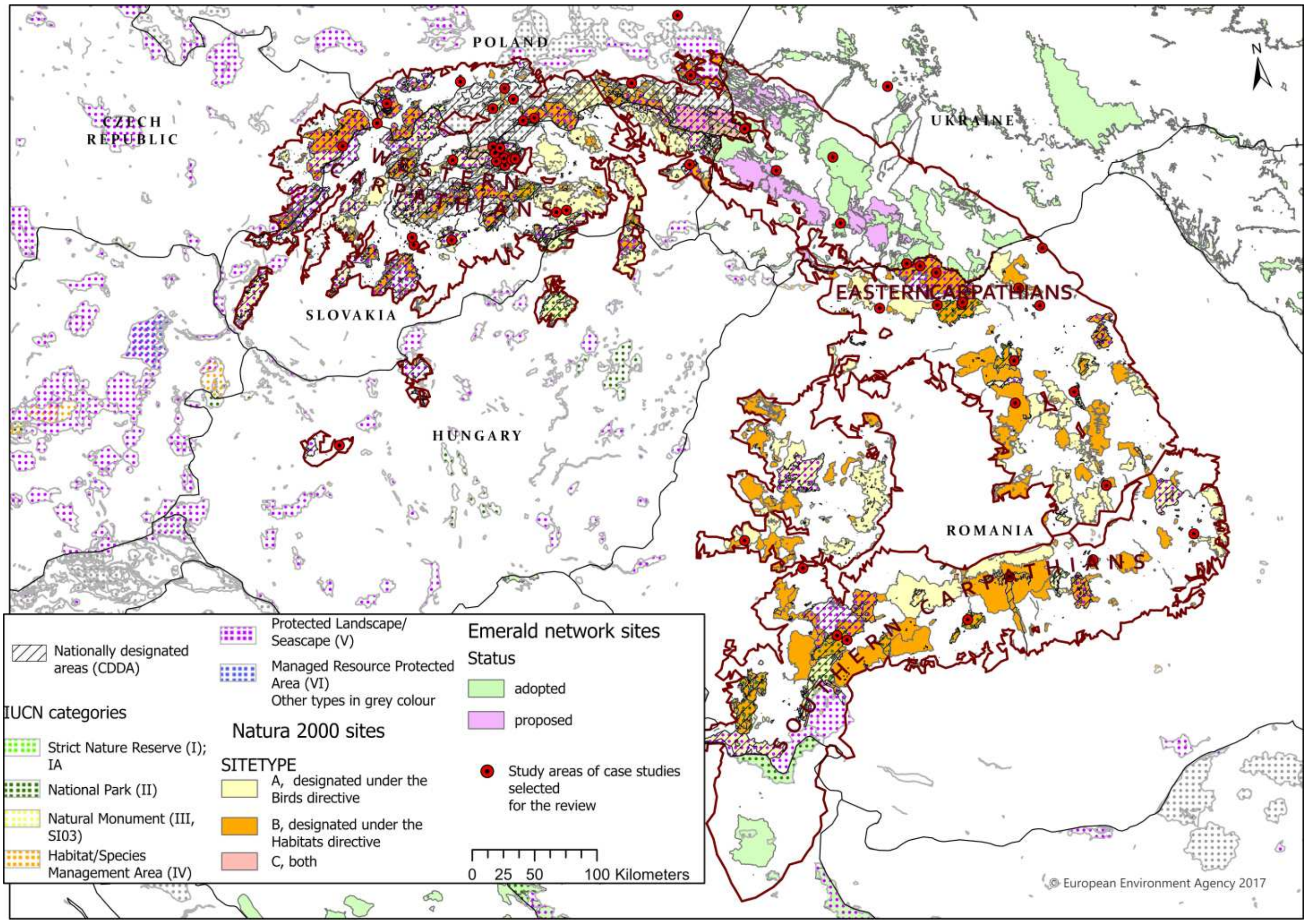
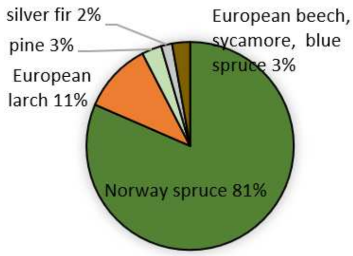
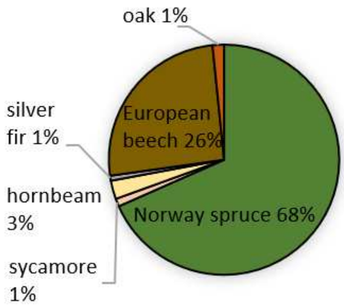
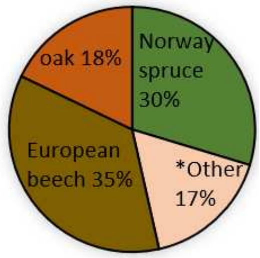


Figure 6. Protected areas in the Carpathians (as of 2022; data are from [245]). Nationally designated areas (CDDAs); Natura 2000 sites in the EU countries; Emerald sites—protected areas in Ukraine (bioreserves, national and regional natural parks) equivalent to Natura 2000 sites in the EU.

Optimizing and balancing wood production is another prerequisite of economically, ecologically, and socially sustainable forest management in the region. Wood production has grown over the last 30 years (especially in Romania and Poland). However, the annual increase in forest area is one of the lowest in Europe (Table 1), and forest development and management differ substantially across the Carpathian countries. For instance, wood for fuel still makes up almost half of production in Ukraine, while Slovakia has shown the most significant decrease in wood and respective fuel production over the last decade. Shelterwood forestry, reduced rotation length practices leading to faster recovery, and timber production while keeping the growing stock low are typical forest management strategies in the Carpathian countries [134,246] (Table 3).

Table 3. Forest composition and management practices in low-mountain areas of the Carpathian subregions for the same areas as in Figure 6 (Western Carpathians—based on [195]; Eastern Carpathians—based on [34]; Southern Carpathians—based on [32]).

Forest Indicators	Western Carpathians	Eastern Carpathians	Southern Carpathians
Forest composition			
Rotation period of harvesting	95–140 years	80–120 years	100–200 years for beech, spruce, sessile oak, and fir, 70–160 years for other oaks
Forestry practices	Mainly sanitary felling, uniform shelterwood regeneration in stands with fir and/or beech admixtures, support of larch or pine deadwood removal	Clear-cut logging, selective and clear-cut sanitary felling to 1100 m a.s.l.	Tree selection, shelterwood, and clear-cutting for small spruce areas and sanitary felling after windthrows and insect outbreaks

* other: unidentified tree species.

At the same time, there is a broad consensus that mixed and more diversified forests increase forest stability and, in the long term, enable higher biomass accumulation and thus carbon sequestration [169,195,218]. This aims at an optimal growing stock and a balanced diameter distribution ensuring a sustainable equilibrium of natural regeneration, growth, and harvest [205,247,248]. Replacing monocultures with more drought-resilient mixtures, including, e.g., silver fir, European beech, oak, and maple, could not only increase biodiversity but also have economic benefits [249,250]. For instance, monodominant forests produce 20 Mg ha^{-1} less biomass than stands with admixtures [223]. Transition of forests are expected to be centered around European beech as a promoter of tree diversity [251–253] holding the capacity to endure harsh conditions [254,255] and outcompete silver fir and Norway spruce [108,256,257]. Establishing a mix of shade-tolerant species, like silver fir, in the understory and light-demanding species, such as oak and maple [204], for the upper canopy may complete future afforestation targets. Mixed European beech–conifer (Norway spruce and silver fir) forests may also enhance the resistance and resilience of Norway spruce [179] and European beech [32,168] to wind and drought disturbances. However, for optimal production in terms of volume yield, height, or volume increment, the portion of Norway spruce should be higher than 50% [108,258] and established under open conditions [259,260]. Regarding the portion of silver fir, mixed forests with up to 20% of silver fir trees were shown to be the most productive [219,225]. In the Southeastern Carpathian forests, the presence of genetically diverse silver fir species within the population of different provenance [261,262] and the collective growth of these species [201] could contribute to drought resilience.

The old-growth Norway spruce and European beech forests preserved in the Carpathians serve as appropriate models for the promotion of natural forest dynamics. It has been demonstrated that old Norway spruce forests (some Carpathian specimens are more than 400 years old) show a high potential for increasing biomass accumulation as a response to a prolonged vegetation period caused by climate change [193] and so do primeval European beech forests [263,264] and old silver fir forests [201]. Accordingly, old forests may be managed with single-tree and group selection felling [265] to make use of the potential of old stands and develop closer-to-nature forestry and thus "climate-smart forests" [247,266–268]. These are aimed at adapting to (i.e., pest outbreaks) and mitigating (i.e., increasing carbon sequestration and surface albedo) global warming [269]. Additionally, the artificial creation of canopy gaps is a promising option in SFM aiming at improving forest diversity and thus vitality (e.g., in abandoned managed forests in national parks [270]). In Norway spruce-dominated forests, it is recommended to establish canopy gaps, which may be bigger with the age of stands (up to 64 m^2 in stands older than 50 years), except for wind-prone areas [108]. Additionally, in European beech-dominated forests, gap openings (small ones of up to 40 m^2) generally promote larger regeneration areas, including broader adjacent zones both in naturally and artificially created gaps [271].

There are also new approaches to forest management after natural disturbances as a part of natural ecosystem dynamics [94,272–275] aimed at increasing biodiversity both in nature conservation (Western Carpathians [91,276,277]) and closer-to-nature forestry (Western Carpathians [278]; Eastern Carpathians [279]). Recommendations to leave post-disturbance withdrawn stands go hand in hand with some evidence of the low impact of sanitary felling on bark beetle spread [280,281]. After disturbances, Norway spruce-dominated closer-to-nature-managed forests produce more seedlings than intensively managed forests in the Tatra Mountains [282] (also see [283]). Post-disturbance natural rejuvenation in these forests, while keeping dead wood [284], may be more efficient and stable (e.g., with respect to bark beetle damage or browsing [135,136,285,286]), though accumulation of carbon long after the disturbance may be higher in less diverse spruce forests [258].

SFM enforcement with a focus on closer-to-nature practices may best happen on a regional scale [287], as individualized approaches often result in greater stand productivity while preserving ecological forest functions [288]. Funding projects for forest reconstruction may be essential to supporting respective initiatives. For instance, the conversion of a monocultural Norway spruce forest into a mixed forest in the Western Carpathians was only financially profitable because of substantial funding [289]. In contrast, restoration of cleared broadleaf forests in small areas of the Southern Carpathians was cost-effective [246]. Silver fir forest reconstruction, though being a long-term process, may be profitable based on the establishment of a forest seed base [109] and protection of planted cultures [290].

Further development of effective SFM strategies with respect to the above-mentioned practices involves close cooperation and coordination of all institutions and stakeholders. The S4C research agenda for 2022–2030 [291] highlights the priority for forest management partnerships among local communities, compossessorates (i.e., traditional social unions for shared use of forests [129]), individual owners, and the state for natural climate solutions, ecological silviculture, and promoting social innovations. The latter has gained importance as a key indicator of successful SFM implementation, and notable progress in this regard is evident in ongoing developments in the Carpathian countries [25,292,293].

7. Conclusions

The literature search revealed a solid though maybe imbalanced (e.g., with respect to regions and topics) basis of scientific literature dealing with Carpathian forests. Several limitations need to be acknowledged given the broad scope of the review. First, the use of a specific search string and the thematic clusters chosen might have limited the finding of articles dealing with the Carpathians but not explicitly mentioning them or addressing topics indirectly related to these clusters. Second, books, conference proceedings, and studies published in non-English languages were not considered in the literature search. Third, the subjective selection of articles in the last step of the search procedure may lead to a bias regarding the identification of appropriate articles related to the defined thematic clusters. Despite these limitations, the literature search not only enabled broad insights into the geographical and topical scale but also made it possible to identify potential knowledge gaps and need for further research activities.

The Carpathian Mountains were characterized in terms of their forests in the period starting from Holocene deglaciation. Climate fluctuations and human activities have led to substantial changes in forest systems, and anthropogenic activities, such as logging, fire activities, and grazing, have shaped the distribution and structure of present-day Carpathian forests. The rapid climate change in recent decades adds uncertainty to the future development of these forest systems; thus, there is a need for new SFM strategies.

These management strategies must be based on valuable predictions of future conditions in terms of climatic, ecological (including, e.g., altered risks of pests), and economical changes (including, e.g., land use changes); their combinations; and forest system responses. Unfortunately, the available data are often insufficient as a basis for projections of future developments in Carpathian forests. For instance, temperature and drought responses of European beech and of other native species in different Carpathian subregions and at different elevations are not yet sufficiently understood. Better knowledge of the performance of these forest species and the entire Carpathian provenance under future conditions would contribute to the understanding of whether and how the establishment of the European beech-, Norway spruce-, and oak-dominant forests mixed with silver fir, hornbeam, and maple sycamore currently strived for may help to mitigate climate change effects. It would also support afforestation strategies and effectively (in terms of ecological, economic, and social balance) combine them with other measures under the umbrella of closer-to-nature forestry.

Due to the enormous geographical variety of the Carpathian landscapes, a high spatial resolution of data sets (climate, soil, forests, etc.) is desirable to improve models and thus predictions of future conditions. Socio-ecological studies could also be important to estimate potential future developments with respect to anthropogenic activities. The literature search of this review revealed that the Eastern, Southeastern Romanian, Ukrainian, and Serbian Carpathians are the least studied regions while holding valuable forest areas of the Carpathians; thus, studies in these areas should be encouraged. Currently, the war situation in Ukraine adds another complexity for forestry as well as respective research activities, as about one-third of the Ukrainian forest area is in occupied areas.

Achieving sustainable forest development in the Carpathians thus remains challenging. Efforts through the Carpathian Convention, forest law amendments, and S4C have been made, but full implementation of sustainable management practices is lacking. Enhancing the connectivity of forests, management, and stakeholders beyond administrative borders and support by respective research could be favorable for adaptive future development of Carpathian forests.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15010065/s1, List S1: List of articles selected and cited in the review, Figure S1: Number of articles per year according to different thematic clusters, Figure S2: Journals in which most of the selected articles were published and their bibliographic coupling, Figure S3: Co-occurrence of terms and their weight in the titles and abstracts of selected articles, List S2: List of studies used for defining the share of tree species in the Holocene in Figure 4, Figure S4: Location of studies used in List S2; Figure S5: Climate (1961–2021) of low-montane areas in different Carpathian subregions.

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