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SCOTS PINE (*PINUS SYLVESTRIS* L.) REGENERATION IN LATVIA: PATTERNS, CHALLENGES, AND FUTURE PROSPECTS – A REVIEW

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Scots pine (*Pinus sylvestris* L.) is one of the most widespread and economically significant conifer species in Europe, playing a critical role in the structure and function of forest ecosystems, including those in Latvia. This review synthesizes current knowledge on the regeneration dynamics of Scots pine in Latvia, identifies key ecological and silvicultural challenges, and outlines prospects for its sustainable management in the context of ongoing environmental change. Artificial regeneration remains the dominant method in forests managed for timber in Baltic States. However, successful both artificial and natural regeneration is increasingly constrained by factors such as climate change, competition from broadleaved species, herbivory pressure, and evolving forest management practices.
Maintaining genetic diversity - especially within marginal and isolated populations – is critical for Scots pine future resilience. Climate change adds complexity by altering seed production, germination, and seedling establishment, while anthropogenic pressures, such as land-use changes and intensive forestry, further threaten regeneration success. Improving regeneration outcomes requires integrating ecological and economic objectives. Adaptive silvicultural strategies, including site-specific thinning, shelter wood systems, and mixed-species planting, can support conifer species natural regeneration and enhance forest resilience. Conservation of genetic resources and attention to non-market ecosystem services - such as biodiversity and carbon sequestration - are also essential.
Scots pine is expected to remain one of the dominant species in Latvian forestry. However, its successful regeneration will depend on a multifaceted approach involving continued research, long-term monitoring, and climate-adaptive practices to ensure its sustainable management under changing environmental conditions.

Keywords: *forest establishment, planting, silviculture, threats*

INTRODUCTION

Scots pine (*Pinus sylvestris* L.) is the most widely distributed species within the *Pinus* genus globally. It occupies a broad elevation range, extending from sea level in the northernmost regions of its distribution to altitudes exceeding 2600 meters in the Caucasus (Mátyás et al., 2004). Across Europe, Scots pine forests currently cover more than 28 million hectares, accounting for over 20% of the continent's productive forest area (Durrant et al., 2016). Scots pine is a key component of boreal forests, yet it shows a remarkable ability to acclimate and adapt to diverse climatic regimes and soil conditions (Bose et al., 2024; Carlisle & Brown, 1968). Scots pine is among the most thoroughly studied tree species in Latvia and the broader Baltic region. In Latvia, forests occupy approximately half of the land area and represent the country's most significant natural resource (Bušs & Mangalis, 1971; Dreimanis, 2016). One-third (33%) of the forestland in hemiboreal Latvia is occupied by Scots pine-dominated stands (Done, Ķēniņa, et al., 2025), while in Lithuania it is around 42 % of whole forests stands (Vitas, 2022). In Finland, Poland, and Sweden, Scots pine is the prevailing species, covering more than half of the forested land (Krakau et al., 2013).

Climate change is expected to strongly alter pine distribution and growth dynamics already during 21st century, whereas annual temperature is going to increase, while precipitation amount will decrease (Brichta et al., 2024). It is projected to gradually shift species range northwards and to higher elevations. Consequently, Scots pine stands are likely to become increasingly fragmented and structurally uneven - current modelling studies project a pronounced latitudinal and altitudinal shift in Europe of suitable habitats for this species (Dyderski et al., 2018; García-López & Allué, 2010; Gül, 2025). Despite the previous Scots pine dominance, habitat assessments indicate that the area and ecological quality of Scots pine–dominated woodlands have declined over the past decades in Latvia. In the coming years Fennoscandia and the Baltic region are likely to benefit from increased growth and productivity as warmer temperatures extend the growing season and enhance photosynthetic efficiency (Matisons, Elferts, et al., 2021).

In Latvia, the extent of artificial regeneration of Scots pine has been declining due to ecological, economic, and policy-related factors. Pine is mainly adapted to dry, sandy soils, which occupy only a small share of the forest area, while Silver birch (*Betula pendula* Roth.) and Norway spruce (*Picea abies* L.) are better suited to more common site types. Birch and spruce also offer shorter rotations and higher market demand, making them more attractive for private owners. Moreover, forest owners often incur substantial losses from intensive ungulate damage to young pine forest, which increases the cost of establishing and further discourages planting. In addition, Scots pine often regenerates naturally on suitable sites, reducing the need for planting. Current forest policies and EU support schemes further promote mixed and diverse stands over monocultures, reinforcing the preference for birch and spruce in regeneration and limiting the role of artificially regenerated pine. Due to the recent rapid spread of the bark beetle (*Ips Typographus* L.) in the Baltic region, the interest in establishing Norway spruce mono-stands is gradually declining. Forest owners have become concerned about the species potential for productive growing under emerging disturbance pressures (Jian et al., 2025).

The ability of pine forests to cope with ongoing climate changes represents a key challenge for forest management in this region. Understanding how climate change influences pine growth is essential for anticipating its potential impacts on the long-term sustainability and productivity of Scots pine stands in hemi-boreal forests. The aim of this study is to identify the principal challenges affecting the growth and distribution of Scots pine in the hemiboreal region under climate change conditions. Furthermore, the study seeks to define priority directions for future research, with particular emphasis on improving Scots pine breeding and seed production, and on developing cost-efficient forest regeneration methods.

RESEARCH METHODS

The aim of this literature review was not to examine the full diversity of information sources available over time, but rather to provide a concise synthesis of existing knowledge on Scots pine regeneration and young tree growth in Latvia. In other words it is the overview of current knowledge in the field. Therefore, no formal categorization of sources was carried out. Instead, information sources were selected based on the relevance of their content to the scope of the review (Kysh, 2013).

Study material was collected using several open access bibliographic databases, including Scopus, Research Gate, and Google Scholar, which were chosen for their extensive coverage of scientific literature. An initial broad survey of publications was conducted, and final selections were limited to studies focusing on Scots pine regeneration methods in Latvia, along with international studies that examine Scots pine growth in other regions under the same or similar conditions. For literature research both "Pinus sylvestris" and "Scots pine" versions were used. Also combinations of following keywords were used "Scots pine and Latvia", "Scots pine and tree breeding", "Scots pine and regeneration", "Scots pine and climatic changes".

The review incorporated not only peer-reviewed literature but also selected grey literature, including thesis, methodological guidelines, and reports from scientific institutions, to ensure comprehensive coverage of region-specific forestry knowledge. All sources were published during the period from 1968 to 2025. In total, 85 sources were included in the final review. Of these, 57 were peer-reviewed scientific articles, 7 were books or book chapters, 11 were conference proceedings, and 10 were additional materials such as thesis, guidelines, institutional reports, and relevant webpages. Sources of information used both in Latvian and English language.

RESEARCH RESULTS AND DISCUSSION

For many centuries Scots pine played a crucial role in the economy of Latvia and the Baltic States, serving as a key resource for construction, shipbuilding, and it was widely used in rural households for fuel, tools, and housing materials. At present, Scots pine remains one of the most valuable tree species in local forestry, contributing significantly to the timber industry and exports. It is also essential for biodiversity, carbon sequestration, and recreational systems (Baumanis et al., 2014; Huuskonen S., Hakala S., Mäkinen H., Hynynen J., 2014; Köhl et al., 2020). The role of Scots pine varies across European countries, ranging from a pioneer species in plantations of degraded agricultural lands to a dominant element within native forest ecosystems. Despite ongoing environmental and management changes, Scots pine is expected to remain a key forest species in Europe in the near future (Girdziušas et al., 2021). The main challenge lies in developing management strategies that are both economically sustainable and capable of delivering the diverse non-market ecosystem services essential for sustainable forest management (Baumanis et al., 2014; Fréjaville et al., 2020; Mason & Alía, 2000).

Tree breeding programme

Scots pine stands established with genetically improved material can achieve 8-15% greater height growth and up to 27% higher stand volume increment, demonstrating the benefits of genetic enhancement on growth performance and overall productivity (Ahtikoski et al., 2012).

In northern Europe, Scots pine regeneration is largely based on planting with seed orchard material from breeding programs. Selection has mainly targeted productivity traits and frost hardiness in this region, with notable genetic gains already achieved (Jansson et al., 2017). Latvia State Forest research institute Silava (LSFRI Silava) is organisation that implements the tree breeding programmes in Latvia. Given the economic significance of Scots pine, breeding programmes have been carried out since the mid-20th century to enhance growth, wood quality, and resistance to biotic and abiotic stresses. The first-generation seed orchards (established in 1970's) were primarily established using plus trees selected from natural stands. Selection criteria included rapid growth, straight stems, and good health. Building on the results of the first-generation orchards, second-generation (since 2000's) seed orchards were established using tested families and clones, whose offspring had been evaluated in progeny trials. The expected outcomes include up to 20–25% higher growth rates and straighter, higher-quality stems (Gailis, 2021). Regional tree breeding initiatives are estimated to achieve genetic gains of up to 30% in growth, thereby improving profitability through increased production of high-quality timber (Zeltiņš et al., 2024). Looking forward, the future prognosis includes the creation of third-generation orchards with stricter selection criteria, genomic-assisted breeding, and international collaboration to ensure adaptation to various climate scenarios (Gailis, 2021). Under climate change, it is essential to study not only tree growth but also pest and disease dynamics, as both are expected to shift and influence forest sustainability. This perspective has only relatively recently been incorporated into tree breeding programs in Latvia (Neimane et al., 2018).

In Latvia, two provenance regions have been defined for the collection of Scots pine reproductive material: eastern and western. Genetic material sourced from the eastern region is suitable for forest regeneration and cultivation throughout Latvia, whereas material from the western region is only permitted for use within that region (Neimane et al., 2009). Berlin et al., (2016) findings emphasized that environmental conditions linked to geographic origin and planting site play a central role in determining the performance of transferred seed sources. Differences in site conditions were shown to strongly influence growth and survival outcomes, highlighting the importance of aligning seed origin with the environmental characteristics of the planting location.

The Linkevičius et al. (2024) study observed a shift in growth rankings over time, where populations initially identified as high performing in earlier stages did not maintain their advantage in later assessments. This highlights the importance of long-term evaluation when selecting genetic material, as early growth performance may not reliably indicate long-term productivity outcomes (Pasternak et al., 2024).

Natural regeneration and planting

For Scots pine, two principal silvicultural regeneration methods are distinguished: natural regeneration and artificial regeneration, which encompasses both direct seeding and planting.

In recent years, forest management in Latvia has relied heavily on artificial regeneration for Scots pine. According to the latest data, approximately 93% of all regenerated Scots pine areas were established through planting or sowing, while natural regeneration accounted for only a small proportion (Meža Nozare Skaitļos un Faktos 2025, 2025). Planted forest trees benefit from the advantages of genetic selection (Zeltiņš et al., 2024), while naturally regenerated trees may achieve faster growth by faster adaptation to the environment (Miezite et al., 2024). Planting represents the predominant method of forest regeneration in Latvia and throughout North Europe (Lula et al., 2025; Nilsson et al., 2010). This approach enables the targeted establishment of desired forest stands and facilitates the continuous enhancement of their quality, biological characteristics, and silvicultural attributes (Zhigunov et al., 2011). There are several types of planting material: bare-root seedlings and container-grown seedlings, each of which requires a specific planting method in forest soil. In Latvia, Scots pine regeneration most commonly uses container-grown seedlings, which are typically planted manually using a planting tube or shovel. In recent years, mechanized forest planting has also been successfully introduced. It is projected that in 2025, approximately 50 % of mechanized established stands in Latvia's state forests will be regenerated with Scots pine (Lazdina et al., 2019).

During the 20th century, direct seeding of Scots pine was a common regeneration method in Latvia. However, its application gradually declined as forest managers increasingly preferred artificial regeneration by planting. Previous studies have shown that on nutrient-poor and sandy soils, direct seeding can still ensure effective regeneration of pine stands (Laine et al., 2016; Židó et al., 2024).This silvicultural approach remains in use in other countries, including Estonia and Finland. In recent decades, seeding practices have been modernized through integration with soil preparation techniques, resulting in mechanized forest seeding. In this system, seed delivery mechanisms are mounted on soil preparation equipment, allowing for precise regulation of seed distribution (Hytönen et al., 2020; Židó et al., 2024). Although direct seeding is often more cost-efficient than planting, it entails higher risks, particularly with respect to seed germination, seedling establishment, and subsequent stand development (Liepiņš et al., 2010). At present, artificial regeneration by planting dominates both in state-owned and privately managed forests in Latvia. Mechanized seeding represents a promising alternative for the future, particularly under site conditions favourable for pine regeneration.

Natural regeneration is recognized as a complex ecological process influenced by a range of environmental factors, including litter thickness, the density and closure of the herbaceous layer, the methods and intensity of timber harvesting, and the condition of the parent stand (Lavnyy et al., 2022). Optimal regeneration for Scots pine tends to occur in areas characterized by sparse ground vegetation and low-stature plants, where competition is minimal (Dumins et al., 2025). Scots pine begins producing cones at the age of 20 to 30 years. Of all potential seeds, only 10-15% are likely to develop into healthy trees in future, as germination rates significantly reduces during natural forest regeneration. Moreover, intensive mortality of seedlings and young saplings occurs within the first five years after seed dispersal (Andersson et al., 2025; Mangalis, 2004). Even seeds of the highest-quality Scots pine generally show germination rates of less than 40% under natural forest conditions. In contrast, seeds germinated under controlled nursery conditions can reach germination efficiencies of up to 90-95% (Baumanis et al., 2014). Natural regeneration of forest stands does not always achieve the stocking density per hectare required by Latvian legislation for recognizing a stand as successfully regenerated. To consider forest land regenerated by pine, minimum of established trees have to be 2000 pines per hectare (Meža Atjaunošanas, Meža Ieaudzēšanas Un Plantāciju Meža Noteikumi, 2012). To achieve the prescribed density, supplementary planting is often necessary, involving additional labour and financial input.

In the absence of active forest regeneration management, dense understory growth can establish, creating suboptimal conditions for the natural regeneration of target tree species. Such areas frequently experience shifts in species composition, with the encroachment of pioneer or broadleaf species that impose competitive pressure on the regeneration and establishment of target species (Vilkriste & Daugaviete, 2005). Although natural regeneration initially requires lower investment, it has several limitations. This method often results in uneven species composition, as well as variation in tree age and height within stand. The quality of the new forest crop is directly dependent on the seeds produced by the previous stand and the surrounding trees (Andersson et al., 2025; Miezīte et al., 2021). The application of soil scarification is recommended as a means of enhancing regeneration success by improving seedbed conditions conducive to germination (Dumins et al., 2025; Lavnyy et al., 2022). Site preparation such as scarification and soil exposure significantly improves seedling establishment and density. Similarly, in Finland and Sweden, light site preparation enhances natural regeneration success. In comparison with trenching, mounding as a soil preparation technique enhances early root architecture for pine, resulting in a wider and deeper root system detectable within the first year after out-planting. Pine exhibits a stronger response to soil preparation methods, with early stand development being primarily influenced by the effects of these methods on seedling root growth (Celma et al., 2019). The rate of height increment in young trees serves as an important predictor of the quality and potential productivity of the forest stand (Jansons et al., 2011). As noted by Liepa (1996), the early height growth in planted Scots pine forests is greater than in stands established through natural regeneration. It is also confirmed in Andersson et al. (2025). Compared to naturally regenerated stands, planted Scots pine stands display higher average diameters at the same height and greater resilience to large pine weevil damage (*Hylobius abietis* L.) (Miezīte et al., 2021).

In the eastern Baltic Sea region, forest management typically relies on clear-cutting. In numerous areas, clear-cuts are prohibited to protect natural values or to prioritize recreational use. Consequently, these forests are more likely to be managed following continuous-cover forestry (CCF) principles, which can also enhance carbon sequestration by increasing the accumulation of CO_2 in living trees and preserve unique biodiversity over time (Baranovskis et al., 2025; Brichta et al., 2024; Peltola et al., 2025). CCF management in Scots pine stands emphasizes maintaining natural forest structures and ecological processes while allowing sustainable timber production. This approach favours selective harvesting over clear-cutting, promotes continuous cover, and supports natural regeneration. Natural regeneration via methods like continuous-cover method provides a cost-effective, ecologically resilient alternative to clear cutting, ensuring seed dispersal continuity, structural complexity, and aesthetic value (Andersson et al., 2025; Luguza et al., 2020; Rums et al., 2020; Zawadzka & Słupska, 2022). The shelterwood method serves as an effective silvicultural practice for regenerating Scots pine stands in Latvia, fostering natural regeneration under controlled canopy conditions. Small canopy gaps create favourable conditions for natural regeneration by offering sufficient light, while limiting competition (Häggström et al., 2023; Pasternak et al., 2024; Rouvinen & Kouki, 2011).

Threats to young stands

Rising annual air temperatures and an increasing frequency of warm days, with significant implications for forest management, manifest climate change in Latvia. The prolonged growing season for trees and understory vegetation enhances conditions conducive to pest proliferation and disease development, posing increased risks to forest health and productivity (Polmanis et al., 2016).

Browsing - Biotic pressures add further challenges. Young Scots pine stands, particularly under 20 years of age, face heavy browsing damage from ungulates. Browsing intensity increases after pre-commercial thinning and in regions with higher deer and moose densities (Andersson et al., 2025; Done, Ķēniņa, et al., 2025). Damage like broken stems, bark stripping, and intensive browsing of lateral branches suppresses tree growth, deteriorates timber quality, and reduces the potential economic value of future stands. Therefore, controlling browsing pressure on Scots pine represents a critical challenge for forest management in Latvia (Done, Ķēniņa, et al., 2025; Wallgren et al., 2013). The share of young Scots pine stands, up to 20 years old, with more than 1% severely damaged or destroyed trees fluctuated considerably, averaging 55% of all surveyed sites (Done, Bagrade, et al., 2025). One of the ways to minimise tree damages is to leave undergrowth layer. In sites where undergrowth is less abundant, a higher proportion of pine trees suffered damage during winter, particularly in stands that had already experienced greater undergrowth browsing the previous summer (Done, Jansons, et al., 2025). In Latvian forestry, several strategies are employed to protect young pine stands. A commonly used approach is the application of taste- or odour-based repellents, such as *Trico* or *Cervacol Extra*, to vulnerable parts of young trees (the terminal shoot and stem) to minimise browsing. Mechanical methods, such as protective spirals placed around the stem, are also applied; these devices are removed once the bark has matured and trees become less susceptible to damage. The combined use of repellents and mechanical protection has proven to be the most effective approach (Done, Ķēniņa, et al., 2025). On small areas, individual tree mechanical protection measures can be successfully applied, but on larger areas, it is recommended the use of fencing (Baumanis, 2013). Excluding large herbivores by fencing replanting areas effectively prevents browsing damage to vulnerable tree species, but the high labour and cost requirements frequently discourage forest owners (Andersson et al., 2025).

Pine weevil - Scots pine regeneration in Latvia faces a significant threat from the large pine weevil, one of Europe's most destructive forest pests. Dubrovskis et al. (2022) report that in clear-cut sites across *Vacciniosa*, *Myrtillosa*, and *Hylocomiosa* forest types, pine weevil damage was identified as the most significant biotic factor affecting Scots pine growth, alongside browsing by ungulates. The risk is particularly high during the first one to three years after harvesting, when seedlings with larger root-collar show a better survival rate (Nordlander et al., 2009, 2011; Wallertz et al., 2005). The pest is found in the greatest numbers in well-aerated sandy soils. Clay and loamy soils and wet mineral soils are less suitable for it. Beyond directly damaging young trees, the pine weevil can contribute to disease spread by carrying spores of *Heterobasidion annosum* (Fries.) Brefeld. the agent responsible for root rot (Šmits, 2013). The primary long-standing alternatives for protecting seedlings from *H. abietis* damage have been various forms of physical barriers. *Conniflex* protection works by coating the stems of conifer seedlings with a layer of hard particles (glue–sand mixture), sized so that *H. abietis* cannot bite through the layer to reach the bark. Applying *Conniflex* to the lower part of conifer seedlings improves their survival. For Scots pine, survival grew from 29% in untreated seedlings to 97% in coated ones (Nordlander et al., 2009). *Conniflex* is applied in nurseries and successfully remains on seedlings for 2-3 years after out-planting (Nordlander et al., 2011). Around 60 % of seedling stem must be covered to achieve highest survival rates (Nordlander et al., 2009). An increasing number of conifer seedlings are being treated with environmentally friendly methods, such as *Conniflex* (AS "Latvijas valsts meži," 2019).

Soil preparation not only improves aeration, elevates soil temperature, enhances nutrient availability, reduces bulk density and competition from surrounding vegetation, lowers subsequent tending requirements, but can partially prevent damage from large pine weevil (Andersson et al., 2025; Celma et al., 2019).

<u>Forest fires</u> - Worldwide, wildfire patterns are evolving, with human activities contributing to their increased occurrence. In forest ecosystems, climate change through extended fire seasons, decreased rainfall, and more frequent droughts, is leading to more frequent and intense wildfires, which are projected to affect an expanding number of areas (Liepa et al., 2025). Fire, the primary disturbance in boreal forests, typically destroys Norway spruce stands, whereas some Scots pine trees on dry sites often survive (Brumelis et al., 2009). Donis et al. (2022) indicates that the probability of survival for Scots pine trees post-fire is positively correlated with tree diameter and negatively correlated with stem-scorching height and the proportion of uncovered root systems. This suggests that larger and mature trees have a higher chance of surviving fire. Regeneration patterns can vary based on several factors, including soil type, fire intensity, and the presence of competing vegetation. It is very common that recently disturbed, nutrient-rich soil territories are recolonized by deciduous tree species, rather than conifers (Dubrovskis et al., 2024; Liepa et al., 2025). Under certain conditions Scots pine can, benefit from forest fires, although the outcome strongly depends on fire intensity, frequency, and stand age. Low to moderate intensity fires often reduce competition by removing understory vegetation and broadleaf species, creating more open conditions with greater light availability and improved access to nutrients and water (Kuuluvainen & Aakala, 2011) Scots pine has evolved a thick lower-trunk bark as an adaptation to withstand low- to moderate-intensity fires (Kuuluvainen et al., 2021). The tree thin bark and shallow root systems render them susceptible to fire-induced mortality, especially during early growth stages (Kuuluvainen & Aakala, 2011; Sullivan, 1993).

Future perspective

Over time, forest management has shifted in response to society's changing demands, concerns about resource depletion, technological progress, and advances in ecological and forestry knowledge (Rytteri et al., 2016). Scots pine is still expected to play a significant role in Latvia's forestry over the long term, providing substantial economic benefits while also fulfilling critical ecological functions.

Research on Scots pine in boreal regions suggests that global warming may significantly affect productivity. However, realizing this potential in practice depends on understanding how various forest regeneration materials respond to climate change and utilizing genetically well-adapted stock (Berlin et al., 2016). Regeneration will likely occur in shorter, more irregular pulses, linked closely to disturbance timing. Increasing climate variability (droughts, frosts, late spring frosts) can reduce seed maturation or seedling survival. Successful regeneration usually requires open conditions created by disturbances such as clear-cutting, fire, or wind throw. Without sufficient disturbance, regeneration is suppressed by shade-tolerant species (Dubrovskis et al., 2022; Luguza et al., 2020; Lundqvist et al., 2019). Climate change is expected to intensify existing stresses, particularly through warmer and drier summers that increase seedling mortality on drought-prone sandy soils. At the same time, milder winters are likely to improve seed production but also enhance the survival of pests and pathogens. These opposing processes will contribute to more variable and less predictable regeneration patterns, with strong dependence on local microsite conditions (Fardeeva et al., 2025).

Maintaining the vitality of Scots pine forests under changing environmental conditions, and amid rising abiotic and biotic pressures, necessitates a strengthened focus on the species adaptive capacity. High genetic diversity is essential to ensure the phenotypic plasticity and long-term adaptability of Scots pine populations (Verbylaite et al., 2017; Żukowska et al., 2023). In Latvia, forest tree breeding programs have historically emphasized not only productivity and wood quality but also tree vitality, facilitating the development of genetically diverse selection materials and a sound seed base for regeneration needs (Matisons et al., 2024; Rieksts-Riekstiņš et al., 2020). Despite these efforts, high costs remain a significant barrier deterring private forest owners from using Scots pine in regeneration. Direct seeding presents a more cost-effective alternative to planting, particularly on nutrient-poor soils. Furthermore, sustainable ungulate management is vital to reduce browsing damage and lower stand protection expenses.

CONCLUSIONS

Scots pine will likely remain a cornerstone of Baltic region forestry under 21st-century climate change, but with shifting risks and management priorities. In Latvia, regeneration is dominantly achieved through artificial methods, particularly planting, which ensures stand establishment and genetic improvement. Pine growth is tightly linked to temperature and moisture balance, underscoring sensitivity to warm season water deficits, also wind exposure will remain notable. Provenance trials across the south-eastern Baltic reveal heritable differences in climate sensitivity, therefore selecting locally adapted or drought-tolerant seed sources can buffer productivity and stability (Matisons, Schneck, et al., 2021). Mixed-species forests provide significant opportunities for silvicultural practice, as they not only enhance resilience and resistance to diverse stressors linked to climate change, but also may improve productivity and reduce risks associated with changing environmental conditions (Mikalajūnas et al., 2021). Scots pine regeneration in Latvia will remain viable if management combines artificial regeneration with climate-smart seed selection and silvicultural practices that enhance long-term resilience. This indicates potential for selective breeding and seed sourcing strategies that could improve resilience under changing climate conditions.

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