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Review

The Potential of European Beech (*Fagus sylvatica* L.) in the Hemiboreal Baltic Region: A Review

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Abstract: As European forests face increasing threats from climate change and disturbances, diversifying tree species can be a crucial strategy to safeguard their ecological functions and climate mitigation potential. European beech is a valuable tree species with a wide distribution across Central and Western Europe. While the current natural distribution of European beech does not extend to the Baltic states, climate change models indicate a potential northward range expansion. This raises the intriguing possibility of introducing beech to Baltic forests as a climate adaptation strategy. Beech's ability to adapt to changing climate conditions, coupled with its potential to enhance biodiversity and provide high-quality timber, makes it an attractive option for forest managers. However, successful establishment and growth of beech in the Baltic region will depend on various factors, including competition with native species, soil conditions, and microclimate. To fully assess the potential benefits and risks of beech introduction, further research is needed to understand its ecological interactions with local species and its response to specific site conditions. By carefully considering these factors, forest managers can develop effective strategies to promote beech's establishment and growth, ultimately contributing to the resilience and sustainability of Baltic forests in the face of climate change.

Keywords: forest resilience; forest adaptation; non-native species; forest regeneration; climate change; species range shifts

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1. Introduction

Despite human efforts in recent decades to mitigate anthropogenically induced global warming, it is evident that fundamental and rapid climate change is an unavoidable future [1]. Forest ecosystems are particularly vulnerable to climate change because of limited adaptation capacity due to extended life longevity of trees [2]. Climatic disruptions as raised temperatures, alteration of precipitation regime, increased frequency of extremal abiotic disturbances (storms, prolonged droughts and fires) are associated with consequent pest and disease outbreaks [3,4].

It is clear that European forests will experience notable transformations in this century [5]. Projections indicate a reduction in the distribution of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) H.Karst.). Conversely, broadleaf species such as English oak (*Quercus robur* L.) and European beech (*Fagus sylvatica* L.) are foreseen to extend their range northward [6].

Enhancing tree species diversity may help mitigate the impact of increasing disturbance regimes on ecosystem functionality and strengthen forests' contribution to climate change mitigation [7]. Public perception of non-native species is generally negative due to concerns about threats to local ecosystems and their potential invasiveness [8]. However, the careful inclusion of various tested non-native tree species in future forest management plans shows significant potential for climate change adaptation and mitigation [9].

The European beech (*Fagus sylvatica* L.; termed ''beech'' in the following) is widely distributed in Central and Western Europe. The ecological range of beech forests is extensive, encompassing a diverse array of soil conditions and altitudes [10]. Featuring approximately 250 recognized applications for its wood, the beech stands out as one of the most important and versatile trees in

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Europe [11]. The natural distribution range in north-eastern Europe reaches South Sweden (Skane, Blekinge, Halland und Småland) and lowlands of Central and Eastern Poland not reaching borders of Baltic states [12]. However, the projections of the translocation of climatic favorability for beech made by [13] show a general north-eastern shift covering the eastern shore of the Baltic sea by the end of this century. Beech has been successfully introduced in Lithuania and Latvia by German foresters already in nineteenth century [14–16] demonstrating not only good adaptation capability but also silvicultural perspectives [17–21]. This suggests that beech could be a valuable addition to the Baltic Sea region's forests. It could not only increase forest resilience and biodiversity but also provide a sustainable source of high-quality timber for the wood processing industry.

This literature review aims to assess the potential for expanding European beech's range into hemiboreal Baltic forests, explore factors influencing its natural migration by examining its historical postglacial expansion, and evaluate the potential impacts of its introduction on enhancing local forest adaptation and ecosystem services. The key scientific questions addressed include: Can the introduction of this species into the hemiboreal forests of the Baltic region enhance the resilience of forest stands in the face of climate change and would the beech be a desirable tree species from a forestry perspective? Answering these questions is crucial for determining whether foresters in the Baltic region should take proactive steps to promote the introduction of the beech and for identifying emerging strategies to facilitate its successful regeneration and adaptation to local conditions.

2. Spread of European Beach Population and Its Constraining Factors

Palaeoecological investigations of post-glacial spread of beech populations suggests that the area covered by this species expanded exponentially from the glacial refugia for a duration of over 10,000 years, experiencing a decline in population growth over the past three thousand years [22]. Three main gene pools are identified across the continent while post-glacial recolonization of Central and Northern Europe originated from Eastern Alps [23].

Considerable body of research are dedicated to understanding the factors behind the successful expansion of this species and the conditions that define the current range limits of beech. The spread of beech in northern Central Europe is linked to gradual climatic changes towards cooler and more humid summer conditions [24], however, in addition to climatic factors, sizable effects on the species' distribution have been exerted by human activities, for example - selective cutting, human-induced fires, and agriculture [25]. Humans in Europe since the Neolithic traditionally have used the fires to extend the grazing area facilitating the initial establishment of beech that took advantage of post-fire ecological succession [26].

Dry conditions during the vegetation season most likely is a factor limiting distribution of beech southwards [27] while north-eastern distribution margins cannot be explained with single macro-climatic factors [28]. Beach trees suffer from extremely low winter temperatures, which potentially limits the distribution of this species [29], however, the critical temperature for 50 % bud damage is very low -4o 0C [30]. Drought stress in combination with spring-frost is a combination most likely hampering beach range distribution northwards [31].

Pollen and charcoal data have been used by Bradshaw & Lindbladh [32] to study the regional spread of beach and Norway spruce in southern Scandinavia. The authors point out that unlike the spruce, whose distribution was largely determined by changes in suitable climatic conditions over time, the distribution of the beech is largely linked to human activities and the prevalence of forest fires. Despite late frosts posing a significant barrier to the northward expansion of beech [27], these resilient trees exhibit high phenotypic plasticity [28,33]. This allows beech populations to adapt and thrive in diverse local conditions.

Climate-growth relationship often are explored by the assessment of variation in tree ring width. Beech is highly suitable for dendroclimatology analysis due to its sensitivity to environmental factors [34,35]. Research examining the growth patterns of 36 beech stands across diverse climatic and environmental settings reveals that late frosts and prolonged cool periods during vegetation phases significantly hinder radial growth [36]. Beech is a sensitive species to the climatic conditions of the

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current growing season. Its growth is positively correlated with precipitation from May to July and negatively correlated with maximum temperatures in June and July [37].

Tree populations growing close to the distribution limits are more sensitive to climatic factors [38,39] thus, from our perspective, it is particularly important to assess the growth sensitivity of beech in relation to climatic and environmental factors in regions close to the northern border of the species' range or in stands established outside this range. Study in Baltics discovered sensitivity of beech radial growth to air temperature in June-August and precipitation amount in the first half of vegetation period and water deficit in summer [40–42] while similar study of southern Sweden beach populations discovered relationships between tree growth and previous summer (July and August) temperatures [43].

Concerns about the impact of climate change on forest vitality in Europe have prompted a series of studies that have modeled changes in forest vegetation zones and the ranges of individual tree species under various change scenarios. Given the great economic importance of beech on the continent, this species has received particular attention in this context. A prominent conclusion suggests that beech, influenced by climate change, is anticipated to contract its range in southern Europe due to escalating water deficits and increased drought risks, conversely, its distribution is projected to expand in high elevation areas, with a notable northward range expansion where growth had previously been limited by low temperatures [44,45]. Beech trees in Central Europe may struggle to survive and grow in low-lying areas as the climate becomes hotter and drier. Conversely, they might flourish in mountainous regions with rising temperatures [36,46]. According to projections substantial area of current beech stands could be outside their bioclimatic niche by 2025 [47].

In summary, the post-glacial spread of beech populations has been influenced by a complex interplay of climatic changes and human activities over millennia. Current range limits are shaped by a combination of drought stress, late frosts, and extreme winter temperatures. The species' sensitivity to environmental factors, particularly in regions near its distribution limits, underscores the importance of ongoing research to understand its growth responses and adaptability in the face of climatic variability.

3. The Future of the Beech Under Climate Change

Enhancement of the forest adaptiveness to the projected impacts of climate change requires complex knowledge on the response of the individual tree species and forest ecosystems to the atmospheric alterations [48,49]. As a dominant species in many temperate forests, beech plays a crucial role in the adaptation of European forests to future climate conditions. While many European countries are characterized by vast expanses of non-site adapted coniferous forests [50], temperate forests naturally should comprise approximately three-quarters deciduous trees, with beech being a key component [10]. In light of recent climate-driven devastation in Norway spruce forests, compelled foresters in many European countries to reevaluate their current forestry practices [51,52]. Replacing or mixing Norway spruce monocultures with more climate-resilient broadleaved species, particularly beech, and mixed forests is strongly recommended [53–57]. However, as evidence of declining vitality in European beech forests grows, concerns about the role of this species in securing the resilience of European forests have recently increased.

Beech, as the species struggles with increased drought, altered precipitation patterns, and late frosts [58–60]. The large leaf area and the fine root system makes beach very drought sensitive [61]. This species is more sensitive to water deficit than other temperate hardwoods [62]. While droughts pose a greater threat to beech growth at the edges of its range with sub-Mediterranean climates [44,63], emerging evidence suggests the vitality of beech is also at risk in its core habitat and at lower elevations [64]. Recently warnings about the vulnerability of beech to climate warming and drought have been received from northern and central Germany [65,66].

Latest research confirm that in the past few decades, drought and precipitation have become more significant limiting factors for the radial growth of European beech, even near its northern distribution limits [43]. Therefore, caution is advised when replacing Norway spruce and Scots pine with beech in Central European forests due to beech's sensitivity to climate extremes such as late frosts, droughts, and heatwaves [67–70].

Despite concerns about the vulnerability of European beech to changing climate conditions, there is optimism regarding the species' adaptability. The notable variability in stomatal and leaf traits within European beech populations—shaped by the interaction of adaptation, acclimation, and plant memory—suggests a strong potential for the species to acclimate to future climate changes [71]. Adaptation to local environments can occur within just a few generations [42,45]. Forest management methods also influence the resilience of this species in the context of climate change. Admixing drought-tolerant species can help mitigate the risk of drought damage to beech stands [72]. Additionally, less intensive forestry practices, which reduce exposure of tree trunks to intense solar radiation, can lower the risk of fungal diseases and enhance drought resilience [73].

The variability in drought and cold adaptation among European beech populations presents opportunities to identify those with enhanced traits. For instance, marginal populations from southern regions and high elevations exhibit greater tolerance to water stress [74,75]. Additionally, adaptive differences in chilling and forcing requirements for budburst between provenances have been observed [45]. Use of drought-adapted provenances and naturally regenerated local populations can reduce the vulnerability of Central European beech stands to drought [76]. Assisted gene flow (AGF) can enhance the resilience of forest trees to climate extremes by promoting genetic diversity and improving adaptation to changing environmental conditions [77]. AGF can aid populations in adapting to climate change by introducing beneficial genetic material. This is particularly valuable for populations that are struggling to survive in rapidly changing climates, such as those found in marginal habitats [78,79].

Strong competitive nature of beech is likely to secure its presence as an admixture species across much of its current range. Still, adjusting tree species composition will be crucial for enhancing forest resilience and improving forests' ability to adapt to climate change requires a deeper understanding of forest structural diversity and multifunctionality [80].

4. Ecosystem Services of Beach Forest

European beech forests play a vital role in environmental sustainability and human well-being by providing a wealth of essential ecosystem services. Due to lighter foliage, the greater brightness, and the varied shapes of the tree's beech forms pleasant stands for visitors, making forests desirable for recreation purposes [81]. Nowadays preserved primeval beech forests in many European countries are added to UNESCO's World Heritage List and protected not only for their ecological significance but also for their cultural and historical importance [82,83]. Constant efforts are made to optimize the management of these forests and to find the most effective strategies for enhancing their biodiversity and socioeconomic benefits [84].

For millennia, charcoal production was a cornerstone of the human economy, serving as the primary source of energy before the widespread adoption of coal [85]. In Europe, this reliance on charcoal led to the large-scale use of beech wood, a practice that significantly impacted the continent's landscape. Large areas of beech woodlands were managed as coppice for the production of firewood, charcoal and potash [86]. Beech forests, once primeval, were degraded by charcoal production, with lasting consequences for forest composition [87,88]. The increasing dominance of coal as a heating source led to a decline in the demand for beech wood, prompting a shift from beech forests to spruce plantations [89].

Although also in modern times most of the harvested European beech wood is used for energy production [90], it can also be employed in applications with higher added value. The fine grain and uniform texture of beech timber make it easy to machine and finish, resulting in high-quality surfaces for furniture and cabinetry [91,92], however, the quality of beech row material can be very variable therefore, a suitable grading system is essential to reduce waste and ensure more efficient use of the wood resource [93].

Coniferous timber is dominating in European roundwood industry; however, the superior wood properties of beech timber makes it as desirable material for production of structural engineered wood products like cross-laminated timber [94]. Beech plywood exhibits high bending strength, modulus of elasticity, and shear strength, making it suitable for various structural applications demonstrating superior performance compared to panels made from other hardwoods (alders) [95]. Beech wood presents a promising feedstock for biorefineries; however, several challenges have to be addressed to make the process chain cost-effective [96]. Beech wood's remarkable fiber properties and inherent light color make it an exceptional choice for producing high-quality paper and absorbent products [97,98].

While timber harvesting is a significant source of economic benefit from European beech forests, it's crucial to consider the broader range of ecosystem services these forests provide when evaluating management scenarios [99]. European beech forests are vital for soil and water quality, contributing to soil fertility, water balance, and nutrient cycling. They are enhancing nutrient cycling an organic carbon storage, however, also contributing to soil acidification [100]. Increase of tree species diversity is beech forests by mixture of other broadleaved species is advised to intensify the rates of N cycling in the stand and within the soil [101]. The bulk density and decomposition index of organic matter in beech forests significantly affect the water storage capacity of forest soils [102]. Beech forests can store substantial amounts of water in the soil maintaining water balance and supporting evapotranspiration processes effectively [103].

Beech forests in Europe have a significant climate mitigation effect and considerable carbon sequestration potential. Mature beech forests may sequester up to 4 tC ha^{-1} $year^{-1}$ [99]. A German study found that forest management practices can enhance cumulative biomass production in beech forests by as much as 19%, thereby improving carbon sequestration [104].

Beech forests generally have lower tree species richness compared to mixed or oak forests because beech trees can dominate the canopy and outcompete other tree species due to their dense foliage and shade tolerance [86]. Budde et al., [105] found that beech admixture decreases plant species diversity. A study in Lithuania asserted that the secondary layer of beech trees negatively affects understory species' richness and abundance -most likely due to reduced light transmission and the poor physical properties of the forest floor litter [106]. However, this dense canopy creates a unique microhabitat that supports a variety of understory plants, fungi, and microorganisms, enhancing biodiversity at other trophic levels [107]. A study in Germany revealed that faunistic species richness in European beech forests is much higher than previously assumed [108]. Forest management practices can play a critical role in maintaining and enhancing this biodiversity [109].

Beech nuts, or "mast," play a crucial role in forest ecosystems as a key food source for numerous wildlife species. They are energy rich and vital food source for a variety of forest animals including large mammals like wild boars and bears [110,111], rodents and birds [112]. The abundance of beech nuts can influence population dynamics, as a plentiful mast year leads to increased reproduction and survival rates for species like rodents and birds. In turn, this affects predator populations and overall forest biodiversity [113].

5. Productivity and Management Practices

Productivity of this species greatly varies according to site types. Soils with good aeration and drainage, along with a pH level ranging from slightly acidic to neutral, are optimal for beech forest growth [114]. Beech forests in the unmanaged, old-growth stands exhibit exceptionally high standing volume, demonstrating the species' ecological stability over time [115]. Reported standing volume of old-growth beech forests in northwestern Carpathians ranged from 452 to 744 m3ha-1 [116], 525 to 1237 m3ha-1 in Transcarpathian Ukraine [117] and up to 1195 m ha-3 in south Carpatian region [114]. Beech exhibits its greatest productivity in mountainous regions. In Serbia, for example, the highest yields from beech stands are found at elevations between 400 and 1200 meters above sea level [118].

The combination of beech and conifer species often results in enhanced growth rates for beech, likely attributed to reduced intra-specific competition. Studies of mixed beech stands with conifers, including Scots pine [119], Douglas fir [120], Norway spruce [121], and silver fir [122] reveal synergistic benefits in terms of yield, structural complexity, and resilience.

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The traditional silviculture system used in European beech dominated forests is the shelterwood system [118,123,124]. Typical rotation period of beech in Central Europe is from 100 to 120 years [125], however, reducing the rotation period of beech forests is suggested as a strategy to mitigate economic risks posed by climate change [126]. Beech is not typically classified as a fast-growing tree species. Similar to oak, beech demonstrates a steady growth rate throughout its rotation period. The periodic annual volume increment (PAI) for beech generally peaks between 70 to 90 years of age [127,128], reflecting its gradual and consistent growth pattern.

Historically, beech forests were extensively managed through coppicing for firewood production. While this practice has declined due to the availability of more convenient fuel sources, some beech stands continue to be managed in this way, with rotation period 16 to 24 years [129].

Beech forests are commonly regenerated using natural methods such as group selection cutting [130,131], and the shelterwood system [132,133]. This species is well-suited to these approaches due to its tolerance of shade [134,135], abundant seed production during mast years [136], and efficient seed dispersal facilitated by rodents and birds [112,137]. However, several factors can impede successful natural regeneration. Irregular seed production [138], damage to seeds by pests and animals [139,140] browsing of seedlings [141,142], drought [143,144], frost damages [145,146], nutrient deficiencies [147,148] or compaction of soils [149] and unfavorable site conditions, such as temporary waterlogging [150], can all significantly hinder beech regeneration. Although the beech is a very shade-tolerant tree species, adequate light is still vital for the successful growth and development of naturally regenerated seedlings [151,152].

Despite higher establishment costs, artificial regeneration of beech is occasionally employed, particularly when natural regeneration is hindered by site conditions or other factors. The growth of beech seedlings in open areas is negatively affected by adverse environmental factors such as drought [153] and frost [154,155], as well as competition from herbaceous plants [156]. Therefore, beech seedlings are often planted either under the canopy of trees [21,157,158] or with the use of other tree species as nurse plants [159]. Vegetation control during the planting of beech under a canopy is often unnecessary due to beech's superior shade tolerance compared to competing vegetation but is essential in open sites to prevent rodent depredation [160].

The popularity of different planting stock types of beech varies across countries, and the technologies used in seedlings production are largely influenced by the forest nurseries production traditions previously used in a particular country. In Slovakia the primary planting material for beech is two- or three-year-old bare-root seedlings while containerized beech seedlings are a less frequent choice [161]. The Czech Republic has a long-standing tradition of using containerized beech seedlings in forestry, appreciating the advantages of producing this planting material, which reduces the time needed to grow seedlings and allows for a flexible response to changing demand [162]. Wildlings and two-years old bare-root seedlings are commonly used in Austria [53]. Danish research has shown that bare-root and containerized beech seedlings of different sizes perform equally well in forest restoration [163].

The planting of European beech is a more versatile and reliable regeneration technique [164], but direct sowing can also be a successful and, notably, cost-efficient method [165]. Sufficient soil moisture, proper site preparation, and rodent control are critical factors for successful seedling emergence and establishment in seeded areas [166–168].

6. Modeling the Future Distribution of Beech Along the East Baltic Coast

The northward shift of beech tree range is well-supported by bioclimatic models, driven primarily by climate change, particularly rising temperatures and changes in precipitation. Studies in Lithuania, north of the current beech distribution, suggest that the local climate may be suitable for several Central European deciduous tree species, including beech, under modeled climate change scenarios [169]. Beech is expected to exhibit an increased range in southern Sweden, owing to its superior capacity to withstand the challenges associated with climate change in comparison to the boreal spruce [170]. A study utilizing data from 21 climate models predicts a northward shift in climatic suitability for beech. This projection allows for the mapping of potential beech distribution

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across the Baltic countries, southern Sweden, Norway, and Finland up to the year 2010 [13]. A similar future expansion of beech distribution was shown in the study by Dyderski et al.,[171].

Despite the consensus among many studies regarding northward shift of the species, predictions of future beech distributions under climate change should be interpreted carefully, given incomplete understanding of the environmental and biological constraints that have shaped plant distributions during the Holocene [27]. Although global warming extends the growing season and thus improves survival rates for many tree species, its impact on the distribution of various species remains uncertain and challenging to forecast. Climate change is projected to lead to higher average temperatures and longer growing seasons, however, the risk of extreme weather events is expected to increase [2]. On one hand, stand-scale disturbances caused by storms and other large events can facilitate the spread of beech at its northern distribution limits [172]. However, as previously discussed, the success of beech regeneration can be significantly reduced by late-spring frosts. Gömöry & Paule [173] demonstrated a positive relationship between beech growth and growing season length, they also highlighted a strong inverse relationship between the timing of bud burst and the risk of frost damage to beech. Since risk of late-spring frost is going to increase with climate change [174,175], this factor could impede the northward expansion of beech, even though other meteorological conditions are becoming more favorable.

In addition to climatic factors, the natural expansion of tree species is significantly influenced by competition with other species for space and resources and limited by their rate of dispersal [24]. Competition can significantly slow down the expansion of the beech's range. Meier et al., [176] demonstrated that biotic factors, such as the presence of potential competitors like Norway spruce, Scots pine, and pedunculate oak, offer a better explanation for the distribution patterns of beech than climate alone.

The current distribution ranges of European tree species are shaped not only by climatic constraints but also by historical factors, as noted by Svenning & Skov [177]. These historical legacies should also be considered when projecting future distribution shifts of beech into the Baltic Sea region. While Norway spruce plantation forests dominates in southern Scandinavia [178], naturally regenerated pioneer broadleaved stands constitute a substantial portion of forests in the Baltic countries [179]. Higher natural regeneration rates in Baltic forests can accelerate beech's spread, provided that suitable seed sources are available. It is worth noting that the region's high proportion of organic, gleyic, and waterlogged soils [180] may limit beech expansion, hindering its competitive response, as these soil types are generally unfavorable for beech growth [28].

The natural expansion of beech, a zoochorous tree species [181] is notably slow, estimated at less than 100 meters per year [172,182]. This rate is insufficient to colonize new, suitable habitats in the face of rapid climate change [183]. Well-adapted, mature beech stands can be found in the western and southwestern regions of Lithuania and Latvia [20,184]. Despite their fragmented distribution, these stands can serve as core populations for beech's broader-scale spread. However, the implementation of a well-considered assisted migration strategy might be essential to bolster the species' natural regeneration dynamics, as discussed by Bolte et al., [170].

7. Conclusions

The hemiboreal forest zone on the eastern coast of the Baltic Sea is characterized by relatively high species diversity and a comparatively high proportion of deciduous trees. Local forestry has traditionally relied on natural forest regeneration, which has allowed for the creation of diverse forest stands. However, globalization and the unpredictable impact of climate change may introduce unforeseen risks to forest regeneration and pose threats to native tree species. An example is the ash dieback experienced in the past decade, caused by a pathogenic fungus introduced from Asia [185], and concerns about the potentially dramatic effects on birch forests due to the European invasion of the bronze birch borer [186], which demands considering various scenarios to enhance forest resilience.

Studies on the adaptation of various introduced tree species are necessary to provide additional alternatives in changing environmental conditions. The European beech is a valuable tree species that could offer new opportunities for forestry in the hemiboreal forest zone of the Baltic Sea region, especially considering its excellent natural regeneration abilities and suitability for use in continuous cover forestry practices. Historical genetic studies of European beech introduced in the Baltic Sea region in Lithuania indicate relatively high genetic diversity and the suitability of various Western European populations for cultivation in the hemiboreal zone of the Baltic Sea region [187]. Trials evaluating the adaptation capabilities of different European beech populations in the Baltic States should continue not only to improve genetic diversity but also to select the highest quality reproductive material, as the quality of trees in historical beech plantations is often poor [19].

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