https://doi.org/10.17221/34/2025-JFS

Forest ecosystem restoration in the Ore Mountains: A review of silvicultural measures addressing environmental degradation

Veronika Hammerová[1], Stanislav Vacek[1], Zdeněk Vacek[1], Jakub Černý[2,3], Jan Cukor[1,2], Josef Gallo[1], Michal Kuběnka[4]*

[1]Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic
[2]Forestry and Game Management Research Institute, Jíloviště-Strnady, Czech Republic
[3]Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic
[4]Faculty of Economics and Administration, University of Pardubice, Pardubice, Czech Republic

**Corresponding author: cerny@vulhmop.cz*

Citation: Hammerová V., Vacek S., Vacek Z., Černý J., Cukor J., Gallo J., Kuběnka M. (2025): Forest ecosystem restoration in the Ore Mountains: A review of silvicultural measures addressing environmental degradation. J. For. Sci., 71: 323–335.

Abstract: The forest dynamics of the Ore Mountains (Krušné hory), Czech Republic, reveal a historical decline of natural mixed forests, especially those dominated by the Hercynian mixture and European beech (*Fagus sylvatica* L.), due to the expansion of metallurgy and glassmaking in the 15th century. This led to large-scale reforestation with Norway spruce [*Picea abies* (L.) Karst.], resulting in single-layered monocultures. Although these monocultures provided valuable timber, they proved highly susceptible to both biotic and abiotic stressors. Throughout the 20th century, the stability of these forests further deteriorated due to air pollution (notably SO_2 emissions), the unsuitable selection of substitute species, and the proliferation of pathogens. The cumulative impact of these disturbances caused soil acidification, degradation, and weed encroachment, severely limiting the regenerative capacity of forest ecosystems in this region. This article presents model examples of species composition shifts, spatial structure changes, and evolving management practices in the Ore Mountains. It discusses strategies for establishing diverse and resilient stands that align with long-term forest planning goals. These approaches aim to maintain both productive and ecological functions of forests under changing environmental conditions while minimising restoration costs. Importantly, forest management and conversion strategies must also account for economic optimisation, ensuring that ecological goals are met in a financially viable manner. The strategies and case studies presented here offer promising, albeit preliminary, directions for future forest management. Their broader application will require further refinement and long-term experimental validation to ensure sustainability in both ecological and economic terms.

Keywords: climate change; economic evaluation; non-timber forest functions; regeneration methods; stand transformation; structurally diverse stands

Supported by the Ministry of Agriculture of the Czech Republic (Institutional support MZE-RO0123) and by the GS LČR (Grant Service of the Forests of the Czech Republic, a state enterprise) under the project 'Stav dospělých bukových porostů pod vlivem klimatických změn na LS Litvínov' ('The state of adult beech stands under the influence of climate change in the area under the administration of the Litvínov Forest District') (No. 139).

© The authors. This work is licensed under a Creative Commons Attribution-NonCommercial 4.0 International (CC BY-NC 4.0).

https://doi.org/10.17221/34/2025-JFS

The expansion of coal mining and industry in northern Bohemia led to severe degradation of ecosystems in the Ore Mountains (Krušné hory), resulting in the large-scale collapse of forest stands. This process caused significant acidification of habitats, including water sources, and in some areas, secondary waterlogging of extensive clearings (Podrázský, Ulbrichová 2004; Šrámek et al. 2008). Various regeneration methods were tested to prevent further damage, focusing on chemical and mechanical-biological amelioration (Balcar et al. 2007). During a transitional period, it was necessary to use non-native tree species, such as controversial blue spruce (*Picea pungens* Engelm.), until site conditions improved enough to allow silviculture of target native tree species, particularly Norway spruce [*Picea abies* (L.) Karst.], European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), and sycamore maple (*Acer pseudoplatanus* L.) (Vacek et al. 2003). While blue spruce helped stabilise forest stands temporarily, it was shown to have generally degrading effects in polluted areas, especially regarding soil-forming and soil-protecting functions (Podrázský et al. 2005a).

The year 1994 marked a turning point in pollution levels, as industrial desulphurisation led to a significant reduction in atmospheric pollutants. However, improved air quality in subsequent years was counterbalanced by a new stress factor – the spread of fungal pathogens, such as bud blight (*Gemmamyces piceae*), which significantly affected forest health (Materna 1999; Černý et al. 2016; Samek et al. 2022). In the second half of the 20th century, the forests of the Ore Mountains underwent extensive breakdown due to air pollution and bark beetle outbreaks (Kubelka 1992; Slodičák et al. 2008b; Podrázský 2014). This process nearly destroyed the mature Norway spruce stands which were subsequently replaced by substitute tree species (STS) with a pioneer strategy, mainly silver birch (*Betula pendula* Roth), rowan (*Sorbus aucuparia* L.), European larch (*Larix decidua* Mill.), with grey alder [*Alnus incana* (L.) Moench] and black alder [*Alnus glutinosa* (L.) Gaertn.] used locally (Balcar, Navrátil 2006; Novák, Slodičák 2006; Podrázský et al. 2006; Balcar et al. 2008). The goal of this substitution was to maintain forest continuity and enhance ameliorative functions. Over the past thirty years, intensive efforts have been made to convert these STS into stable stands composed of target native tree species, increasingly using close-to-nature forest management approaches (Balcar et al. 2007; Poleno et al. 2009; Čacká, Skála 2016). The conversion of STS into natural forest ecosystems requires time, purposeful planning, and implementation, as it is essential for ensuring the long-term stability of regional forests (Vacek, Balcar 2002, 2004).

An integral part of the measures aimed at stabilising forest ecosystems in polluted areas has also included interventions to improve forest soil properties and stand health through chemical treatments (Borůvka et al. 2005; Vacek et al. 2009). Long-term liming was carried out to raise soil pH and neutralise acidification caused by air pollution, thereby stabilising the chemical properties of forest sites (Jirgle 1986; Lochman 1986; Vacek et al. 2019; Gallo et al. 2021). In addition to liming, experiments were conducted in the Ore Mountains with the application of magnesium fertilisers (e.g. SILVAMIX) to improve the nutrition and health of spruce stands (Podrázský et al. 2005b). These interventions were complemented by a range of other studies focused on restoring soil fertility, nutrient dynamics, pollution impacts, and the responses of individual tree species to altered site conditions (Podrázský et al. 2003a; Podrázský 2008; Kapička et al. 2010).

Nowadays, climate change poses an additional major threat to forest ecosystems, including those in the Ore Mountains. Recently, significant changes have been observed, such as more unevenly distributed precipitation, rising air temperatures, and increased frequency of extreme weather events (Gallo et al. 2014; Novotný et al. 2023; Vacek et al. 2023). These events are often accompanied by extended drought periods, more frequent episodes of windthrow, and a longer vegetation period with higher evapotranspiration demands (Romeiro et al. 2022; Altman et al. 2024). This has led to more frequent bark beetle outbreaks, and devastating spruce stands (MoA 2023; Šimůnek et al. 2024). The rapid dieback of these forests caused by climate change further increases the risk of biodiversity loss and ecosystem instability, which are threatened by various anthropogenic pressures (Visconti et al. 2015; Johnson et al. 2017). The main anthropogenic driver is climate change, which reduces forest species diversity and significantly influences their adaptive capacities (Pacifici et al. 2015; Urban 2015). More frequent heatwaves, droughts, and storms, along with increased pathogen attacks, are be-

https://doi.org/10.17221/34/2025-JFS

coming increasingly important abiotic and biotic stressors for forest ecosystems (Bolte et al. 2009). These factors disrupt tree phenology, physiology, community structure and ecosystem functions, underscoring the need for flexible management practices that promote ecosystem resilience (Bellard et al. 2012; Vacek et al. 2023).

Given these threats, increasing emphasis is being placed on adapting forest management and silvicultural methods to new climatic conditions (Keenan 2015; Vacek et al. 2020a). Adaptive forestry provides a framework that allows for site-specific decision-making, ongoing integrated monitoring, and adjustments based on environmental feedback (Roshani et al. 2022). This approach promotes the use of mixed-species stands, changes in rotation period and tree density, supports natural regeneration processes, and favours the introduction of tree species better suited to future conditions (Jandl et al. 2019; Vacek et al. 2021, 2023). Incorporating microhabitat diversity, creating structurally heterogeneous stands, and ensuring functional redundancy among species are crucial strategies to maintain essential ecosystem services and reduce the risk of forest degradation (Bolte et al. 2009).

This review article, based on 100 sources, addresses the degradation of STS and their conversion into stable forest stands composed of target native species under the influence of climate change. Its main objective is to present the most suitable conversion approaches that consider local site conditions and enable the rapid establishment of functional and climate-resilient stands. The intended outcome is forests with greater resistance to current biotic and abiotic stressors and the capacity to withstand future climate change impacts.

HISTORICAL DEVELOPMENT AND AIR POLLUTION CALAMITY

The historical development of forest ecosystems in the Ore Mountains (Krušné hory) indicates the predominance of stands composed of the Hercynian mixture – forest communities consisting predominantly of Norway spruce and European beech, accompanied by silver fir on wetter and more fertile sites, and occasionally also sycamore maple and European larch (Kubelka 1992; Vacek et al. 2003; Ekoles-Projekt 2021; ÚHÚL 2021). There is currently no unified opinion on the original occurrence of larch in these forests. Although historical sources state that the trade in larch timber in the area dates back to the 16th century, part of the professional community still considers larch to be an introduced species. Da Ronch et al. (2016) refer to larch as native to the Jeseníky Mountains and eastern Bohemia. However, recent palaeobotanical research in the Czech Republic indicates a significantly wider natural distribution area, including several locations in northern Bohemia (Pokorný et al. 2023).

Many original beech and spruce-beech stands were logged during the 15th century due to the expansion of medieval glass production (ÚHÚL 1969; Vacek et al. 2003). Beechwood was extensively used as a source of energy, and potash (K_2CO_3) was obtained from its ash (Cílová, Woitsch 2012). Approximately 1 t of beech wood (1 m^3) was required to produce 1 kg of potash (Černá, Frýda 2010). The harvested areas were gradually reforested and transformed into monocultural spruce stands (Oulehle et al. 2007). The demand for spruce timber, particularly for mining purposes, remained a priority for at least the next 400 years. This high demand for mining and construction-grade timber led to forest management practices focused on producing desirable assortments at minimal cost (Reinhardt-Imjela et al. 2018). As a result, single-layered spruce stands became widespread (Průša 2001; Kriegel 2002). Although these stands yielded high proportions of technically usable timber, they also formed extensive and vulnerable monocultures (Slodičák et al. 2008b). Subsequent episodes triggered by biotic or abiotic factors led to widespread forest decline (Materna 1999).

In recent decades, the forest ecosystems of the Ore Mountains have undergone further dramatic transformations. Before 1989, large quantities of sulphur were deposited in the mountain region through acid rain, resulting from heavy air pollution emitted by industrial centres in Saxony, northern Bohemia, and Silesia – an area historically referred to as the 'Black Triangle' (Scheithauer, Grunewald 2007; Kupková et al. 2018). The most significant of these episodes was the calamitous dieback of the entire plateau of the Ore Mountains during the 1960s through the 1980s (Kubelka 1992; Materna 1999; Slodičák et al. 2008b), similar to events in other parts of the Sudetes (Král et al. 2015; Putalová et al. 2019; Vacek et al. 2020b). This phenomenon was primarily a result of brown coal mining and burning in the Podkrušnohorská

Journal of Forest Science, 71, 2025 (7): 323–335

https://doi.org/10.17221/34/2025-JFS

Basin, leading to an air pollution crisis (Šrámek et al. 2008). Complete forest dieback was accompanied by soil acidification (pH 2.1–3.0), weed invasion (mainly *Calamagrostis* spp.), complete depletion of raw humus, and soil degradation, often associated with secondary waterlogging of harvested areas (Podrázský, Ulbrichová 2004). In the 1980s, sulphate ion deposition on the ridges of the Ore Mountains reached levels up to 150 kg·ha^{-1} per year (SMUL 2004; Suker et al. 2010). Spruce monocultures rapidly died due to SO_2 acid deposition, with significant disruption of soil biogeochemical processes (Grunewald, Bastian 2015). By the 1990s, large areas of the Ore Mountains, particularly in the eastern part, were deforested (Vacek et al. 2003). Since then, emission sources have been gradually eliminated, mainly through the closure and desulphurisation of brown coal power plants (Vacek, Balcar 2002). From the late 1980s onwards, atmospheric deposition markedly decreased (Scheithauer, Grunewald 2007), leading to the gradual revitalisation of forest ecosystems.

Subsequent large investments in liming and fertilisation to STS were intended to mitigate ongoing soil degradation until air pollution levels could be reduced to acceptable thresholds (Balcar et al. 2007). The key year for emission reduction (particularly SO_2) was 1994 and the years that followed. However, after 1996, there was a widespread decline of STS stands triggered by fungal pathogens and the unsuitability of some introduced tree species (Černý 1995; Vacek et al. 2003; Shetti et al. 2024).

The restoration of these large-scale calamity areas has since been carried out using site-appropriate target tree species, in accordance with current legislation (Slodičák et al. 2008a). However, in addition to very high costs (approx. EUR 16 000 per ha for conversion – information obtained in 2023 from the Litvínov Forest District through oral communication), the long-term viability of these new stands must be considered. For instance, Pulkrab (2008) reported direct costs ranging from EUR 9 000 to EUR 10 760 per ha, which, adjusted for 2023 inflation (3.31%), equates to EUR 14 680 to EUR 17 520.

The most vulnerable aspect of newly established stands appears to be their even-aged structure across large areas, with a lack of additional vertical layers (Kubelka 1992; Balcar et al. 2007; Balcar, Slodičák 2008). Although composed of multiple target tree species, these forests will likely once again become large, even-aged monocultures, provided they reach maturity – requiring simultaneous regeneration across extensive areas, with a high harvesting percentage over a short regeneration period. These risks can be partially mitigated through appropriate spatial arrangement of tree species, intensive tending, and the use of classical stand-reinforcing elements such as gaps, buffer zones, and barriers (Lokvenc 1988; Vacek et al. 1994b; Poleno et al. 2009). Nonetheless, even if these stands reach physical maturity, they remain highly susceptible to premature disintegration (Ekoles-Projekt 2021).

Forest management on the plateau of the Ore Mountains during the air pollution calamity initially proceeded unsystematically, based primarily on practical experience. However, over time, it became increasingly systematic as scientific knowledge of the ecological integrity of local forest ecosystems advanced (Müller 2013; Grunewald, Bastian 2014).

SILVICULTURAL MEASURES FOR REGENERATION

For this article, the selected area was the plateau of the Ore Mountains (Krušné hory) in the vicinity of the Fláje reservoir, which includes forest management units (FMUs) predominantly of type 73 (management of acidic sites in mountain altitudes), and to a lesser extent FMUs 79 (management of waterlogged sites in mountain altitudes), 77 (management of gleyed sites in mountain altitudes), and 71 (management of exposed sites in mountain altitudes). Marginally represented are also FMUs 53 (acidic sites in higher altitudes), 59 (waterlogged sites in higher and mid altitudes), 57 (gleyed sites in higher altitudes), 51 (exposed sites in higher altitudes), and 55 (nutrient-rich sites in higher altitudes). The most widespread FMU 73 in the area is characterised by the following forest site types (FST): 7K (acidic spruce-beech forest), 7M (poor spruce-beech forest), and 7N (stony acidic spruce-beech forest; Viewegh et al. 2003).

Due to acid rain, the soil in the area has undergone acidification and partial degradation. Large-scale deforestation led to secondary waterlogging (Podrázský, Ulbrichová 2004). During the extensive regeneration aimed at mitigating secondary waterlogging, suppressing the herbaceous layer, and enabling mechanised slash removal, large-scale soil preparation was carried out, including heavy machinery use (Podrázský et al. 2003b). This caused

https://doi.org/10.17221/34/2025-JFS

secondary site degradation due to soil horizon displacement. These issues were further exacerbated by the absence of microclimate, resulting from the lack of vegetation cover, which hindered the use of climax tree species in the initial regeneration phase due to their ecological requirements.

For the successful regeneration and tending of young forest stands on sites in higher and mountain altitudes, the following principles are essential:

Regeneration methods

– Maximise the use of existing microclimatic conditions. Whenever possible, promote natural regeneration, paying attention to species diversity and vertical structure. Stands may be supplemented over a decade or longer, which helps achieve height differentiation and consequently improves resistance to adverse climatic conditions (Poleno et al. 2009; Vacek et al. 2023).
– Ensure the genetic appropriateness and ecophysiological condition of planting stock (Ratnam et al. 2014).
– When using containerised seedlings, pay close attention to planting methods and use certified containers that prevent root deformation, thereby improving the mechanical stability of young stands against abiotic stressors (Landis et al. 1990).
– Respect the ecological requirements of tree species concerning the site conditions.
– Where site conditions allow, initiate reforestation immediately after felling to prevent the development of competing vegetation and take full advantage of the raw humus layer. This is only feasible on sites with remaining stocking above 0.7.
– Design regeneration layouts to minimise wind flow, with emphasis on the width and length of the regeneration patches. Favour shelterwood systems and retain up to 10% of the stand for natural development and decay, especially to support biodiversity.
– Ensure high-quality soil preparation (Poleno et al. 2009).
– Always establish a layout network in young stands to guide future tending and access (Leugner et al. 2023).

Tending methods

– Prioritise individual tending over schematic thinning, even in naturally regenerated stands. Apply positive selection for promising and target trees while retaining the lower layer as much as possible. In the 6th and 7th forest vegetation zone (FVZ), focus tending on strengthening the stand against abiotic impacts.
– Maintain long crowns and low centres of gravity in target trees, following the principles of Bohdanecký thinning (Bohdanecký 1890).
– In age- or height-differentiated stands, treat stand segments individually (Schädelin's method; Schädelin 1942).
– Always consider the ecological requirements of each tree species concerning the specific site conditions (Tesař et al. 2011).

Adaptive management options

– Adaptive forest management aims to maintain and enhance forest functionality as a prerequisite for fulfilling future demands for ecosystem services (Wagner 2004).
– It is a dynamic management approach, in which silvicultural practices and decisions are continuously monitored and revised based on research findings, ensuring the fulfilment of both wood-producing and non-producing functions (Millar et al. 2007).
– Among the aforementioned regeneration and tending practices, adaptive strategies are best implemented through changes in tree species composition and stand structure, adapted to specific site and stand conditions using close-to-nature methods (Vacek et al. 2023).
– Forest responses and adaptation depend on species phenology, autecology, provenance, age, intra- and interspecific competition, and stand structure (Reyer et al. 2009).
– At the local scale, tree species differ in their capacity to cope with environmental changes, which must always be considered.
– Selecting appropriate tree populations is essential, as trees must cope with varying growing conditions depending on their vertical structure and vitality, while withstanding extremes. This also affects species synecology by altering competitive interactions (Pretzsch, Ďurský 2002; Wagner, Fischer 2007).
– Adaptive management should support the resilience of forest ecosystems to stress and damage, and their capacity to dynamically respond to environmental changes, particularly those related to climate change (Vacek et al. 2023).

https://doi.org/10.17221/34/2025-JFS

EXAMPLES

The provided facts indicate the necessity of modifying the forest regeneration strategy of STS, including management methods. If a large clear-cut area is already created, the need for reforestation – whether through suitable planting or seeding – is undeniable. However, regeneration methods can be combined, considering the requirements of individual tree species, their physiological capabilities, and, ultimately, their economic utilisation. The reconstruction of these stands on the plateau is, however, essential, as confirmed by several studies (e.g. Balcar et al. 2007; Slodičák et al. 2008b). Possible management directions for these stands are outlined in the following two examples:

Example 1: Large clear-cut area

– After proper soil preparation, the large clear-cut is regenerated by sowing a pioneer species, such as silver birch or downy birch (*Betula pubescens* Ehrh.) (costs approximately 800 EUR·ha^{-1}, as communicated by the Litvínov Forest District).

– The stand regenerates without significant additional costs for protection against weed species (under normal conditions, no protection against game), as suggested by Vacek et al. (1987, 1994a).

– A suitable ecotype of pioneer birch does not require substantial tending, as the focus is not on production quality (Vacek et al. 1994a, 2007b). However, tending operations in these sites can improve production quality (Slodičák et al. 2008b), albeit with corresponding silvicultural costs (Pulkrab 2008). The intensity and strength of tending in birch stands on acidic sites (FVZ 6–7) will be lower compared to nutrient-rich sites at mid-elevations.

– At 40 years, the birch stand should be thinned in small patches (about 20–30% of the area), with wood production consisting of 15–20% pulpwood and the remainder being chips (according to the Litvínov Forest District). This is followed by the introduction of suitable climax tree species through artificial regeneration, differentiated according to the FST, reflecting the improved air quality and climate conditions that facilitate the revitalisation of target species and, locally, natural regeneration (Balcar et al. 2007; Slodičák et al. 2008a). After the regeneration of target tree species, the site is enriched, especially with the leaf litter of these species (Kulhavý et al. 2008; Podrázský et al. 2010).

– After securing the target tree species' seedlings, further regeneration components are added. By the time the stand reaches 50–60 years, regeneration should cover 80% of the area. The production consists of 50–60% pulpwood and 40–50% chips (based on oral communication with the Litvínov Forest District). Regeneration focuses on the main target tree species, differentiated according to specific site and stand conditions (cf. Mauer, Tesař 2005; Balcar et al. 2007).

– Stand closure should be optimally achieved in stands aged 70–80 years. The production composition consists of 60–80% pulpwood and 20–40% chips (according to the Litvínov Forest District). The stand can be supplemented with other resistant target tree species (e.g. beech, hornbeam, elm, alder) to increase species diversity and the stability of the new mixed stand (Pretzsch et al. 2017). Natural regeneration of the original birch, including regeneration from the first regeneration components, can be utilised (almost at no cost). At the beginning of the regeneration cycle, it is essential to create a proper segmentation network to aid in orientation within the forest stands (Bystrický 2020).

– The stand is regenerated at acceptable costs, being species-diverse, age-differentiated, and spatially structured. Natural regeneration allows for the development of the lower strata, and the stand reaches a deep vertical canopy closure. This type of stand is prepared to resist a wide range of biotic and abiotic adverse factors. The segmentation network facilitates access to the stand, reduces the cost of future tending interventions, and, with its edge trees, strengthens the stand structure, especially against abiotic factors (Chroust 1997). In such a stand, the transition to a richly structured forest, using selection principles, can be initiated (Vacek et al. 2007a, 2022).

Example 2: Management of retained stands of predominantly original target tree species

– Although the occurrence of these stands is less frequent than in Example 1, they are genetically valuable, and therefore, proper silvicultural care must be provided.

– After confirming the genetic suitability of the retained stand for establishing a new generation

https://doi.org/10.17221/34/2025-JFS

of forest in the given locality, site-inappropriate native and introduced tree species are removed, as they negatively affect the site conditions (cf. Vacek et al. 2007b).

– Selected parts of the forest stand (or the entire residual stand) should be thinned according to the tree species, site, and hydrological conditions, aiming for a stocking of 0.6 to 0.7, leaving all interspersed trees.
– Soil preparation should be carried out, typically based on the mass seed year. This preparation can be combined with different methods depending on the type of weeds and the site (e.g. chemical preparation twice or a combination of mechanical preparation with chemical treatment, or various types of mechanical soil preparation like milling or mini-excavator). Attention must be paid to soil preparation. If the seed year is unsuccessful (e.g. late frost), mechanical or chemical preparation must be repeated. Mechanical soil preparation should be done at least four months in advance (excluding winter periods – air temperatures above 10 °C). Caution is needed when sowing seeds on freshly prepared soil, as seeds can be buried too deeply, allowing weeds to gain an advantage. For this reason, it is recommended to lightly cover the seeds with soil (Poleno et al. 2009).
– After successful regeneration, i.e. with secured growth, the area should gradually be sheltered.
– During the first tending intervention, selected individuals in regeneration groups should be released (1–2 individuals per 1–5 m^2, depending on the species and site). Some of the regeneration will eventually die due to natural processes, while others will create multiple lower layers, so-called replacement trees. This will result in deep vertical closure and future mechanical stabilisation of the stand with reduced tending costs. However, attention must be paid to stand segmentation (Poleno et al. 2009; Dobrovolný 2014; according to the Litvínov Forest District).
– The retained forest stand should be fully stocked (selected individuals may be left for the next rotation period). Tending measures continue, including thinning/cutting (only promising and target trees are released by removing direct competitors). The material from tending operations is generally left in the stand, especially at higher elevations, as it is not economically viable to process and remove it (information obtained personally from the Litvínov Forest District). The height of the upper managed layer fluctuates around ±1/4 of the height of the remaining mature stand. Height differentiation should be maintained throughout the stand's existence (Poleno et al. 2009).
– When harvesting the selected target trees in the upper layer, considering future regeneration, the forest manager enters the phase of applying management principles for a richly structured forest (Vacek et al. 2007a). In these conditions, this is a long-term process, with a horizon of up to 60 years.
– If possible, managed elements created from the residual population of the current stands can be incorporated into reinforcing regeneration bands during large-scale regeneration on calamity areas (Vacek et al. 2007b).
– During this process, which lasts up to 60 years, additional suitable tree species, including climax species, can be introduced into the stand, as recommended by Balcar et al. (1999, 2007).

RECOMMENDATION

In the assessment of forest regeneration methods in the 6^{th} and 7^{th} FVZ of the studied area, natural regeneration of autochthonous tree species proves to be an effective and ecologically suitable method for ensuring the long-term mechanical stability of forest ecosystems. Forest stands established through natural regeneration not only have significantly lower initial costs, but also exhibit faster early growth, often without the need for weeding, chemical or mechanical protection against game. The high stand density enables the removal – repeatedly if needed – of malformed or game-damaged individuals. It has been observed that on all monitored sites in the 6^{th} and 7^{th} FVZ, damage caused by ungulates is lower – whether browsing, bark stripping, or debarking. Monitoring the effects of abiotic factors, especially rime and glaze ice, revealed that stands in the initial development stage (before the first pre-commercial thinning) show comparable resistance. A clear exception is seen in stands regenerated under the remnants of the parent stand, where damage is consistently lower due to the protective cover. In stands originating from natural regeneration, significantly lower damage by rodents – especially voles – was also recorded.

https://doi.org/10.17221/34/2025-JFS

Artificially established stands, in addition to higher establishment costs, tend to suffer – particularly on poor or exposed sites – from drought stress, biotic damage (voles), shorter shoot leader growth, and repeated demands for weed and game protection. Reduced shoot elongation is naturally associated with a longer time to secure the stand and thus with increased costs. An evident advantage is the possibility of spatially arranging individual tree species on the site according to regeneration objectives. However, this is closely linked to the ecological requirements of individual tree species based on the forest site types. Climax species cannot be introduced safely except under the shelter of an existing stand or later under the protection of a developing young stand.

Tending of artificially established stands can be assessed primarily in terms of cost, future resistance to abiotic factors, or game damage. Due to the low density of planted individuals per ha, it is essential to minimise errors in both the selection and execution of silvicultural interventions, which must always be thoroughly and professionally planned. The stand's framework should be shaped by a maximum of two interventions using positive selection aimed at releasing promising or target individuals. A higher number of interventions increases the risk of reduced stand stability due to damage from wet snow, as canopy closure often drops below 80%. When applying thinning, it is essential to consider the tree species, its age, horizontal and vertical structure, and site conditions.

Tending should begin no later than the growth phase of individuals between a height of > 1.3 m and with a diameter at breast height up to 5 cm. In these altitudes, it is appropriate to carry out two low-intensity interventions within a single decade (a silvicultural interval of 5 years). If not established during regeneration, a segmentation network should be introduced into the forest stand. In naturally regenerated stands, tending should always focus only on releasing promising individuals in the upper canopy layer. The lower storey should only be modified in exceptional cases, for future development or for improving stand accessibility. Over time, damaged target individuals can be easily replaced. Height differentiation created by staggered establishment is always advantageous and should be maintained in small groups to support the formation of mosaic-like stands, especially on the most climatically extreme sites. Generally, tending through individual selection places high demands on the professional competence of both technical and manual personnel.

CONCLUSION

In close-to-nature forest management, the emphasis is always placed on the question of how a natural forest stand would look on a given site and within a specific FVZ, in the absence of human intervention. During the successional development of ecosystems on a particular site, nature often operates through processes that can be characterised as naturally occurring monocultural arrangements. While in the 4th FVZ, monospecific beech stands are considered a natural and stable community, in the 7th and 8th FVZ, the presence of spruce monocultures is often misinterpreted. Many experts consider the 'monospecific spruce stand' to be a permanently disturbed, artificially created ecosystem, which contradicts the natural development of vegetation in the region. Even natural spruce stands on suitable sites can, under certain conditions, represent the most stable and vigorous form of high forest. For example, Vacek et al. (2007b) reported that a richly structured autochthonous spruce stand was up to four times more resistant to pollution stress than an allochthonous, uniform spruce stand.

What has placed pure spruce stands among the so-called unsuitable cultures is not their low species diversity, but rather structural uniformity and inappropriate management practices applied to these sites in the past. Setting aside the suitability of the species and the site, we arrive at the real issue – the forest management method applied in the locality. Due to inappropriate tending practices, naturally regenerated stands fail to develop into age-, height-, and diameter-differentiated stands capable of withstanding both biotic and abiotic stressors. Therefore, it is essential to abandon ecologically unjustified silvicultural interventions that result in unnatural, unstable, species-poor, dense, single-layered, and even-aged monocultures.

For these reasons, adaptive management must be an integral part of the overall forest management strategy for the plateau region of the Ore Mountains. The adaptive strategies presented here focus on the development of forests that are suited

https://doi.org/10.17221/34/2025-JFS

to future climate scenarios and can be combined with general risk minimisation concepts through the blending of suitable tree species, preferably of autochthonous provenance. Therefore, continued research and development of these strategies remains essential. It is also crucial to demonstrate to society the benefits derived from forest ecosystems, as this is the only way to achieve sustainable forest management that emphasises adaptability in the face of future challenges.

REFERENCES

Altman J., Fibich P., Trotsiuk V., Altmanova N. (2024): Global pattern of forest disturbances and its shift under climate exchange. Science of the Total Environment, 915: 170117.

Balcar V., Navrátil P. (2006): Význam, postavení a druhové složení porostů náhradních dřevin v Krušných horách. In: Slodičák M., Novák J. (eds): Lesnický výzkum v Krušných horách. Proceedings of a National Scientific Conference, Teplice, Apr 20, 2006: 91–100. (in Czech)

Balcar V., Slodičák M. (2008): Přeměny porostů náhradních dřevin. In: Slodičák M., Balcar V., Novák J., Šrámek V. (eds): Lesnické hospodaření v Krušných horách. Edice grantové služby LČR. Strnady, Forestry and Game Management Research Institute: 341–357. (in Czech)

Balcar V., Kacálek D., Vacek S. (1999): Rekonstrukce porostů náhradních dřevin prosadbami buku lesního *Fagus sylvatica* L. In: Slodičák M. (ed.): Obnova a stabilizace horských lesů. Proceedings of a National Conference with International Participation, Bedřichov v Jizerských horách, Oct 12–13, 1999: 135–140. (in Czech)

Balcar V., Slodičák M., Kacálek D., Navrátil P. (2007): Metodika postupů přeměn porostů náhradních dřevin v imisních oblastech. Lesnický průvodce – Recenzované metodiky pro praxi, 3: 34. (in Czech)

Balcar V., Pěnička L., Slodičák M., Navrátil P., Smejkal J. (2008): Zakládání porostů náhradních dřevin a jejich současný stav. In: Slodičák M., Balcar V., Novák J., Šrámek V. (eds): Lesnické hospodaření v Krušných horách. Edice grantové služby LČR. Strnady, Forestry and Game Management Research Institute: 121–141. (in Czech)

Bellard C., Bertelsmeier C., Leadley P., Thuiller W., Courchamp F. (2012): Impacts of climate change on the future of biodiversity. Ecology Letters, 15: 365–377.

Bohdanecký J. (1890): Popis vycházky konané českou lesnickou jednotou dne 4. srpna 1890 do lesů panství Vorlického. Vereinsschrift für Forst-, Jagd- und Naturkunde, 165: 1–27.

Bolte A., Ammer C., Löf M., Madsen P., Nabuurs G.J., Schall P., Spathelf P., Rock J. (2009): Adaptive forest management in central Europe: Climate change impacts, strategies and integrative concept. Scandinavian Journal of Forest Research, 24: 473–482.

Borůvka L., Podrázský V., Mládková L., Kuneš I., Drábek O. (2005): Some approaches to the research of forest soils affected by acidification in the Czech Republic. Soil Science & Plant Nutrition, 51: 745–749.

Bystrický R. (2020): Zpřístupnění lesů: Metodika a pracovní postupy. Brandýs and Labem, ÚHÚL: 50. (in Czech)

Čacká J., Skála V. (2016): Krušné hory – pohoří se zapomenutou historií i současností. Sborník příspěvků. Prague, Czech Forestry Society: 86. (in Czech)

Černá E., Frýda F. (2010): Sklo vrcholného středověku – současný stav a perspektivy studia historických technologií. Archaeologia Historica, 35: 1–2. (in Czech)

Černý J. (1995): Recovery of acidified catchments in the extremely polluted Krusne hory Mountains, Czech Republic. Water, Air, and Soil Pollution, 85: 589–594.

Černý K., Pešková V., Soukup F., Havrdová L., Strnadová V., Zahradník D., Hrabětová M. (2016): Gemmamyces bud blight of *Picea pungens*: A sudden disease outbreak in Central Europe. Plant Pathology, 65: 1267–1278.

Chroust L. (1997): Ekologie výchovy lesních porostů. Opočno, Forestry and Game Management Research Institute: 277. (in Czech)

Cílová Z., Woitsch J. (2012): Potash – A key raw material of glass batch for Bohemian glasses from 14th–17th centuries? Journal of Archaeological Science, 39: 371–380.

Da Ronch F., Caudullo G., Tinner W. (2016): *Larix decidua* and other larches in Europe: Distribution, habitat, usage and threats. In: San-Miguel-Ayanz J., de Rigo D., Caudullo G., Houston Durrant T., Mauri A. (eds): European Atlas of Forest Tree Species. Luxembourg, Publication Office of the European Union: 108–110.

Dobrovolný L. (2014): Postupy zvyšování diverzity smrkových porostů využitím reprodukční schopnosti vtroušených jedinců buku. Strnady, Forestry and Game Management Research Institute: 28. (in Czech)

Ekoles-Projekt (2021): Textová část LHP: LHC Litvínov. Platnost 1. 1. 2021 – 31. 12. 2030. Kniha I. Jablonec nad Nisou, Ekoles-Projekt: 227. (in Czech)

Gallo J., Kuneš I., Baláš M., Nováková O., Drury M.L. (2014): Occurrence of frost episodes and their dynamics in height gradient above the ground in the Jizerské hory Mts. Journal of Forest Science, 60: 35–41.

Gallo J., Vacek Z., Vacek S. (2021): Quarter of a century of forest fertilization and liming research at the Department of Silviculture in Prague, Czech Republic. Central European Forestry Journal, 67: 123–134.

Grunewald K., Bastian O. (2014): Ecosystem Services – Concept, Methods and Case Studies. Berlin, Springer: 312.

https://doi.org/10.17221/34/2025-JFS

Grunewald K., Bastian O. (2015): Ecosystem assessment and management as key tools for sustainable landscape development: A case study of the Ore Mountains region in Central Europe. Ecological Modelling, 295: 151–162.

Jandl R., Spathelf P., Bolte A., Prescott C.E. (2019): Forest adaptation to climate change – Is non-management an option? Annals of Forest Science, 76: 48.

Jirgle J. (1986): Význam vápnění lesních půd pro obnovu lesa v Krušných horách. Sborník ČSVTS. Ústí nad Labem, Czech Association of Scientific and Technical Societies: 45–54. (in Czech)

Johnson C.N., Balmford A., Brook B.W., Buettel J.C., Galetti M., Guangchun L., Wilmshurst J.M. (2017): Biodiversity losses and conservation responses in the Anthropocene. Science, 356: 270–275.

Kapička A., Petrovský E., Grison H., Podrázský V., Křížek P. (2010): Magnetic measurements of atmospheric dust deposition in soils. In: Ho Oh J. (ed.): Advances in Geosciences: Vol. 16: Atmospheric Science. Singapore, World Scientific Publishing: 311–319.

Keenan R.J. (2015): Climate change impacts and adaptation in forest management: A review. Annals of Forest Science, 72: 145–167.

Král J., Vacek S., Vacek Z., Putalová T., Bulušek D., Štefančík I. (2015): Structure, development and health status of spruce forests affected by air pollution in the western Krkonoše Mts. in 1979–2014. Central European Forestry Journal, 61: 175–187.

Kriegel H. (2002): Přeměny porostů náhradních dřevin v Krušných horách. Zprávy lesnického výzkumu/Reports of Forestry Research, 47: 119–124. (in Czech)

Kubelka L. (1992): Obnova lesa v imisemi poškozované oblasti severovýchodního Krušnohoří. Prague, Ministry of Agriculture of the Czech Republic: 133. (in Czech)

Kulhavý J., Šrámek V., Lomský B., Fiala P., Matějka K., Borůvka L., Menšík L. (2008): Stav lesních půd zájmové oblasti. In: Slodičák M., Balcar V., Novák J., Šrámek V. (eds): Lesnické hospodaření v Krušných horách. Edice grantové služby LČR. Strnady, Forestry and Game Management Research Institute: 71–98. (in Czech)

Kupková L., Potůčková M., Lhotáková Z., Albrechtová J. (2018): Forest cover and disturbance changes, and their driving forces: A case study in the Ore Mountains, Czechia, heavily affected by anthropogenic acidic pollution in the second half of the 20th century. Environmental Research Letters, 13: 095008.

Landis T.D., Tinus R.W., McDonald S.E., Barnett J.P., Dumroese R.K., Haase D.L., Nisley R.G. (1990): The Container Tree Nursery Manual: Seedling Processing, Storage, and Outplanting (No. 674). Washington, D.C., US Department of Agriculture, Forest Service: 200.

Leugner J., Souček J., Špulák O., Martiník A. (2023): Obnova kalamitních holin přes přípravný les. Certifikovaná metodika. Strnady, Forestry and Game Management Research Institute: 36. (in Czech)

Lochman V. (1986): Vliv imisních spadů do lesních ekosystémů u Moldavy v Krušných horách na chemismus vody odtékajících do zdrojů. Lesnictví-Forestry, 42: 438–448. (in Czech)

Lokvenc T. (1988): Možnost využití autochtonních dřevin pro zalesňování v horských oblastech. In: Možnosti obnovy a zvýšení stability porostů v oblastech pod vlivem imisí. Proceedings of a National Conference, Ústí nad Labem, Oct 13–14, 1988: 46–54. (in Czech)

Materna J. (1999): Development and causes of forest damage in the Ore Mts. Journal of Forest Science, 45: 147–152.

Mauer O., Tesař V. (2005): Východiska a návrh postupů obnovy lesních porostů v imisní oblasti východního Krušnohoří. In: Obnova lesních porostů v imisní oblasti východního Krušnohoří. Conference Proceedings, Hora Svatého Šebestiána, June 2, 2005: 77–90. (in Czech)

Millar C.I., Stephenson N.L., Stephens S.L. (2007): Climate change and forests of the future: Managing in the face of uncertainty. Ecological Applications, 17: 2145–2151.

MoA (2023): Zpráva o stavu lesa a lesního hospodářství 2022. Prague, Ministry of Agriculture of the Czech Republic: 134. (in Czech)

Müller F. (2013): Die Anwendung von Ökosystemansätzen auf der Landschaftsebene/Berichte. Geographie und Landeskunde, 87: 295–313. (in German)

Novák J., Slodičák M. (2006): Možnosti ovlivnění stability náhradních porostů smrku pichlavého (*Picea pungens* Engelm.). In: Slodičák M., Novák J. (eds): Lesnický výzkum v Krušných horách. Proceedings of a National Scientific Conference, Teplice, Apr 20, 2006: 347–357. (in Czech)

Novotný S., Gallo J., Baláš M., Kuneš I., Fuchs Z., Brabec P. (2023): Silvicultural potential of the main introduced tree species in the Czech Republic – Review. Central European Forestry Journal, 69: 188–200.

Oulehle F., Hofmeister J., Hruška J. (2007): Modeling of the long-term effect of tree species (Norway spruce and European beech) on soil acidification in the Ore Mountains. Ecological Modelling, 204: 359–371.

Pacifici M., Foden W.B., Visconti P., Watson J.E.M., Butchart S.H.M., Kovacs K.M., Scheffers B.R., Hole D.G., Martin T.G., Akcakaya H.R. (2015): Assessing species vulnerability to climate change. Nature Climate Change, 5: 215–225.

Podrázský V. (2008): Tvorba povrchového humusu při zalesňování zemědělských ploch a po buldozerové přípravě v Krušných horách. Zprávy lesnického výzkumu/Reports of Forestry Research, 53: 258–263. (in Czech)

https://doi.org/10.17221/34/2025-JFS

Podrázský V. (2014): Český pohraniční hvozd – realita nebo mýtus? Zprávy lesnického výzkumu/Reports of Forestry Research, 59: 51–54. (in Czech)

Podrázský V., Ulbrichová I. (2004): Restoration of forest soils on reforested abandoned agricultural lands. Journal of Forest Science, 50: 249–255.

Podrázský V., Vacek S., Ulbrichová I. (2003a): Effect of fertilisation on Norway spruce needles. Journal of Forest Science, 49: 321–326.

Podrázský V., Remeš J., Ulbrichová I. (2003b): Biological and chemical amelioration effects on the localities degraded by bulldozer site preparation in the Ore Mts. – Czech Republic. Journal of Forest Science, 49: 141–147.

Podrázský V., Ulbrichová I., Moser W.K. (2005a): Využití břízy a smrku pichlavého při obnově porostů na plochách s nenarušenou vrstvou nadložního humusu. Zprávy lesnického výzkumu/Reports of Forestry Research, 50: 75–78. (in Czech)

Podrázský V., Vacek S., Remeš J., Ulbrichová I. (2005b): Application of Mg-fertilizers to prevent and to decrease Norway spruce yellowing. Journal of Forest Science, 51: 43–48.

Podrázský V., Remeš J., Ulbrichová I. (2006): Rychlost regenerace lesních půd v horských oblastech z hlediska kvantity nadložního humusu. Zprávy lesnického výzkumu/Reports of Forestry Research, 51: 230–234. (in Czech)

Podrázský V., Vacek S., Vacek Z., Raj A., Mikeska M., Boček M., Schwarz O., Hošek J., Šach F., Černohous V., Bílek L., Hejcman M., Nosková I., Baláš M. (2010): Půdy lesů a ekosystémů nad horní hranicí lesa v národních parcích Krkonoš. Kostelec nad Černými lesy, Lesnická práce: 304. (in Czech)

Pokorný P., Hošková K., Prach J., Šída P., Bednář P. (2023): Nová paleobotanická data prokazují původní status modřínu opadavého (*Larix decidua* Mill.) v Severních Čechách. Zprávy lesnického výzkumu/Reports of Forestry Research, 68: 197–205. (in Czech)

Poleno Z., Vacek S., Podrázský V., Remeš J., Štefančík I., Mikeska M., Kobliha J., Kupka I., Malík V., Turčáni M., Dvořák J., Zatloukal V., Bílek L., Baláš M., Simon J. (2009): Pěstování lesů III. Praktické postupy pěstování lesů. Kostelec nad Černými lesy, Lesnická práce: 952. (in Czech)

Pretzsch H., Ďurský J. (2002): Growth reaction of Norway spruce [*Picea abies* (L.) Karst.] and European beech (*Fagus sylvatica* L.) to possible climatic changes in Germany. A sensitivity study. Forstwissenschaftliches Centralblatt, 121: 145–154.

Pretzsch H., Forrester D.I., Bauhus J. (2017): Mixed-Species Forests. Ecology and Management. Berlin, Springer: 653.

Průša E. (2001): Pěstování lesů na typologických základech. Kostelec nad Černými lesy, Lesnická práce: 593. (in Czech)

Pulkrab K. (2008): Posouzení jednotlivých variant navržených hospodářských opatření. In: Slodičák M., Balcar V., Novák J., Šrámek V. (eds): Lesnické hospodaření v Krušných horách. Edice grantové služby LČR. Strnady, Forestry and Game Management Research Institute: 369–389. (in Czech)

Putalová T., Vacek Z., Vacek S., Štefančík I., Bulušek D., Král J. (2019): Tree-ring widths as an indicator of air pollution stress and climate conditions in different Norway spruce forest stands in the Krkonoše Mts. Central European Forestry Journal, 65: 21–33.

Ratnam W., Rajora O.P., Finkeldey R., Aravanopoulos F., Bouvet J.M., Vaillancourt R.E., Kanashiro M., Fady B., Tomita M., Vinson C. (2014): Genetic effects of forest management practices: Global synthesis and perspectives. Forest Ecology and Management, 333: 52–65.

Reinhardt-Imjela C., Imjela R., Bölscher J., Sulte A. (2018): The impact of late medieval deforestation and 20th century forest decline on extreme flood magnitudes in the Ore Mountains (Southeastern Germany). Quaternary International, 475: 42–53.

Reyer C., Guericke M., Ibisch P.L. (2009): Climate change mitigation via afforestation, reforestation and deforestation avoidance: And what about adaptation to environmental change? New Forests, 38: 15–34.

Romeiro J.M.N., Eid T., Antón-Fernández C., Kangas A., Trømborg E. (2022): Natural disturbances risks in European Boreal and Temperate forests and their links to climate change – A review of modelling approaches. Forest Ecology and Management, 509: 120071.

Roshani, Sajjad H., Kumar P., Masroor M., Rahaman M.H., Rehman S., Ahmed R., Sahana M. (2022): Forest vulnerability to climate change: A review for future research framework. Forests, 13: 917.

Samek M., Modlinger R., Baťa D., Lorenc F., Vachová J., Tomášková I., Pešková V. (2022): *Gemmamyces piceae* bud blight damage in Norway spruce (*Picea abies*) and Colorado blue spruce (*Picea pungens*) forest stands. Forests, 13: 164.

Schädelin W. (1942): Die Auslesedurchforstung als Erziehungsbetrieb hochster Wertleistung. 3rd Ed. Bern, Haupt: 147. (in German)

Scheithauer J., Grunewald K. (2007): Saurer Regen und Waldsterben im ehemaligen Schwarzen Dreieck (Osterzgebirge). In: Zepp H. (ed.): Ökologische Problem-räume Deutschlands. Darmstadt, WBG: 111–132. (in German)

Shetti R., Boonen K., Smiljanić M., Tejnecký V., Drábek O., Lehejček J. (2024): Do trees respond to pollution? A network study of the impact of pollution on spruce growth from Europe. Environmental Pollution, 350: 124012.

Šimůnek V., Vacek Z., Vacek S., Švanda M., Hájek V., D'Andrea G. (2024): Norway spruce forest management

https://doi.org/10.17221/34/2025-JFS

in the Czech Republic is linked to the solar cycle under conditions of climate change – From tree rings to salvage harvesting. Journal of Space Weather and Space Climate, 14: 37.

Slodičák M., Balcar V., Novák J., Šrámek V. (2008a): Lesnické hospodaření v Krušných horách. Edice grantové služby LČR. Strnady, Forestry and Game Management Research Institute: 121–141. (in Czech)

Slodičák M., Novák J., Navrátil P. (2008b): Výchova lesních porostů v Krušných horách. In: Slodičák M., Balcar V., Novák J., Šrámek V. (eds): Lesnické hospodaření v Krušných horách. Edice grantové služby LČR. Strnady, Forestry and Game Management Research Institute: 317–340. (in Czech)

SMUL (2004): Waldschadens- und Waldzustandsberichte 1993 bis 2003. Graupa, Sächsisches Staatsministerium für Umwelt und Landwirtschaft: 56. (in German)

Šrámek V., Hadaš P., Lachmanová Z., Fadrhonsová V., Vortelová L., Lomský B., Kulhavý J. (2008): Imisní zatížení Krušných hor. In: Slodičák M., Balcar V., Novák J., Šrámek V. (eds): Lesnické hospodaření v Krušných horách. Edice grantové služby LČR. Strnady, Forestry and Game Management Research Institute: 45–70. (in Czech)

Suker C., von Wilpert K., Puhlmann H. (2010): Acidification reversal in low mountain range streams of Germany. Environmental Monitoring and Assessment, 174: 65–89.

Tesař V., Balcar V., Smejkal J., Lochman V., Nehyba J. (2011): Přestavba lesa zasaženého imisemi na Trutnovsku. Brno, Mendel University in Brno: 176. (in Czech)

ÚHÚL (2021): Oblastní plán rozvoje lesů – Přírodní lesní oblast 01 Krušné hory. Plzeň, Ústav pro hospodářskou úpravu lesů Brandýs nad Labem, pobočka Plzeň: 635. (in Czech)

Urban M. (2015): Accelerating extinction risk from climate change. Science, 348: 571–573.

Vacek S., Balcar V. (2002): Strategy of forest restoration in the Czech part of the 'black triangle'. In: Gardiner E.S., Breland L.J. (eds): Proceedings of the IUFRO Conference on Restoration of Boreal and Temperate Forests: Documenting Forest Restoration Knowledge and Practices in Boreal and Temperate Ecosystems, Vejle, Apr 28 – May 2, 2002: 147–170.

Vacek S., Balcar V. (2004): Sustainable management of mountain forests in the Czech Republic. Journal of Forest Science, 50: 526–532.

Vacek S., Lepš J., Tesař V. (1987): Skladba mladých březových porostů na Trutnovsku. Lesnictví, 33: 343–360. (in Czech)

Vacek S., Tesař V., Lepš J. (1994a): The composition and development of young mountain ash and birch stands. In: Tesař V. (ed.): Management of Forests Damaged by Air Pollution. Proceedings of the IUFRO Workshop, Trutnov, June 5–9, 1994: 87–96.

Vacek S., Lokvenc T., Balcar V., Henžlík V. (1994b): Strategie obnovy a stabilizace lesa v horských oblastech. In: Jurásek A., Vacek S. (eds): Stav horských lesů Sudet v České republice. Opočno, Forestry and Game Management Research Institute: 25–50. (in Czech)

Vacek S., Zingari P.C., Jeník J., Simon J., Smejkal J., Vančura K. (2003): Mountain Forests of the Czech Republic. Prague, Ministry of Agriculture of the Czech Republic: 320.

Vacek S., Simon J., Remeš J., Podrázský V., Minx T., Mikeska M., Malík V., Jankovský L., Turčáni M., Jakuš R., Schwarz O., Kozel J., Valenta M., Lička D., Hlásny T., Zúbrik M., Krejčí F., Třešňák J., Hofmeister Š. (2007a): Obhospodařování bohatě strukturovaných a přírodě blízkých lesů. Kostelec nad Černými lesy, Lesnická práce: 447. (in Czech)

Vacek S., Matějka K., Simon J., Malík V., Schwarz O., Podrázský V., Minx T., Tesař V., Anděl P., Jankovský L., Mikeska M. (2007b): Zdravotní stav a dynamika lesních ekosystémů Krkonoš pod stresem vyvolaným znečištěním ovzduší. Folia Forestalia Bohemica. Kostelec nad Černými lesy, Lesnická práce: 216. (in Czech)

Vacek S., Hejcman M., Semelová V., Remeš J., Podrázský V. (2009): Effect of soil chemical properties on growth, foliation and nutrition of Norway spruce stand affected by yellowing in the Bohemian Forest Mts., Czech Republic. European Journal of Forest Research, 128: 367–375.

Vacek S., Vacek Z., Ulbrichová I., Remeš J., Podrázský V., Vach M., Bulušek D., Král J., Putalová T. (2019): The effects of fertilization on the health status, nutrition and growth of Norway spruce forests with yellowing symptoms. Scandinavian Journal of Forest Research, 34: 267–281.

Vacek Z., Prokůpková A., Vacek S., Cukor J., Bílek L., Gallo J., Bulušek D. (2020a): Silviculture as a tool to support stability and diversity of forests under climate change: Study from Krkonoše Mountains. Central European Forestry Journal, 66: 116–129.

Vacek Z., Vacek S., Prokůpková A., Bulušek D., Podrázský V., Hůnová I., Putalová T., Král J. (2020b): Long-term effect of climate and air pollution on health status and growth of *Picea abies* (L.) Karst. peaty forests in the Black Triangle region. Dendrobiology, 83: 1–19.

Vacek Z., Cukor J., Vacek S., Linda R., Prokůpková A., Podrázský V., Gallo J., Vacek O., Šimůnek V., Drábek O., Hájek V., Spasić M., Brichta J. (2021): Production potential, biodiversity and soil properties of forest reclamations: Opportunities or risk of introduced coniferous tree species under climate change? European Journal of Forest Research, 140: 1243–1266.

Vacek S., Remeš J., Vacek Z., Bílek L., Štefančík I., Baláš M., Podrázský V. (2022): Pěstování lesů. Czech University

https://doi.org/10.17221/34/2025-JFS

of Life Sciences Prague, Faculty of Forestry and Wood Sciences: 343. (in Czech)

Vacek Z., Vacek S., Cukor J. (2023): European forests under global climate change: Review of tree growth processes, crises and management strategies. Journal of Environmental Management, 332: 117353.

Viewegh J., Kusbach A., Mikeska M. (2003): Czech forest ecosystem classification. Journal of Forest Science, 49: 74–82.

Visconti P., Bakkenes M., Baisero D., Brooks T., Butchart S.H., Joppa L., Alkemade R., Di Marco M., Santini L., Hoffmann M., Maiorano L., Pressey R.L., Arponen A., Boitani L., Reside A.E., van Vuuren D.P., Rondinini C. (2015): Projecting global biodiversity indicators under future development scenarios. Conservation Letters, 9: 5–13.

Wagner S. (2004): Möglichkeiten und Beschänkungen eines funktionsorientierten Waldbaus. Forst und Holz, 59: 105–111. (in German)

Wagner S., Fischer H. (2007): Klimawandel – Wie reagiert der Waldbau? ProWALD, 3: 4–7. (in German)

Received: April 20, 2025
Accepted: May 26, 2025
Published online: July 22, 2025