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Review

Silver Fir (*Abies alba* Mill.): Review of Ecological Insights, Forest Management Strategies, and Climate Change's Impact on European Forests

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Abstract: The silver fir (*Abies alba* Mill.) is among the most valuable conifers in Europe for ecological and economic reasons. Throughout the course of history, primarily in the 20th century, its share in stands has been declining due to ill-suited management practices, especially clear-cut management, air pollution (SO_2 and NO_X emissions), and wildlife-induced damage. This literature review compiles findings from 338 scientific papers. It describes futures for silver fir and its distribution, ecological requirements, threats and diseases, seed production and nurseries, and forest management practices with emphasis on ongoing climate change. Based on recent knowledge of fir ecology and population dynamics, small-scale shelterwood and selection management have been introduced in fir stands, which have also stabilized them. Fir is an essential species for maintaining high stability and biodiversity, especially on planosols and in waterlogged habitats. Owing to its shade tolerance and environmental plasticity, it can coexist very well with many tree species in mixtures, which can increase the productive potential of stands within the natural range in Europe. The average stand volume of mature fir stands ranges from 237–657 m^3 ha^{-1}. For its successful natural regeneration, it is essential to reduce cloven-hoofed game and thus prevent bud browsing damage. The attractiveness of fir in terms of heavy browsing is the highest of all conifers (52% damage). On the other hand, fir is a species relatively resistant to bark stripping and the spread of secondary rot compared with Norway spruce (*Picea abies* [L.] Karst.). Under global climate change, fir is expected to shift to higher elevations with sufficient precipitation, while in the southern part of its natural range or at lower elevations, outside water-influenced habitats, it is likely to decline. Climate change is intricately linked to the heightened prevalence of forest pathogens with significant damage potential in Europe, necessitating careful consideration and strategic adaptation within management practices of fir forests.

Keywords: forest management; fir ecology; climate change; biodiversity; threats; natural regeneration

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1. Introduction

From ecological and economic perspectives, silver fir is one of the most significant coniferous tree species in Europe [1–6], as well as in Czechia [7–9]. Originally, fir was the most abundant coniferous tree species in Czechia; its share of an area in the natural species composition is reported to be 19.8% [10]. According to Málek and Novák and Dušek [11,12], significant changes are evident in the representation of fir throughout history—in the year 1200: 20%, 1600: 30%, 1800: 23%, and 1900: 10% of the total area of Czechia. The increase in fir representation, up to 30%, was likely supported by more widespread grazing under deciduous trees and raking of their litter, thus improving the conditions for the germination of fir seeds [13–16]. On the other hand, the proportion of fir in Czechia was only 3% in 1950, 2.1% in 1970, and it declined to 0.9% in 1998. Currently, fir grows on an area of 32,272 ha, i.e., 1.2% of the forest area of Czechia [10], and its share in forest regeneration is gradually increasing (approximately 1500 ha annually; [10]). A similar trend is also visible in other European countries, for example, Germany or Italy [17,18].

Fir is a climax species [19] that cannot thrive at lower elevations (below ~500 m a.s.l.) and in warm regions (especially in the Mediterranean—Spain and Italy), as it is limited by lower precipitation [20], but it can be compensated by higher soil water content and sufficient air humidity [21]. However, fir does not grow on permanently (only seasonally or temporarily) waterlogged sites [22]. In Northern Europe and in mountainous areas, silver fir is limited by low temperatures and late frosts that extend into the early part of the growing season [23,24].

As an indicator of various types of atmospheric contamination [25], the distribution of fir was strongly affected by the air pollution crisis (especially high concentration of SO_2) in the second half of the 20th century [7,26–28]. The synergism of air pollution with the occurrence of silver fir woolly aphid (*Dreyfusia normannianae*), balsam woolly aphid (*Dreyfusia piceae*), and poor management practices (inappropriate silviculture practices, clear-cut systems, and insufficient pest control) have also been reported [4,5,8,29]. The convergence of pollution and pest outbreaks, compounded by lower tree vitality, underscores a critical nexus driving fir forest degradation. This interplay not only amplifies the susceptibility of weakened trees to pests, but also amplifies the overall decline in forest resilience [21,30].

Decreases in silver fir stand densities are also hastened by game-induced damage through bud browsing, bark stripping, browsing, and fraying [7,31–35]. These activities not only stunt the growth of silver fir regeneration, which is very palatable for deer and other wildlife, but also leave it vulnerable to diseases and environmental stresses [36,37]. Without proactive conservation efforts to address game damage and active silviculture practices, the future of silver fir populations remains uncertain [38,39].

Current fir dieback is mainly attributed to climate change [5,8,28,40,41]. In particular, warm summers and recurrent drought have a significant negative impact on the health of silver fir [2,21,41–43].

The main thesis of this literature review of 338 studies aims to assess the role, opportunities, and risks, with a focus on supporting the planting and silviculture of silver fir in European forestry, when Norway spruce is in decline due to climate change. The secondary objectives focus on a detailed review of (i) species description and distribution, (ii) ecological requirements, (iii) threats and diseases, (iv) habitat and stand conditions, (v) seed production and nursery management, and (vi) close-to-nature forest management with an emphasis on the ongoing climate change.

2. Silver Fir Features and Its Distribution

Silver fir has a sturdy, cylindrical trunk and a conical to cylindrical crown, often becoming a flattened "stork's nest" in mature trees (Figure 1). It typically grows 30–60 m tall with a trunk diameter of 1–2 m. Its root system, either tapering or heart-shaped, has deep lateral roots and ensures the mechanical stability of the stand. The bark, initially smooth and whitish–grey, darkens and splits with age. Fir wood is yellowish–white with clear annual rings and lacks resin ducts. Its needles, 18–30 mm long and 2 mm wide, are dark-green and glossy on top with pale stomatal bands below. The male strobili measure 2 cm long and female strobili are 2.5–4.5 cm long, appearing on the upper branches. The cones, which are 10–18 cm long, turn from greenish–blue to brown as they mature. The fir flowers in April–May and the cones ripen by September of the same year, with a lifespan of 300–600 years [3,19,44–47].

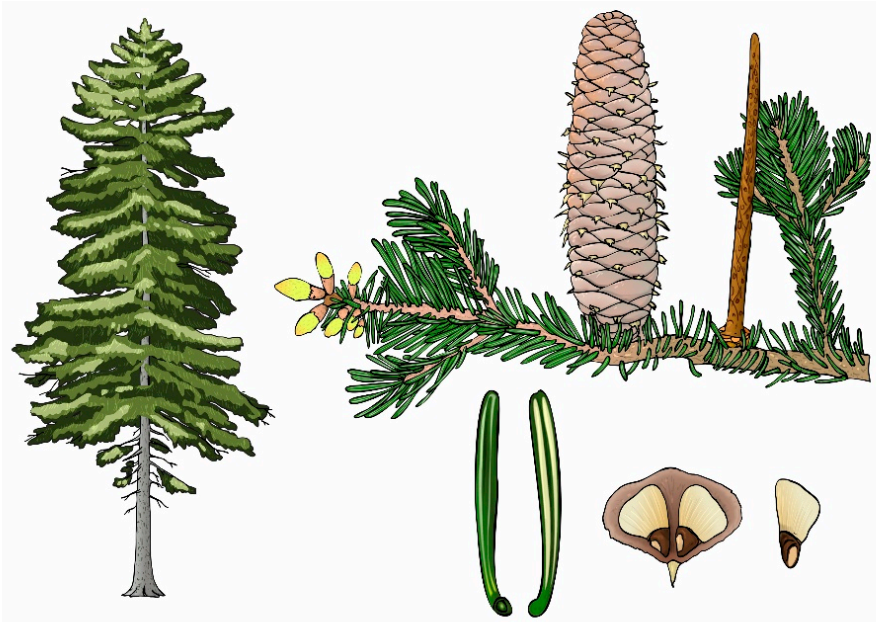

Figure 1. Tree habitus, branch with cones, needle, and scales with the seed of silver fir (*Abies alba* Mill.; author: Josef Macek).

Silver fir grows primarily in Central and Southern Europe [48,49]. Its distribution range is relatively small, patchy, and limited to the mountainous regions of Europe, but its potential range is significantly larger (Figure 2). In comparison, the distribution area of Norway spruce or Scots pine is considerably more extensive [50,51]. In the south, fir grows from the Pyrenees through Corsica, Italy, and the Dinaric Mountains, representing the southern edge of silver fir's natural distribution. Its southernmost limit is in the Southern Apennine Peninsula in Calabria, while the westernmost range closes up in the Eastern Pyrenees, where it also forms the upper boundary of the forest. Further west, there is a small, isolated population in the Normandy hills of northwest France and another in central France. A more continuous distribution begins in the western foothills of the Alps in eastern France and the Jura, Vosges, and German Black Forest. The northern boundary of the fir traverses the Weser Uplands in northwestern Germany, the Thuringian Forest, the foothills of the Ore Mountains (Krušné hory), and the Giant Mountains (Krkonoše), and then the Malopolska and Lublin Uplands in Poland. It reaches its northern limit near Warsaw and in the Białowieża Forest. The eastern boundary continues into the Eastern and Southern Carpathians. Inside the Alpine system and in the Tatra Mountains, it grows in small, scattered patches. However, silver fir also occurs in the lowlands, for example, in France, Poland, and Ukraine [2,3,19,26,45,47,52,53]. It is the leading co-dominant tree, primarily in forest altitudinal zones (FAZ) 4–6 (400–1200 m a.s.l.; [54]). In these typical habitats, silver fir (share 10%–20%) forms mixed forests together with European beech (*Fagus sylvatica* L.; 20%–40%) and Norway spruce (*Picea abies* [L.] Karst.; 50%–80%), characterized by a complex internal structure, the so-called Hercynian mixtures [55–57]. Montane forests, composed of these three tree species, cover a total area of more than 10 million hectares in Europe [58].

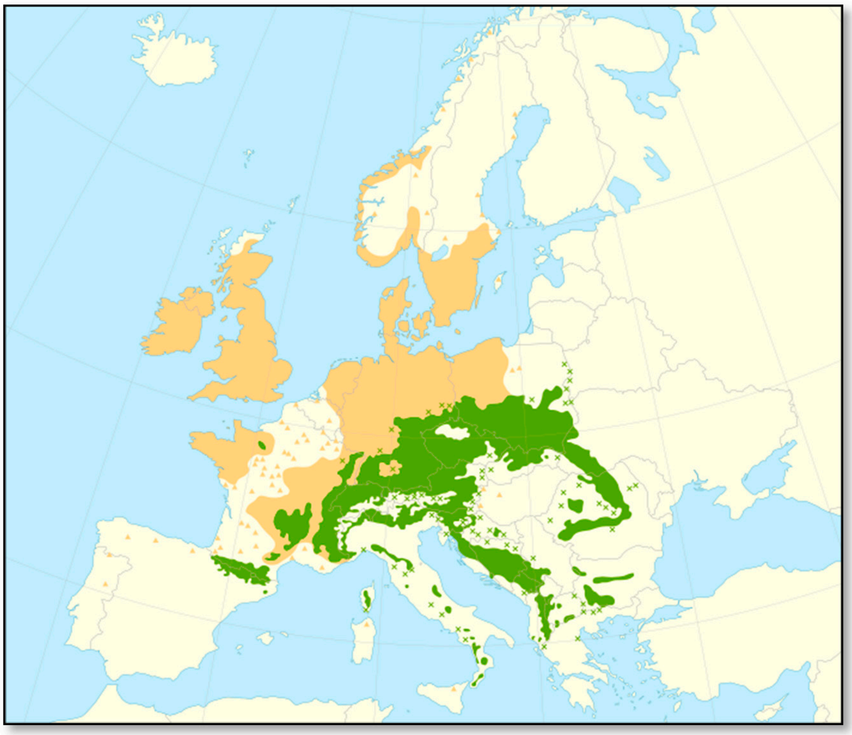

Figure 2. Map showing the native range (green color) and introduced/naturalized range (orange color) of silver fir (*Abies alba* Mill.) in Europe [59]. Green crosses represent native isolated populations and orange triangles are introduced/naturalized isolated populations.

3. Ecological Requirements and Productivity

Abies alba grows optimally under a predominantly oceanic temperate cool and humid climate with mild winters, ideally resembling the continental climate in Poland. In Europe, it grows from 135 to 2900 m above sea level [44]. Fir–beech forests in the central part of its distribution range are considered the optimal habitats for silver fir, i.e., to the south from Czechia, at altitudes of about 800–1200 m a.s.l., with precipitation of 1000 mm or more [45]. At lower altitudes, silver fir occurs in cooler and wetter basins and also on alluvial plains at the northern boundary of its range [60]. Severe, dry winters and dry, hot summers are unsuitable for fir. It is sensitive to late frosts, i.e., in spring [19,45,47,61].

Silver fir is a tree species that could benefit from the anticipated climate change, especially in terms of dispersal to higher altitudes with sufficient precipitation, except in areas with severe winters [26,56,62]. However, it has considerable moisture requirements and requires higher air humidity than other species [4,21]. The annual precipitation in its current range varies widely from ~700 to 2500 mm with optimum precipitation of 1500 mm, ideally not falling below 700–800 mm yr^{-1} [26].

Silver fir is known for its ability to tolerate shade for several decades [63]. Fir undergrowth can grow in heavy shade for as long as 120 years, attaining heights of 1–2 m in Central Europe. Its light requirements are influenced by a complex of other climatic factors (heat, precipitation, humidity, and airflow) and soil factors. The more favorable the habitat conditions, the lower the light requirements of the fir. In contrast, at cooler, higher elevations or on drier and mineral-poor soils, even at the lower limit of its range, the light requirements of fir trees are significantly higher [13,14]. Fir grows primarily on deep, moderately fertile to rich and moist to seasonally or temporarily waterlogged soils. However, it can adapt and grow on stony or peaty soils. In some areas, its optimal habitat is limestone (Western Alps, Jura). This tree species is irreplaceable on heavier loess soils, especially on planosols at mid- and higher altitudes [14]. In mixed forest stands, fir positively influences soil properties because the accumulation of needles stimulates the formation of the humus layer, especially compared with spruce [64]. In mixed stands, silver fir also positively contributes to creating and maintaining a stand environment, especially considering that it can thrive as a component of the lower layer for a long time. Fir in mixed stands balances extremes in temperature, humidity, and airflow limitation [62].

Silver fir is a high biomass-producing tree species (Table 1). For example, at a mean height for the main stand of 30 m, the stock volume reaches 580 m^3 ha^{-1} [65]. The average stock volume of mature fir stands ranges from 237 to 657 m^3 ha^{-1} and the stand basal area from 20.6 to 70.0 m^2 ha^{-1} (Table 1). However, timber processors are not yet able to adequately exploit the high-quality and standard production of fir timber compared with spruce, and therefore, the produced mass is not sufficiently cost-efficient (caused by the low proportion of fir in the species composition). An interesting feature of the change in the timber market during the years of the historically greatest bark beetle outbreaks in Czechia (2016–2020) is the fact that the price of fir timber in roundwood assortments increased significantly and is currently at the same level as that of spruce [66]. Bark beetle salvage logging of coniferous species (especially Norway spruce) increased from 1.5 mil. m^3 annually in the period of 2003–2015 to 23 mil. m^3 in 2019 [67]. The significant increase in roundwood prices in the last decade (up to 146%) has been the result of a substantial destabilization of the Central European timber market, caused by natural disturbances linked to climate change, a shortage of wood in the context of increased demand, and higher timber harvesting compared with required increments [68]. Furthermore, unaffected mature fir stands at the harvesting age are rarely affected by climate change and salvage logging compared with the vulnerable Norway spruce [21].

Table 1. Overview of selected available publications related to silver fir (*Abies alba* Mill.) production parameters in Europe.

Study	Country	Altitude (m a.s.l.)	Age (y)	DBH (cm)	Height (m)	Basal Area (m^2 ha^{-1})	Stock Volume (m^3 ha^{-1})	Density (Trees ha^{-1})	Climate Classification
[69]	Bosnia and Herzegovina	up to 1078	max. 165			28.7–45.7	274–590	588–732	Dfb
[9]	Croatia	876–978	73–76	28.4–32.2	19.4–22.6		227–361		Cfa
[8]	Czechia	660–710	56–146	28.9–40.7	18.0–26.0	43.4–53.3	486–594	336–816	Dfb
[70]	Czechia	940–1100	158–189	23.0–27.0	13.0–15.0		450–560		Dfb
[71]	Czechia	640–800	68		29.0–34.0		333		Dfb
[9]	Czechia	660–790	63–76	25.8–31.8	21.2–23.6		346–398		Dfb
[72]	Czechia	330	45	18.0–22.0	17.0–19.0		164–372	714–1042	Cfb
[7]	Czechia	670–730	108–126	15.4–34.9	22.8–37.6	20.6–43.5	237–598	456–1624	Dfb
[73]	France	1350–1500	109-141		20.3–20.8	27.1–42.2		558–748	Dfb
[74]	Italy	1200	max. 130			35.0–45.9	336–356	1175–1215	Cfb/Csb
[9]	Italy	944–1324	66–75	23.0–28.1	18.7–25.4		220–289		Csb
[75]	Poland	337–889	40–115	15.9–46.5	14.1–31.5	35.5–43.8	322–657	211–1852	Cfb/Dfb
[76]	Poland	550–600	68–78	24.6–30.0	24.9–25.5	27.6–37.9	362–533	569–752	Dfb
[77]	Poland	300–725	40–150	21.0–39.0	27.3–31.0	34.0–70.0		382–715	Cfb/Dfb
[78]	Poland	194	60	33.1	22.2		301	378	Cfb
[7]	Poland	520	124	34.5	35.2	43.3	591	464	Dfb
[79]	Romania	700–950	100–130	7.6–45.0	5.8–31.6	35.0–45.0	299		Dfb
[80]	Slovakia	400–970	98–127	22.2–44.1	19.9–34.4	46.6-53.8			Cfb/Dfb
[81]	Slovenia	850	108–132			33.4		207	Dfb
[82]	Ukraine	750–1045	94–132	36.0–48.0	28.0–30.0		324–550		Dfb

Notes: climate classification according to Peel et al. [83]: Cfa—humid subtropical climate, Cfb—oceanic climate, Csb—warm-summer Mediterranean climate, Dfb—warm-summer humid continental climate.

Fir is the slowest growing tree species in the first 10–15 years compared with beech and spruce, although it can tolerate a lack of light for a long time. Therefore, it can only succeed in the regeneration process if it has a head start of at least 15–20 years over other tree species that grow more vigorously in their early stages [84,85]. Another prerequisite for its successful growth is sufficiently diverse stands in which fir can maintain a vertically extended crown compared with a short part of the trunk without branches [8,86]. Subsequently, the height increment of fir accelerates until around year 15, peaks at 30–40 (–70) years or much later under unfavorable conditions, and persists for over 100 years. The volume increment peaks at around 55–65 years, i.e., relatively late [45]. As a result of climate change (longer growing season and increase in annual mean temperature), a significant increase in the annual volumetric increment of fir trees, from 7.2 to 11.3 m^3 ha^{-1} y^{-1}, has been recorded in European mountains from 1980–2010 [58].

Fir's ability to tolerate shading and regenerate under it makes fir suitable for multi-layer, mixed-aged stands and for single and group mixed-selection forests, which are characterized by selective tree harvesting, continuous canopy cover, rich diversity and vertical structure, and sustainable management [4]. In mixed stands, its strengthening function against windthrow and its beneficial effect on soil is highly valued [64,87]. This is also true in the case of the Hercynian mixture, which used to be the most common composition of natural stands at mid and mountain altitudes in Central Europe [88]. In ravines and on scree, fir mixtures evolved, e.g., with maples (*Acer* spp.), in warmer habitats with European hornbeam (*Carpinus betulus* L.), and in poorer habitats with Scots pine (*Pinus sylvestris* L.). Lime (*Tilia* spp.), sessile oak (*Quercus petraea* [Matt.] Liebl.), rowan (*Sorbus aucuparia* L.), or hazel (*Corylus avellana* L.) occur as subsidiary species. In the Pyrenees, it accompanies mountain pine (*Pinus uncinata* Ramon ex DC) on the uppermost border in the context of elevation. In other habitats, fir is usually found only as an admixed or interspersed tree species [89]. It maintains its presence here primarily due to its ability to survive in the understory for a long time or its ability to grow on alternately wet and waterlogged soils [8,16,56,90].

In forest stands, fir affects soil mainly by its quality of litter and its relatively low decomposition rate [76,91,92]. Specifically, litter of deciduous species with rapid decomposition rates typically break down within a few months (C/N ratio = 12–25), whereas slower decomposition of litter is observed in conifers, such as silver fir, which may take several years due to their higher C/N ratio (>40) [93]. Spatial structure also influences soil conditions through litter [94]. The amount of litter is higher under the tree canopy than in the openings [95,96]. Differences in the spatial structure of stands greatly influence thermal, light, and moisture conditions, and thus affect the rate of litter decomposition [97–99]. Stand gaps are characterized not only by increased light, heat, and precipitation, but also by faster decomposition of organic litter [100,101] and higher nutrient concentrations in the soil solution [102]. In addition, soil heterogeneity is enhanced by the cluster distribution of concentrated roots and, thus, higher water and nutrient consumption in mixed stands [103,104].

Generally, the success of natural regeneration, apart from ground vegetation [105], depends on the properties of the topsoil horizons [106], which is a condition for seed germination, root development, relationships with soil microflora, and the availability of water and nutrients [99]. Compared with spruce, fir is characterized by a lower acidification capacity and a higher C/N ratio [107]. Třeštík and Podrázský [108] reported a lower (54%) accumulation of forest floor humus in fir stands and significantly higher total nitrogen and calcium contents compared with spruce. A higher accumulation of total carbon in the Ah soil horizon was observed beneath spruce than beneath fir [109]. In tree biomass, fir fixes a lower amount of carbon compared with spruce, because fir allocates more carbon to the crown and spruce to the stem [110].

In the natural species composition, fir reaches the highest proportion in the ecological series of gleysols and planosols, up to 70%. The groups of forest habitat types include *(Fageto-) Abietum variohumidum mesotrophicum*, *Abietum piceosum variohumidum acidophilum*, *Abietum piceosum variohumidum oligotrophicum*, *Abietum quercino-piceosum paludosum mesotrophicum*, and *Abietum quercino-piceosum paludosum oligotrophicum* [111]. In these habitats, fir forms a full spectrum of mixed stands, with beech, spruce, oaks, sycamore maple (*Acer pseudoplatanus* L.), black alder (*Alnus glutinosa* [L.] Gaertn.), silver birch (*Betula pendula* Roth.), European aspen (*Populus tremola* L.), and Scots pine [89]. It is often the main species in montane forest phytocenoses, such as silver fir and European beech (*Abieti-Fagetum*), subcontinental silver fir forests (*Galio-Abietion*), upland fir forests (*Querco-*

Abietetum), and slope forests of silver fir (*Abietetum albae*) in Switzerland [112]. It also forms forest phytocenoses with spruce *Piceetum subalpinum sphagnetosum* [112].

As a long-lived species, fir is considered an important ecological and functional stabilizer of European forests [3]. It stabilizes soil, retains water, and is less susceptible to snow and ice damage than Norway spruce [113,114]. Silver fir is an essential species for maintaining high biodiversity in forest ecosystems due to its tolerance to shade, ability to survive extended periods in the understory and respond when light conditions become more favorable, plasticity to environmental conditions, and ability to coexist with numerous tree species [7,63,115].

Fir is normally the most differentiated tree species in terms of age, height, and diameter, which makes natural forests with a higher proportion of fir trees close to selection forests in their structure [116,117]. With a higher representation of beech at the expense of spruce, the regeneration and growth of fir is more continuous, creating a vertical and multi-layered canopy [118]. A higher spruce share creates a typical horizontal fir and spruce canopy at the optimum stage as a consequence of the fact that the lifespan of trees is longer than the duration of their height growth. The optimum stage, also characterized by stagnation of natural regeneration, usually occupies about 20% of the area of natural forests, and its duration is expressed in the same period over the entire development cycle, i.e., about 80 years according to studies from Slovakia and the Czechia [90,119].

At the main level of the stand of both selection and cultural forests (extensively managed by human activities over time in terms of density, species composition, and structure), there is typically a gradual rotation of the dominant tree species occurring in differently sized areas [116,120]. It is clear that, especially in forest altitudinal zones 5 (600–900 m a.s.l.) and 6 (800–1200 m a.s.l.), there is a gradual rotation of generations of fir, spruce, and beech in their typical stand mix at the main stand level. This is likely due to the shorter lifespan of beech and its requirements for specific light and soil conditions [55,90,121–123].

The interspecific substitution of trees in the same stand is also seen in the context of their different light uses [124]. Firs primarily use the short-wavelength blue component of the solar spectrum (400–430 nm; [125]) and are more sensitive to the lack of this component than to the overall reduction in light intensity that occurs in shaded conifer stands [89,116,126]. This fact also explains the better regeneration of firs under spruce than under fir canopy, a historically observed phenomenon [4,61,127].

The competitive abilities of tree species in mixed stands also change depending on the soil properties [128]. Acidic soils reduce the vigor of beech, and calcareous soil reduces the vigor of spruce. With increasing acidity and excessive soil moisture, fir and spruce establish at the beech optimum, while nitrogen-rich soils reduce conifer vigor [55]. According to Ellenberg [129] and Tinner and Lotter [130], fir is more competitive than beech in locations with low temperatures and high summer rainfall. According to historical records, abundant summer precipitation is more crucial for fir than low temperatures [130].

Complex layered stands, where the growth space is fully utilized, exhibit an inverse relationship between the amount and biomass production of the understory (lower story) and the biomass of the main stand (upper stories; [76,131–134]). Changes in the upper story, combined with canopy disturbance, are quickly reflected in a changed light regime of the understory, and thus in an increase in its biomass. The main cause of overyielding in multi-layered stands is their light-use efficiency [135]. Hence, the reduction in the canopy, whether natural or artificial, affects the structure and vigor of natural regeneration [84]. In forests of the typical Hercynian mixture of forest altitudinal zones 5 and 6, the requirements of fir, spruce, and beech for light, nutrients, and water do not differ substantially, while light intensity plays the most important role in growth [56,136,137]. Tree species differ significantly in their ability to survive in the long term under reduced light conditions while maintaining fully functional and efficient photosynthetic processes [138]. Fir, an extremely shade-tolerant species, has a distinct competitive advantage, especially over spruce, in low light conditions [55,131,137]. This fact was also confirmed by the preserved montane mixed forests of the Romanian Carpathians by Stancioiu and O'Hara [133]. These studied stands are located at an altitude of 800–1300 m a.s.l., and the age of the main stand is 70–350 years. Their results showed that, at low light intensity (percentage of the above-canopy light, PACL < 20%–35%; BA > 30 m^2 ha^{-1}), fir and beech clearly outgrow spruce, and the latter can even be eliminated from the regeneration as it develops. Under medium-light conditions (PACL = 35%–70%; BA = 15–35 m^2 ha^{-1}), the growth abilities of all three species are equal, while under open conditions (PACL > 80%–90%; BA < 15–20 m^2 ha^{-1}), all of the three species show the same development, with spruce tending to outgrow the other two shade-tolerant species [133]. Another factor is the reduction in the height increment of fir under direct sunlight (PACL > 80%–90%) compared with the maximum growth when shaded (PACL = 50%–80%; [133]). The fact that strong interventions into the main stand canopy are more favorable for spruce and beech than for fir has been noted by many authors [38,116,131,138–140].

Numerous studies confirmed that mixed stands can have higher biomass productivity than monocultures in suitable habitats [122,141–144]. Silver fir and Norway spruce also grow faster in mixed stands than in monocultures, and their complementary effect increases with improved growing conditions, i.e., resource availability or climatic conditions [145–147]. However, an increase in the complementarity and productivity of these species occurs because of their different light requirements, which also affects the absorption of photosynthetically active compounds by radiation or light-use efficiency [142].

In the last 40–60 years, a significant decline in fir in forest stands and its gradual replacement by spruce or naturally spreading beech have been observed, both in the Hercynian and Carpathian regions [7,148–153]. Especially in forest altitudinal zones 5 and 6, the predominance of beech regeneration over fir regeneration has been documented. European beech has profited (acceleration of growth, fructification, and regeneration abundance) more from climate-changed growing conditions compared with other tree species and could have changed the competition relationship in favor of beech [154,155]. In the well-preserved Dobroč Primeval Forest in Slovakia, the percentage of natural regeneration of fir was around 60% in 1935, followed by a significant decline. Korpel [90] reported only a 20% share of fir in the late 1970s and 1980s. This phenomenon has been interpreted as a common substitution of tree species occurring during the development cycle in virgin forests [90,119]. However, the negative influence of game on fir regeneration was evident at the time, and as the regeneration continued to decrease in many areas, this has been assessed as an unnatural and negative development that is unlikely to be reversed naturally within the evolution of the forest stand in Switzerland, Czechia, France, and other countries [7,36,118,156].

4. Threats and Diseases

One of the most striking aspects of the ecology of silver fir is its recurring decline, which has been observed in Europe since the 1500s [127,157–159]. The rapid decline of fir in Central Europe has been associated primarily with the intensification of human activity in forests and the development of industry [160–164]. However, data on fir dieback dates from well before the mass industrial expansion of the 20th century [7,8,16,26,116,165,166]. Fir dieback and its reduced natural regeneration have been observed from the 1960s to the 1990s. The decline was first interpreted as a consequence of the natural range of fir reaching its outer boundaries [167], but in the 1970s and 1980s, fir dieback of varying intensities was observed across the entire natural range of the species [158,168].

Owing to their high sensitivity to air pollution [169,170], fir trees have been reported to be in decline as a result of the ensuing stress [8,27,28,61,171–174]. In particular, SO_2 pollution has been a critical factor in the decline of silver fir in the 20th century [173]. The worsening situation was reflected in reduced growth and increased tree mortality [5,173]. There were predictions that silver fir would eventually experience general dieback due to air pollution [175], but in the interim, the SO_2 concentrations declined significantly. In Europe, SO_2 emissions peaked in the early 1980s and from that point until 1995, decreased by 50% [176,177], which triggered a rapid recovery in fir growth and vigor [27,43,178]. Fir stands regenerate in the most affected areas following a reduction in air pollution [7,173]. According to Bošel'a et al. [27], Bountgen et al. [43], and Mikulenka et al. [8], this is due to the combination of air pollution decrease and an increase in temperature. Bošela et al. [27] stated that the most significant factors that positively affect radial growth in the Western Carpathians are the decreases in the air concentrations of SO_2 and NO_3 and the increases in temperature in April, June, and July. Although there are differences between the areas in all four regions, a rapid acceleration of the increment in the last two to three decades was observed, reaching values between 150 and 300% compared with previous periods. Similarly, in the forests of the Sudeten Mountains, there has been a significant regeneration of silver fir since the high annual SO_2 concentrations (30–50 $\mu g \cdot m^{-3}$) subsided [179].

Natural silver fir regeneration has increased its dominance in Pyrenean subalpine forests in recent years, as well as in some mixed forests in Spain [180] and in other European forests [70]. However, some studies suggest a different response of silver fir along the edges of its natural range [181]. A retreat of silver fir from warmer and drier areas has been observed in Slovenia, especially in fragmented forests and at the limits of fir's distribution range [182]. Its dieback is often attributed to climate change [28,40,41,183–186]. The negative impact of climate warming has been observed in southwestern Europe [2], chiefly in the Mediterranean region, where the decline in silver fir is related to increased aridity [2,178,187]. In particular, warm summers and recurrent drought have had a significant impact on the health of silver firs [2,41–43,188]. The narrow genetic variation of silver fir in Europe may have limited its adaptability to current conditions in terms of climate change [158,189–191]. Adaptation to drought is coupled with slow growth, but independent from phenology in marginal silver fir populations [192]. Populations with "start early and grow slowly" strategies have higher water use efficiency [193]. The provenances' ranking by resistance, recovery, and resilience in radial growth revealed that a number of provenances from Bulgaria, Italy, Romania, and Czech Republic placed in the top ranks. Assisted migration may support the adaptation process and help to conserve and increase genetic diversity, especially at the species distribution edges [194].

Infestation by bark beetles (*Pityographus pityographus* Ratz.; *Pityokteines vorontzovi* Jac.; *Pityokteines spinidens* Reitt.) has been observed in southern France, which could partly explain the high mortality [195,196]. The decline in firs during the period of the ecological disaster (1980s and 1990s) has often been associated with the damage to fir stands by the silver fir woolly aphid (*Dreyfusia normannianae*) and balsam woolly aphid (*Dreyfusia piceae*; [197,198].

In the northern Carpathians (Czechia and Slovakia), Slovenia, and Croatia, silver fir has declined due to the spread of beech and, to a lesser extent, Norway spruce, and due to the failed regeneration as a result of the cloven-hoofed game population increase [7,118,148,182,199,200]. The retreat of silver fir from its natural stands, as well as from artificial regeneration, is aggravated in many locations by game-induced damage (especially red deer—*Cervus elaphus* L., roe deer—*Capreolus capreolus* L., sika deer—*Cervus nippon* Temminck, European muflon—*Ovis aries musimon* Pallas, and fallow deer—*Dama dama* L.) through bud browsing, bark stripping, browsing, and fraying [7,31,33–35,124,201,202]. Table 2 clearly shows the high attractiveness of silver fir in terms of bud browsing damage (52%) across Europe. Higher damage in montane forests was also recorded for sycamore (56%) and rowan (55%), compared with minimal damage in Scots pine (5%) and Norway spruce (17%).

Table 2. Overview of selected available publications related to the proportion of browsing damage (%) in selected tree species with an emphasis on silver fir (*Abies alba* Mill.).

Study	Country	Climate Classification	Altitude	Fir	Beech	Spruce	Rowan	Maple	Ash	Pine
[203]	Czechia	Dfb	450–1033	41	16	14	31	22	42	0
[204]	Czechia	Dfb	1000–1257	8	44	0	35	64		
[205]	Czechia	Dfb	725–765	36	12	3	57	100		
[70]	Czechia	Dfb	940–1100	100	78	48	76	91		
[7]	Czechia	Dfb	520–730	88	30	9				
[118]	Czechia	Dfb	740–920	100	56	18	94			
[32]	Czechia	Dfb	420–440	53	23	25	50	34	23	
[206]	Czechia	Dfb	640–810	68	6	2	82	100		
[207]	Germany	Dfb	443–1334	50	47	33	28	39		
[201]	Italy	Dfc/Dfb	900–2300	42		14				2
[208]	Italy	Dfc/Dfb	800–2500	41	15	13	46	46	39	14
[209]	Italy	Dfb	900–1694	96	13	62				
[210]	Poland	Dfb	223–364	19	15			48		
[211]	Poland	Dfb	800–1600	33	1	1	40	39		
[212]	Switzerland	Dfc/Dfb	380–3000	6	3	1	62	29	19	
Mean				**52**	**26**	**17**	**55**	**56**	**31**	**5**

Notes: climate classification according to Peel et al. [83]: Dfb—warm-summer humid continental climate, Dfc—subarctic climate.

One of the most serious threats, not only to fir, but to all conifer saplings, is the removal of bark from the tree trunks by cloven-hoofed animals (browsing and bark stripping). As a result of this damage, not only is the vascular cambium disrupted, but above all, the quality of the timber is compromised by secondary infestation with fungal pathogens and the development of stem rot. This is especially true for Norway spruce, whose value as merchantable timber decreases rapidly due to bark damage and subsequent decay [213–217]. In contrast, there is minimal knowledge of the effects and consequences of game-induced bark removal on silver fir. Bazzigher and Schmid [218] and Kohnle and Kändler [219] only reported that bark damage in silver fir was less detrimental than that in Norway spruce, while also suggesting that fir timber is less susceptible to stem rot. However, neither the reasons for the increased susceptibility of Norway spruce to decay nor the mechanisms of resistance of silver fir to the spread of rot and subsequent decay are currently known. Metzler et al. [220] reported that, unlike silver fir, Norway spruce has resin canals, which may be the reason for the spread of fungal pathogens after bark damage by game. Game-induced bark damage to silver fir was partially studied in terms of histological changes by Oven and Torelli [221,222], and concerning growth and vitality by Pach [223–227], who reported a decrease in timber quality, reduced vitality and growth of fir trees, and the spread of rot. This rot can manifest itself in timber discoloration, a more advanced level of its development, and even the decomposition of the wood mass (so-called soft rot), which very negatively affects the mechanical stability of the affected stands. Timber discoloration, as the initial stage of rot, can be the result of fungi, bacteria, and the reaction of wood to pathogens [214,228–230].

Thus, bark damage is less harmful in silver fir than in Norway spruce, and its timber is also less susceptible to stem rot [219]. Trees damaged by browsing and bark stripping are generally more vulnerable to a lack of precipitation, while healthy trees are more responsive to temperature [231], which may play a significant role in terms of climate change. Healthy trees can increase its production potential in cooler and higher-elevation areas due to the increasing average air temperature, while damaged trees will have a higher risk of mortality due to drought in lowlands. Various measures are taken in an attempt to prevent damage to forest stands by wildlife, notably methods of individual or group protection and the use of commercial repellents [232–235]. However, these short-term measures do not address the long-term problem of continuous increases in population density as well as the distribution range of wild ungulates [236,237]. These changes in the population dynamics of ungulates are driven by many factors, including changing climatic conditions [238,239].

Silver fir decay results from the spread of rot through injured bark. *Heterobasidion abietinum* infects primarily silver fir and causes stem rot, particularly in Southern Europe [240–242], where firs are often affected by drought during summer. However, in Central Europe, this fungus does not cause any tangible problems in fir, likely due to the more favorable climatic conditions or to the low abundance of this fungus [241,243]. *Phellinus hartigii* occurs on silver firs with injured bark in Central Europe ([244,245]; Figure 3). Widespread deterioration in the health and dieback of the genus *Abies* Mill. due to other pathogens have been observed in Europe in recent years. Increased forest degradation of silver fir forests, presumably due to climate change, was found, for example, due to infection of the phytopathogenic bacterium *Lelliottia nimipressuralis* in Ukraine [246] or the fungi responsible for Herpotrichia needle browning, including *Nematostoma parasiticum* [247]. Fir stands can also be infested by the hemiparasitic mistletoe (*Viscum album* L.), which attacks a wide range of woody plants [248–250]. This parasite and the subsequent invasion of microorganisms—such as fungi or bacteria—cause mechanical and aesthetic damage to the timber, reducing its increment and commercial value [251–254].

Figure 3. Intensive, repeated bud browsing by game (**left**), earlier damage by browsing and bark stripping (**middle**), and subsequent infestation by *Phellinus hartigii* (**right**) (Photo: Stanislav Vacek).

Natural and anthropogenic disturbances play a principal role in the dynamics of forest ecosystems and influence stand structure and regeneration processes. In Europe, wind and fire are the most severe abiotic disturbances [2,255], and insect infestation is the primary driver of biotic disturbance [123]. Silver fir is relatively resistant to wind, snow, and ice storms compared with other dominant tree species, such as Norway spruce [4,194]. Disturbance regimes in forests dominated by silver fir are characterized predominantly by small-scale events, such as a single tree falling, while large-scale events, such as windstorms or forest fires, are rare [256]. Large-scale events have been increasing, especially in natural silver fir sites in recent years. Annual disturbance-based tree mortality of silver fir has been accelerating and was the highest (compared to Norway spruce, Douglas-fir, European beech, and oak) in Germany during the period of 1929–2014 [257]. Extensive mortality of fir trees was observed after the drought in 2018 in Czechia [258].

5. Impact of Climate Change

Ongoing climate change is currently exhibiting widespread impacts on forest ecosystems and thus on all forest management, which should adapt to changing conditions. Existing climate models predict an increase in average air temperatures during the 21st century, as well as an increase in the frequency of extreme weather events, such as storms, floods, heat waves, and dry periods [123,194,259,260]. Appropriate forest management measures include abandoning monocultures, establishing mixed stands, and promoting the cultivation of natural regeneration [261,262]. A large number of studies report positive relationships between species diversity and forest productivity [122,263], and it has also been confirmed that diversity in forest species composition increases resistance to biotic insect pest calamities [261,264]. Therefore, declining forest stands in Central Europe are often replaced by mixtures of tree species in an attempt to adapt forests to climate change [255,262,265,266]. Much of the Central European forest landscape is still dominated by Norway spruce, despite its documented susceptibility to drought, wind, bark beetles, etc. Numerous studies from across Central Europe confirm that the area suitable for growing Norway spruce will continue to decrease with ongoing climate change [40], even at higher altitudes [267]. Compared with Norway spruce, silver fir and European beech are less susceptible to short summer droughts [265,268,269].

Fir is not considered a dominant tree species in most European countries at present, nor will it be in the future in relation to ongoing climate change, but only an interspersed or admixed species in mixed stands. The range of silver fir, together with Norway spruce and European beech, shows a decline under climate change scenarios. Conversely, sweet chestnut (*Castanea sativa* Mill.), wild service tree (*Sorbus torminalis* Crantz), and European white elm (*Ulmus laevis* Pall.) expand their range potential, and along with European hornbeam, they hold the potential to contribute significantly to the sustainable adaptation of European forests [270]. In nutrient-rich and gleyed habitats at mid- and higher altitudes, a slightly higher proportion of fir is expected due to its ameliorative and stabilizing properties [271]. However, in stands with a high proportion of fir, it is necessary to maintain its share through natural regeneration [8]. Therefore, adaptation measures (monitoring and management, silviculture practices, genetic selection, etc.), taking into account the variability in climatic conditions, must be adopted to mitigate the negative impacts of climate fluctuations [189,272–276].

Living organisms can choose between two strategies for survival in a rapidly changing environment: migration to more suitable habitats or local persistence through adaptation [277]. The third option is extinction. These potential strategies apply to trees in forest ecosystems that have limited migratory capabilities, although significant climate change makes them very relevant [278]. Tree populations begin to migrate when existing habitat conditions are unsuitable for survival [279]. Our knowledge of tree migration rates under global climate change is still limited. However, the differences between the observed migration rates and tree habitat displacement rates under ongoing climate change are considerable [280]. Among others, Feurdean et al. [281,282] estimated the maximum migration rate for the early successional stages of pioneer trees, such as birch, willow, or Scots pine, to be 225–540 m yr^{-1}, while for climax trees, such as silver fir and European beech, it ranges between 115 and 385 m yr^{-1} depending on the mode of seed dispersal by wind or animals. Numerous climate change scenarios predict a horizontal spread of up to several kilometers and a vertical spread of up to tens of meters per year [283]. For these reasons, tree migration is significantly slower than the rate of forest habitat change [284]. Moreover, the significant forest fragmentation of much of Europe has substantially reduced the rate of tree migration [285].

6. Seed Production and Nursery Management in the Context of Climate Change

Climate change is altering worldwide forests by influencing tree mortality, yet regeneration is pivotal in shaping the forthcoming tree generation and will dictate the configuration and makeup of future stands. Regeneration hinges not only on average seed production, but also on the yearly fluctuations and synchronization among plants in seed production, a phenomenon recognized as mast seeding [286]. In the case of fir, fertility occurs at 25–35 years on isolated trees and at 60–70 years in a dense forest stand [287,288]. Depending on latitude and altitude, fir trees flower from May to mid-July. Seed years occur at two-year intervals at lower altitudes, while at higher altitudes, they occur every 3–5 years [289,290]. The differences in fir fertility of cones in Romania reached up to 11.2 times when comparing good mass years to poor years [291]. The mean dispersal distances of seeds from trees ranged from 9.9 m in pure fir stands to 21.5 m in mixed forest in Spain [292].

The cones mature from September to October. They grow on the upper third of the crown, from where, after disintegration, the seeds are released by May of the following year [293]. Therefore, the best time to harvest cones is in September, ideally just before they fully ripen, while the cones are still intact [294–297]. At this time, the cones contain 30%–70% water [294,298] and the seeds contain about 40% water [299]. The harvesting period depends on the altitude and the amount of precipitation in a given year. The cones can be harvested as early as mid-August and at higher altitudes as late as October [289,300]. The harvesting period is closely related to the cone-to-seed ratio and the germination capacity of the seed. The later the harvest, the higher the cone-to-seed ratio and germination. A recurrent level of 14% has been reported for fir cones [301,302]. Fir seeds should be collected at morphological (hard) maturity, which precedes physiological maturity, when the seeds can germinate [298]. Fir cones are usually collected manually by picking from standing or felled trees [303] or from seed orchards established for this purpose [291]. Using Czechia as an example, the expanding production of silver fir seed material points to rising demand for fir seed material in the context of an increased need for seedlings for the reforestation of large clearings following the 2017–2019 bark beetle calamity ([67]; Table 3).

Table 3. Production of seed material, estimated weight of seed (in kg) (cone-to-seed ratio of 10%), and average seedling yield according to the standard of the silver fir quantity in Czechia in 2010–2022 [10].

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
Production (thous. kg)	42.1	59.0	30.5	95.3	7.7	48.6	19.5	15.2	79.0	5.9	115.7	42.7	134.5
Seed amount (thous. kg)	4.2	5.9	3.1	9.5	0.8	4.9	1.9	1.5	7.9	0.6	11.6	4.3	13.4
Seedling numbers (mil. pcs)	12.6	17.7	9.2	28.6	2.3	14.6	5.8	4.6	23.7	1.8	34.7	12.8	40.3

In Czechia, the share of artificial regeneration converted to hectares ranged from 79.8 to 83.6% for 2010–2022. The seedling numbers in Table 3 show that fir's reproductive material can be used for the regeneration of approximately 5000 ha per year according to the minimum numbers during afforestation determined by law. The annual artificial regeneration of fir in Czechia ranges from 872 to 1635 ha per year. These figures show a substantial overproduction and the supply of other EU member states with silver fir reproductive material. The seed productivity of stands under ongoing global climate change is highly variable across various locations in Czechia. The need for collecting high-quality reproduction material is constantly increasing [10]. In Central Europe, interannual variations in the population-level seed production of fir increased during the past half-century. However, the population-level temporal autocorrelation in fir seed production became more negative during the last decades in the context of climate change [304]. Seed quality is influenced by the forest altitudinal zone, which reflects the amount of precipitation and air temperature during the growing season. The highest seed quality in Czechia was recorded in forest altitudinal zones 2 and 3 (200–500 m a.s.l.), where water-affected habitats suitable for fir are often found [305]. The germination of fir seeds, which depends on provenance and pre-sowing preparation [306], is generally low, around 40% [307,308], and on the southern border of the distribution range, it is even lower, reaching only ca. 28% [309]. Provenances from Calabria in Italy, for example, performed very well and should be the first choice of origin for future planting because of the deleterious effects of climate change in Britain [310]. The Carpathian provenances from Rogów were evaluated according to the index of cultivation and breeding as very good in Poland [311]. Fir exhibited greater resistance to heat stress for the provenance cultivated in the warmer sites [41].

Bezděčková and Řezníčková [306] found that fir seeds stratified for 3 to 4 weeks at 3 °C germinated better at an alternating temperature of 20/30 °C than at a constant 20 °C. The long-term storage of fir seeds is accomplished by gradually reducing the water content in the seeds to 9%–11% and storing them at −8 to −15 °C in cooling boxes [302]. Seedlings are generally grown on substrates sowings with a specific pH (4.2–6.0), favoring soil-based substrates for bare-root seedlings and peat-based substrates for containerized ones [292,293,312]. Inoculation with ectomycorrhizal fungi, such as *Lactarius* spp., improves seedling quality and survival [294–296]. Sowing on mineral soils is usually performed in autumn to benefit from natural seed stratification, although artificial stratification in the spring at 3–5 °C for 21 days is essential to avoid spring frosts [281,282,297]. Fir seedlings need constant moisture, adequate shading, and are susceptible to frost damage, but grow to 5 cm in the first year and 8–25 cm in the second year [280,298,299].

In nurseries, bare-root seedlings are usually grown in shaded conditions for two to three years to promote growth and vigor [299,300]. Seedlings are usually collected manually or mechanically in the spring, with precautions to minimize root hair damage [301,302]. Root system reductions are performed to prevent growth deformities after replanting [302].

It is essential to conduct health inspections related to pests prior to transplanting, especially for seedlings that have been stored [303–305]. After collection, roots should be immediately protected and possibly treated with anti-desiccants to improve seedling survival [303,307]. The standard growing period for bare-root seedlings is up to seven years, with innovative methods using air cushions to expedite growth [308,309]. Proper handling and protection from weather conditions from nursery to planting are critical to prevent damage and ensure the survival of transplanted seedlings [310,311,313].

7. Close-to-Nature Silvicultural Systems and Climate Change

The basic principle of close-to-nature forestry, defined as the integration of different silvicultural systems, such as selection, irregular shelterwood, and free-style silviculture, each adapted to the specific conditions and goals of a particular site, is the continuous and gradual improvement of forest stands and sites, promoting a holistic view of forest ecosystems [314]. The study by Čater et al. [315] deepened our understanding of optimizing silvicultural systems for light conditions, essential for the growth and regeneration of tree species, such as silver fir and European beech. It found significant variations in the assimilation rates of beech and fir under varying light intensities in the Carpathian and Dinaric Mountains, indicating that each tree species exhibits distinct growth responses to available light [315,316].

Recent research by Adamič et al. [317] underscores the varying responses of silver fir to climate factors across different regions of the Carpathian Massive. This study revealed that the regeneration efforts may significantly depend on local climatic conditions, particularly precipitation and air temperature patterns. These findings suggest that site-specific climate considerations are crucial in planning silvicultural practices for fir, especially under the impacts of climate change [317]. In addition to the climate, the most crucial factors for fir regeneration, its survival for advanced growth, and further development are suitable habitat, light, soil, and air humidity. For the light requirements of fir, Jaworski [313] stated that seedlings emerge at light intensities of 1%–5% of maximum light. They require at least 5% of maximum light to survive until the following year. Up to the age of 15, the optimum conditions for fir are 15%–25% of maximum light. In the shade, growth is suspended, and saplings tend to form a flat crown [318]. Its emergence in the third year of life is an indicator of adequate light conditions of regenerating stands. For the next 10 to 20 years, the height growth of fir remains relatively low. When a height of about 50 to 80 cm is reached, illumination should be increased by the slow, gradual opening of the parent stand, initiating the height increment and following close-to-nature forestry principles. The transition to full release must be slow and smooth [319,320]. The critical consequences of changes in the growth rhythm of trees in Saxony were addressed by Meyer [127], who searched for the causes of fir dieback at the northern limit of its distribution. Informed by numerous analyses of fir trunks with normal crowns and growth dependencies based on Backman's function, Meyer derived the course of a "normal development line" [321]. He did the same for diseased and poorly growing fir trees. From the developmental line of healthy and diseased trees, he concluded that the development of all healthy trees was slower in their early years than that of diseased trees with deformed crowns. This implies that fir trees in the studied same-aged stands did not experience a period of suppressed growth in their early years. Too rapidly releasing growth and even stimulating seedling growth in the nursery alters the growth course of fir trees in the early years of development [56,322]. This presumably sets a specific growth rhythm for fir trees, whereby, as a shade tree, they respond to altered conditions. It is possible that, in this way, a climax tree can become a pioneer tree, i.e., with an altered growth rhythm in its early years and early maturation, but also with premature senescence and a lower final wood mass. An abrupt change in the light regime can cause reduced resistance, increased susceptibility to diseases, and a likely change in hereditary characteristics [321].

Fir can tolerate long periods of suppression without weakening their vital energy under natural conditions. However, firs that evolved in clear-cut forests for several generations did not experience long-term shelter from the parent stand, i.e., they changed their nature and required increased illumination from the beginning of their growth. If they are suddenly exposed to the shade of the shelterwood for a longer period, they fail to adapt and become critically weakened [116]. Annual ring analyses indicate that withering firs with dried-out crowns and a more pronounced decline in recent increments generally showed significantly higher diameter increments in their youth than relatively healthier firs with less weathered crowns in the same stand [323]. This implies a greater threat to fir trees that were released more rapidly in the seedling or sapling stages than those that were gradually thinned and experienced slower development.

Fir's requirements for the other component of radiation—heat—must be considered in close connection with light. From this point of view, fir is a relatively demanding tree species, especially when compared with spruce [116]. Because fir assimilates well in the shade, it also requires a reasonable moisture regime, as it transpires more and has a higher demand for CO_2 and water. Higher transpiration is predominantly characteristic of self-seeding firs. They transpire more than older trees [324,325]. Therefore, their regeneration and quality growth depend not only on light, but also on the soil and air humidity, and—above all—sufficient precipitation during the growing season of at least 350 to 400 mm [319]. Firs are susceptible to short-term droughts, severe winters, late frosts, and air currents [326,327]. Therefore, fir can be considered one of the most sensitive and demanding coniferous tree species because, in addition to the already mentioned requirements for light, moisture, and heat, it needs deep, nutrient-rich, loose soils with sufficient water in the upper soil layers for successful growth, preferably around springs in flat terrain, on slopes with water-holding soil, and generally on sites influenced by water [328,329].

Regarding silvicultural practices, fir is not suitable for the clear-cutting management method with artificial regeneration (due to specific light requirements, soil condition preferences, limited regeneration capacity, and competition with other tree species), which was widespread in Central Europe in the past [86,118,330–332]. Contrarily, shelterwood, selection, or even border (group) management methods are suitable [4,7,205,333] or as underplanting under pioneer tree species in the restoration of salvage clearings [334]. The recommended management of silver fir forests involves either single-tree selection systems or an irregular shelterwood method, with a regeneration phase lasting between 20 and 40 years [335,336].

From the perspective of future forest management principles, it is therefore essential to know the forest types that will be most suitable in terms of their species, age, and spatial composition under future climatic conditions [123,231,337]. Determining this is particularly challenging given the increasing pressure of rapid climate change [338].

8. Conclusions

Silver fir has the potential to play a crucial role in the future composition of Central European forests, particularly due to its relative resistance to abiotic and biotic factors. Its adaptability and shade-tolerant nature enable it to fulfill both productive and non-productive functions in mountainous forests and water-influenced habitats at lower altitudes. Adaptive management, which supports the establishment of mixed stands with silver fir, is essential for enhancing the stability and biodiversity of these ecosystems. The use of small-scale clear-cutting and selection-cutting methods that mimic natural processes is key to promoting structural differentiation within forest stands. Additionally, addressing high game densities is vital to ensure successful natural regeneration. Research indicates that silver fir is less competitive in areas undergoing rapid and extensive changes, thus recommending selective cutting or irregular shelterwood systems for better adaptation.

Given the anticipated climate changes, including extreme weather events such as storms, droughts, frosts, and increasing average temperatures, the distribution of silver fir is expected to shift to higher elevations and northwards. It is essential to actively manage the genetic pool of silver fir, considering the transfer of highly variable and vital populations from regions like the Carpathians to Central Europe. This genetic management is crucial for mitigating the negative effects of climate change and ensuring the species' survival.

The conservation of silver fir requires a holistic approach that integrates active forestry and wildlife management. This includes implementing strategies to cope with climate change, such as increasing species and structural diversity, maintaining and enhancing genetic variation within tree species, and increasing the resistance of individual trees to biotic and abiotic stress. Shorter cutting cycles and a lower intensity per cut, focusing on silver fir trees of various sizes and ages, are suggested under warmer climate conditions.

The successful conservation and regeneration of silver fir will depend on a combination of adaptive silvicultural practices, genetic management, and effective wildlife control measures. By adopting these strategies, forest managers can enhance the resilience of forest ecosystems, ensuring that silver fir continues to thrive in the face of ongoing environmental changes.

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