Structural and Tree Species Diversification as a Challenging Task in Forests of the Air-polluted Jizera Mountains, Czech Republic

Authors: Kuneš, Ivan, Baláš, Martin, and Lánský, Pavel

Source: Mountain Research and Development, 40(2)

Published By: International Mountain Society

URL: https://doi.org/10.1659/MRD-JOURNAL-D-19-00059.1

Mountain Research and Development (MRD)
An international, peer-reviewed open access journal
published by the International Mountain Society (IMS)
www.mrd-journal.org

MountainDevelopment
Transformation knowledge

Structural and Tree Species Diversification as a Challenging Task in Forests of the Air-polluted Jizera Mountains, Czech Republic

Ivan Kuneš[1]*, Martin Baláš[1], and Pavel Lánský[2]
* *Corresponding author: kunes@fld.czu.cz*

[1] *Czech University of Life Sciences Prague, Faculty of Forestry and Wood Sciences, Kamýcká 129, 165 00 Praha 6–Suchdol, Czech Republic*
[2] *Forests of the Czech Republic, State Enterprise, Přemyslova 1106/19, Nový Hradec Králové, 500 08 Hradec Králové, Czech Republic*

The Jizera Mountains (Jizerské hory) are a part of the Black Triangle, which, in the past, was one of Europe's most polluted regions. Situated on the Czech–Polish border, these mountains were heavily affected by extreme SO_2 and NO_x loads emitted from coal power plants in the piedmont. During the 1970s and 1980s, the upper plateau of the Jizera Mountains experienced substantial forest decline due to air pollution. Dying stands were felled on more than 12,000 ha. Modernization of the energy industry after 1989 has led to a significant reduction in air pollution in the Black Triangle. Therefore, replanting the clear-cut areas in the Jizera Mountains became possible during the 1990s, and a new generation of forests has covered the upper plateau of the mountains. However, these even-aged, mainly spruce stands urgently need to be diversified in terms of age, structure, and species composition. This is not an easy task due to extreme microclimate, acidified soils, and damage to plants by rodents and deer. In 2007, a project aimed at the diversification of local ecosystems was initiated. The project is based on a system of diversification centers and corridors containing a species admixture (broadleaf trees and silver fir), which is protected from game, to form a web that enriches the age and spatial structure of forests on the upper plateau and complements their species composition. Initially, these centers and corridors were placed in more sheltered and accessible places and planted with the standard planting stock in combination with large-sized transplants (<100 cm). Through silvicultural measures, the web became successively denser and expanded to sites with less environmental protection. Supportive measures like initial fertilization of plantations and the biochemical amelioration of depleted soils have also been implemented.

Keywords: *forest restoration; broadleaf; silver fir; biodiversity; planting stock; Black Triangle.*

Peer-reviewed: *April 2020* ***Accepted:*** *June 2020*

Introduction

The Jizera Mountains are the northernmost mountains in the Czech Republic. In the 1970s and 1980s, the upper plateau of the Jizera Mountains (50°46′N, 15°16′E) experienced substantial forest decline due to air pollution (SO_2 and NO_x) and acidification of mountain ecosystems (Akselsson et al 2004; Vašát et al 2013). Modernization of the energy industry in the region reduced the air pollution (Hrkal et al 2006; Kolář et al 2015), and, through an enormous effort by foresters and environmentalists, the plateau was replanted (Karpaš and Hušek 2014). New forests established during the 1990s, after the air pollution was addressed, are predominantly even-aged spruce plantations (Figure 1). On the upper plateau, Norway spruce (*Picea abies* Karst.) naturally dominated. However, silver fir and broadleaves were also present in the tree species composition. The spruce stands need to be diversified with an admixture of native broadleaves (Balcar et al 2011) and silver fir (Balcar and Kacálek 2008b). They also need to be diversified in terms of spatial structure and age. Such diversification could increase their resistance to environmental and anthropogenic stresses (Guo et al 2019; Hisano et al 2019). Previous attempts to reintroduce broadleaves and silver fir to young spruce forests in the Jizera Mountains in the 1990s mostly failed (Kuneš et al 2012). This paper describes a newer management-oriented diversification project on the upper plateau launched in 2007. The aim of the article is to describe the project principles and summarize the promising experience more than a decade after it was first implemented.

Conditions and methodology of the project

Administration of forestry and nature conservation in the Jizera Mountains

The Jizera Mountains were designated the Protected Landscape Area (PLA) Jizerské hory (Jizera Mountains) in 1968. The administration office of PLA Jizera Mountains is part of the Nature Conservation Agency of the Czech Republic (NCA CR), a governmental body responsible for protection and conservation of nature and landscape across the whole territory of the Czech Republic. The NCA CR is also involved in activities related to the Convention on

FIGURE 1 Jizerka, one of a few settlements on the upper plateau of the Jizera Mountains, in 2017. The forests covering the upper plateau are mostly spruce, post-pollution plantations that require diversification. (Photo by Martin Baláš)

Biological Diversity (CBD 2012) in the Czech Republic, to which the project presented in this article contributes. The forests in the Jizera Mountains are for the most part managed by the state-owned enterprise Forests of the Czech Republic (LČR). The forestry managers in the Jizera Mountains have to obey the legislation on conservation and are therefore supervised by the administration office of PLA. The diversification project has been implemented in the forest district Jizerka (LČR). The project is promoted by LČR and NCA CR in terms of funding as well as organizational support.

Characteristics of the diversified area

The upper plateau of the Jizera Mountains is situated at 700–1000 masl. The major part of the plateau is formed of granites and granodiorites. The soils in the diversified area are mostly Entic and Haplic Podzols (Borůvka et al 2005). The soils are strongly acid, reaching the exchangeable pH in a range of 3–4, and show a decreasing trend in concentrations of available phosphorus. The soil chemistry of the humus layer and mineral soil in the Jizera Mountains was described by Lomský et al (2011). Mean annual temperature on the plateau ranges between less than 4°C and 5.5°C. Annual precipitation is between 900 and more than 1400 mm. Mean annual concentration of SO_2 was significantly reduced from values often exceeding 50 $\mu g/m^3$ (Karpaš and Hušek 2014) in the late 1980s to values mostly below 5 $\mu g/m^3$ at present. The forest on the upper plateau is currently dominated by spruces: mostly native Norway spruce (*Picea abies* Karst.) with some admixture of exotic species such as Colorado blue spruce (*Picea pungens* Engelm.), and Serbian spruce (*Picea omorica* (Pančić) Purkyně). The proportion of spruce stands was ca 90%, and stands of dwarf pine (*Pinus mugo* Turra) accounted for 3.5% of the forest area on the upper plateau in the early 2000s (Slodičák et al 2005). The forest district of Jizerka covers 2087 ha, which represents roughly 23% of the Czech part of the upper plateau.

The choice of species

The choice of tree species for diversification was limited exclusively to autochthonous taxa. We used European beech (*Fagus sylvatica* L.), silver fir (*Abies alba* Mill.), sycamore maple (*Acer pseudoplatanus* L.), and mountain elm (*Ulmus glabra* Huds.) on more sheltered sites. On the exposed summits of the mountains, we planted pioneer species such as rowan (*Sorbus aucuparia* L.) and Carpathian birch (*Betula pubescens* var. *carpatica* (Waldst. & Kit. ex Willd.) W.D.J. Koch). In places where the humus layer was disturbed, soil-improving stands of nitrogen-fixing speckled alder (*Alnus incana* /L./ Moench.) complemented the aforementioned species.

Reasoning behind the species choice: Beech, fir, and spruce were formerly the main components of climax natural forests in the Jizera Mountains (Vacek 2003) before human activities began to influence the tree species composition in favor of Norway spruce. Maple and elm were associated with climax communities in the local stands. At higher elevations, beech, fir, elm, and maple accompanied spruce on more sheltered sites, whereas pioneer Carpathian birch and rowan naturally colonized rock outcrops, screes, peat bog margins, and disturbed sites in the area. These pioneers can form nurse stands for planted climax species. Speckled alder naturally occurs along the water courses on the slopes of the Jizera Mountains. Nevertheless, the results of our previous research showed that planted speckled alder was able to grow satisfactorily under harsh conditions, even above the elevational zone of its common distribution, especially if spot-fertilized with basic amendments containing Ca, Mg, K, and P (Kuneš et al 2012). Therefore, the alder was also included in our diversification activities.

Novelty aspects and principles of the diversification project

In contrast to the previous diversification schemes realized in the 1990s, several novel aspects were implemented within our project (Box 1).

Implementation of the research outcomes: The project capitalizes on growth performance and survival information from experimental plantations established on the upper plateau of the Jizera Mountains in the 1990s and during the first decade of the new millennium. These outcomes were complemented by results from the adjacent Krkonoše (Giant) Mountains (GPS: 50°43′N, 15°37′E) and the Krušné hory (Ore) Mountains (GPS: 50°29′N, 13°11′E). All of these mountains belong to the former Black Triangle region (Hrkal et al 2012; Křeček and Hořická 2001). When preparing and optimizing the diversification strategy, we

BOX 1: Novel aspects and principles

In comparison to the previous diversification schemes, the project contains the following novel aspects:

- **Implementation of the research outcomes** from experimental plantations established on the upper plateau of the Jizera Mountains or in other mountains of the Black Triangle;
- **Inclusion of a system of diversification centers and microcenters** designed to provide consistent protection from game-browsing for broadleaf trees and fir planted in spruce stands;
- **Use of large-sized, bare-rooted planting stock** of broadleaf trees with high-quality root systems (**saplings**) that complement the standard common-sized plants (container or bare-rooted seedlings);
- **Testing of precisely applied fertilization** to counteract the soil acidity and promote the survival and growth of the planted tree species to diversify the stands.

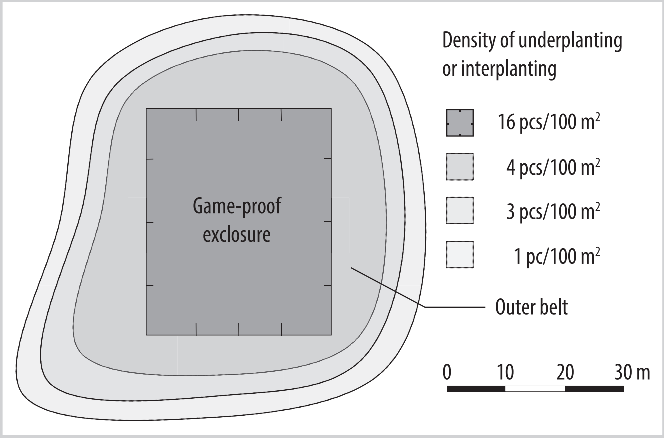
considered the published scientific data on European beech and sycamore maple (Balcar and Podrázský 1995; Balcar and Kacálek 2008a; Balcar et al 2011; Špulák 2011), silver fir (Balcar and Kacálek 2008b), mountain elm (Balcar et al 2009), birches (Balcar 2001; Kuneš et al 2007), rowan (Podrázský and Moravčík 1992; Kuneš, Baláš, Zahradník, et al 2014), speckled alder (Kuneš et al 2012; Kuneš, Baláš, Koňasová, et al 2014), and Norway spruce, as well as Colorado blue spruce (Slodičák and Novák 2008; Špulák 2011; Špulák and Kacálek 2016; Špulák et al 2019).

An important topic was the soil chemistry and the application of basic amendments to counteract the soil acidity, replenish the most lacking nutrients, and provide some initial support to the forest plantations. This question was to some extent addressed within the aforementioned works on particular tree species. However, general studies on soil chemistry in the area (Borůvka et al 2005; Lomský et al 2011), as well as some conceptual literature on fertilization (Miller 1981), also influenced our project. We used the findings of our research (systems knowledge sensu Hurni et al 2009) when outlining the strategy of our diversification project.

System of diversification centers and microcenters: The system consists of centers (standard centers and microcenters) and corridors interlinking them. A standard center consists of a central game-proof exclosure (from 20 × 20 m to 50 × 50 m) that is surrounded by an outer belt, where the broadleaf trees and fir were planted at a lower density than in the fenced exclosure (Figure 2). The trees in the outer belts were protected individually, usually with plastic-tube shelters or with tree guards. Microcenters are represented by small game-proof exclosures (from 6 × 6 m to 12 × 12 m) and do not have outer belts. Corridors are linear or strip plantations of broadleaf trees connecting the diversification centers.

The successive introduction of broadleaf trees and silver fir to the spruce stands began with the careful selection of the most convenient places for diversification centers. These places were easily accessible from forest roads to facilitate construction, inspection, and maintenance of game-proof fencing and individual tree shelters, plus the application of rodent repellents. Moreover, occasional traffic on the forest roads (vehicles of forest staff, cyclists, hikers, cross-country skiers) would prevent the game from concentrating around the new plantations. If possible, these places were selected to provide the planted broadleaves and fir with a beneficial environment in comparison to the immediate surroundings (sheltered microsites, more favorable humidity regime, etc). The introduction of broadleaf trees and fir also involved, under certain circumstances, making small openings in the coniferous stands or utilizing existing ones. This was often connected with the tending of Norway spruce and with conversion of allochthonous Colorado blue spruce. The centers and microcenters were interlinked in steps by interplanting or underplanting corridors in the advanced stages of forest diversification. In this way, a web diversifying the stands in terms of structure, species composition, and age was gradually created within the area (Figure 3).

FIGURE 2 Scheme of a standard diversification center consisting of a central game-proof exclosure and outer belt with trees protected by plastic tubes or tree guards. pc, piece.



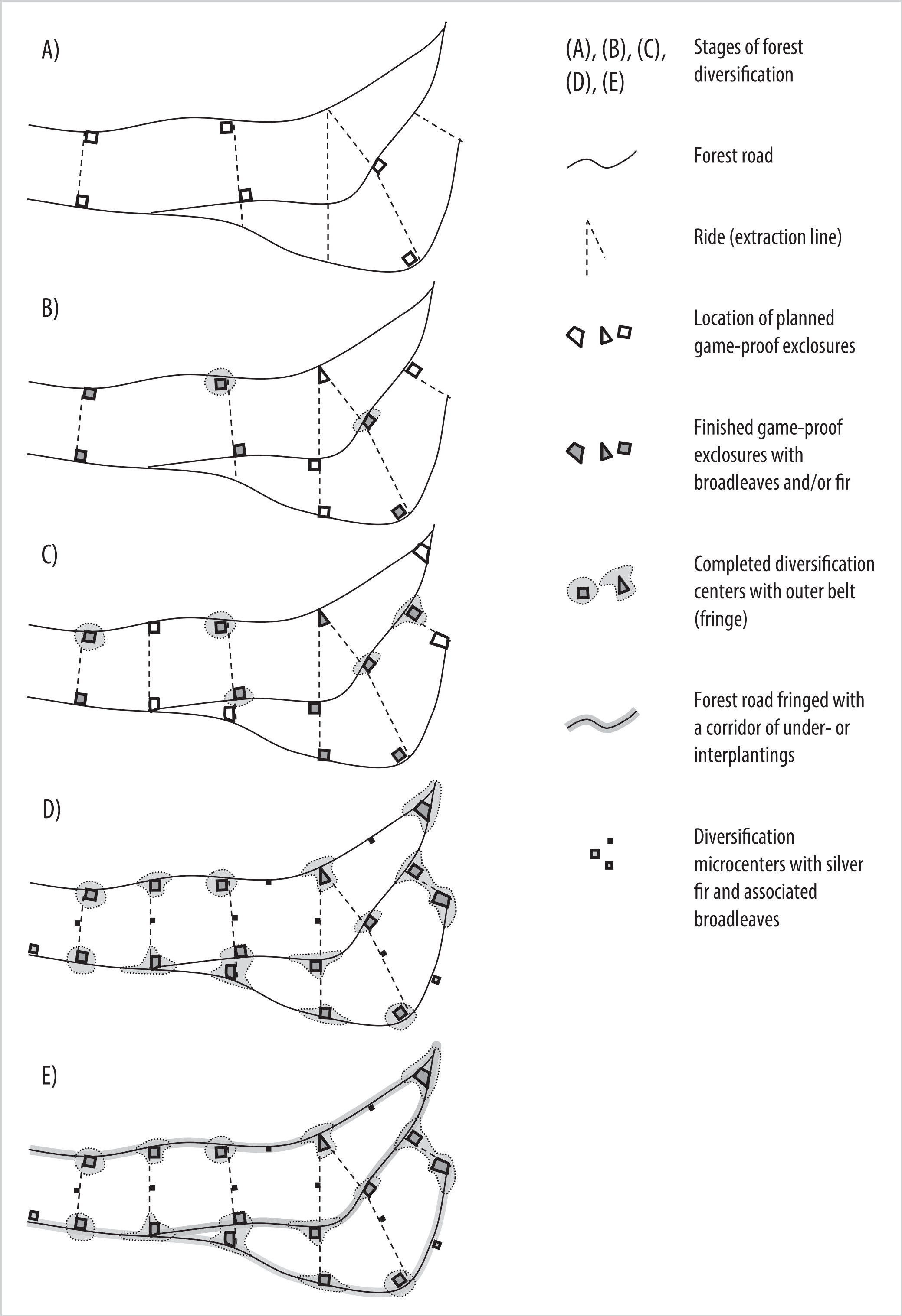
In contrast to the mostly unsuccessful large-scale diversification schemes of the coniferous stands realized in the past, the diversification centers enable better protection of the interplanted admixture from game and easier care after planting.

Saplings: Saplings (ca 100–150 cm in height) were produced using an innovative nursery technology (Burda et al 2015). The root systems of the saplings were dense and compact with a high proportion of fibrous roots. The root systems were well shaped (no deformities) with roots concentrated under the stem of the saplings. Therefore, the planting holes did not have to be large (Figure 4): planting holes with dimensions of 30 × 30 × 30 cm were sufficient. Nonetheless, these minimum dimensions of planting holes should be strictly respected.

The quality root systems were achieved by several transplantations and root pruning, even in the advanced phase of production when the plants are already a considerable size. The use of specially designed machinery enabled intensive production of saplings and thus kept production costs low (depending on the species approximately US$ 1.0–2.2 per tree). Together with the saplings, a common-sized (ca 20–40 cm in height) bare-

 https://doi.org/10.1659/MRD-JOURNAL-D-19-00059.1

FIGURE 3 Successive introduction of broadleaf trees and silver fir to the spruce stands is based on selecting convenient places for interplanting or underplanting the stands with a desirable admixture. The diversification centers gradually form a web within the diversified forest area. The centers should also be interlinked by interplanting or underplanting corridors in the advanced stages of forest diversification.



rooted or container-grown stock was used for broadleaf and silver fir planting.

Fertilization to counteract soil acidity and support new plantations: Since the naturally poor and acid soils in the Jizera Mountains were further impoverished by anthropogenic acidification due to air pollution (Pavlů et al 2007), new plantations of broadleaf trees and fir were initially fertilized. We exclusively used slow-release fertilizers applied to the individual trees. The nutrient composition of the fertilizers reflected the nutritional status of the existing spruce stands

FIGURE 4 Bare-rooted saplings (depicted European beech) used in the diversification project to complement the common-sized planting stock. The fibrous root systems of the saplings are concentrated under the stem. The aboveground parts of the saplings are formatively pruned to reduce the growth and occurrence of coarse lateral branches. (Photos courtesy of Pavel Burda Forest Nurseries)

and, eventually, also the soil chemistry at the diversified sites. The nutritional status was assessed on the basis of foliar analyses (Kuneš et al 2011). If N was needed to expedite the initial growth of plantations (apart from soil bases and P), it was applied as the condensation products of urea and formaldehyde (Jahns et al 1999, 2003; Jahns and Kaltwasser 2000) to avoid increased nitrification activity in the soil (Aarnio and Martikainen 1995).

Realization experience and recommendations

As mentioned earlier, we utilized the systems knowledge yielded from the research when defining the project principles and strategy of our diversification project. However, implementation of the project brought experience (transformation knowledge sensu Hurni et al 2009), which will be important to successfully transfer the project strategy and apply it elsewhere.

Planting stock

The bare-rooted saplings of broadleaves grew satisfactorily. These complement the small, common-sized plants under specific conditions. Taking rowan as an example, this was documented by Kuneš, Baláš, Zahradník, et al (2014). For beech and maple, photo documentation is available in Figures S3, S5, and S6, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00059.1.S1.

If left unprotected, the taller conspicuous trees are more vulnerable to browsing than small plants (Miller et al 1982). However, if the protection is provided, large planting stock can more efficiently utilize the lifespan of individual shelters or game-proof fencing. An important advantage of the saplings was the fact that their terminal buds were safely above the ground-frost zone and the level of competing weeds. On the upper plateau, *Calamagrostis villosa*/Chaix/ J. F. Gmel. is dominant in the herbaceous layer (Pyšek 1993; Křeček et al 2010); this is a tough competitor to trees (Gloser and Gloser 2000). The large saplings are usually better at competing with it.

Planting and protection of trees

We recommend planting bare-rooted broadleaf trees in autumn. Spring is preferred for silver fir, if bare-rooted seedlings are outplanted, but autumn is better if container firs are used.

Because of the snow, rime, hoar frost, and ice coating in winter, the saplings (when not inside the plastic shelters) need to be supported by wooden poles. The support poles must be produced from seasoned (dried) sawn timber, since seasoned timber does not split as easily when rammed into the ground. More durable hardwood (oak, ash, black locust) is better suited.

Polyvinylchloride (PVC) grafting tape is best to fasten the saplings to the poles, because it is flexible enough to allow the tree stem to thicken, even if the clamp fastening a tree to the support pole is tightened. Adequately tightened 8-form clamps are important to maintain their position on the support pole and prevent the trees from damage by rubbing (wind abrasion). Details are given in Figure S7, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00059.1.S1.

Silver fir, rowan, beech (Kamler et al 2010; van Beeck Calkoen et al 2019), maple, and elm (Simončič et al 2019) are palatable to red and roe deer (*Cervus elaphus* L.; *Capreolus*

FIGURE 5 Diversification center (GPS: N 50°49.15022′, E 15°21.12077′) situated in a frost pocket close to the Jizerka settlement on the upper plateau of the Jizera Mountains. (A) A newly established center in the summer of 2009; (B) 7 years later with plantation of Carpathian birch (*Betula carpatica*), see the light-green crowns in the background, introduced to an older stand of Norway spruce (*Picea abies*), dwarf pine (*Pinus mugo*), and blue spruce (*Picea pungens*). (Photos by Ivan Kuneš)

capreolus L.) and/or hares (*Lepus europaeus* Pallas). In the outer zones (ie outside of the fenced exclosures), protection was provided by plastic tube shelters (Figures 2, 5) or tree guards (Figure S4, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00059.1.S1). The plastic shelters must be at least 170 cm tall. Recently, we have used seamless, twin-walled tube shelters that are 180 cm tall. Fencing must be robust to resist the deformation forces of snow cover and rime. It should be approximately 170–190 cm tall to be red-deer safe (Figure S9, *Supplemental material*, https://doi.org/10.1659/MRD-JOURNAL-D-19-00059.1.S1).

Comparison of fenced game-proof exclosures and individual shelters: The fenced game-proof exclosures and individual shelters complement each other (Figure 5), since both have strengths and weaknesses. Game-proof exclosures, if well built and maintained, are the best protection against hoofed game. However, their construction is expensive. The overall construction cost of fencing is currently approximately US$ 6,050.00 per km in the region. Therefore, the spatial density of planted broadleaves and/or silver firs in the exclosures must be relatively high to be economically justifiable (Figure 2), which increases the risk of damage caused by rodents (mice and voles), a serious hazard to young broadleaved plantations (Flousek 1999; Mauer and Palátová 2011). For example, the mortality of beeches in the game-proof fenced experimental plantations in the Jizera Mountains was predominantly caused by voles (*Microtus agrestis* L.). Observations suggest that the rodents prefer beech and maple to rowan and birch.

Nevertheless, all broadleaves, as well as silver fir, are not safe from rodents, particularly when the rodent populations are in gradation. In the outer fringes of the diversification centers, hoofed game remain a key factor affecting the development of forest plantations. A year after planting, the proportion of rowan and maple saplings in the 170 cm tall plastic shelters that had damaged terminal shoots due to game browsing ranged from 54% to 70% depending on the size of the trees. If the terminal shoot of a tree reaches over the upper rim of the shelter, it becomes more vulnerable to browsing. Therefore, when the terminal shoots grow out of the plastic shelters, they should be treated annually with repellent to prevent browsing by red deer. Regular inspection and maintenance of the stabilization poles is also required.

The effectiveness of plastic shelters to protect trees from rodents is disputable. The rodents were often able to get inside the shelters and nibble the saplings. However, in contrast to the spacing inside the fenced exclosures, the individually protected saplings outside the centers are less densely spaced. This reduces the risk of damage. Moreover, the individual shelters protect the trees from hares that are often able to get to exclosures.

Diversification centers should be equipped with outer fringes only in places where a higher frequency of (human) visitors and activities prevents deer from staying for a longer time (proximity to hiking routes, forest road crossings, etc).

Initial fertilization: In the Jizera Mountains, P and K seem to be the most frequently limiting elements in the mineral nutrition of forest plantations (eg Kuneš et al 2011). European beech, silver fir, and mountain elm would probably respond positively to initial slow-release N–P–K(–Mg) fertilization. An addition of slow-release nitrogen should help the young plants to revive and overcome the transplant shock. A positive response can also be expected in the case of speckled alder with P–K–Ca–Mg amendment. Initial fertilization of Carpathian birch seems unnecessary. The composition and dosage of the amendment should always be adjusted to the particular situation. We recommend applying pelletized fertilizers on the surface of the soil around the standard seedlings and saplings in circles of approximately 40 and 60 cm diameter. The pellets should be distributed at equal distances around the perimeter of a crown projection and incorporated into the soil, so that they are in the humid soil environment.

Time requirements related to manual planting of the saplings: In the course of planting the saplings in the central exclosures of the enrichment centers, the time to accomplish particular phases was recorded. The selected work phases and their mean time requirements were as follows: delivery of a pole and a sapling (28 seconds), digging a hole and planting a tree (259 seconds), installing a support pole (58 seconds), fixing the tree to a pole (58 seconds). The total mean planting time (planting of 1 sapling by 1 worker) was 393 seconds (ie 6:33 minutes). In other words, 9 saplings can be planted by a person per 1 hour.

Since planting of bare-rooted broadleaves is recommended in autumn (shortened autumn daylight period) and with regard to the specific local conditions (remote localities of plantations), the 5-hour real work time per day (8-hour shift) was only considered. Therefore, the 1-day mean performance of 1 worker was about 45 completely planted saplings with stabilization (support poles) installed. The optimal size of a labor group to achieve maximum work efficiency was 5 workers.

If we count an hourly wage in the region of approximately US$ 7.95, then the overall outplanting cost is approximately US$ 1.42 per sapling including installation of a support pole (8-hour shift and 5-hour working time calculated). The calculation is derived from data published by Balᚠet al (2011) and converted to a recent price level (2019). The time to plant the saplings may vary. The aforementioned time requirements are related to stony, shallow soils. On deeper and less skeletal soil profiles, the time may be significantly shorter.

Uncertainties related to the system of diversification centers and saplings

The technique of diversification described in the article is relatively new in forestry, and there are still questions to be answered. For example, in the coming years, the development of roots and root system architecture of the saplings in the acidic and impoverished mountain soils will be investigated.

The production of saplings takes ca 3–6 years, which requires planning silvicultural operations several years in advance. Only the top-quality seedlings are selected to produce saplings, which is necessary and understandable from a nursery perspective. This selection, nonetheless, could narrow the genetic base of the planting stock. This bottleneck effect should be reduced by the fact that saplings are not to be used extensively, and, within the project, they are combined with common-sized planting stock.

If hoofed-game browsing is eliminated (well-built fenced exclosures), damage by rodents and hares or by frost, snow, and rime could occur. However, this hazard is perhaps even greater for common-sized planting stock than for saplings. Above all, the most serious uncertainty is related to the high stock of hoofed game in the region. Even if the technological system works, the overall success of the admixture introduction is conditional on the reduction of grazing pressure from hoofed game in local ecosystems.

After more than a decade, we can assume that the most important step in promoting the diversification of the forests was the provision of a system consistently protecting the young broadleaved trees and fir plantations from hoofed game. The overabundance of hoofed game affecting the tree species diversity is a major problem not only in the Jizera Mountains, but also in the other formerly air-polluted mountains of the Black Triangle, such as the Krkonoše (Giant) Mountains and the Krušné hory (Ore) Mountains.

Sharing the experience and knowledge among different stakeholders

The transformation knowledge derived from the project is particularly relevant to three main groups of stakeholders within the field of forestry and nature conservation: practitioners, practice-oriented researchers, and students of the respective study programs. The practitioners (foresters, environmentalists, representatives of state administration) and practice-oriented researchers are mostly informed during field workshops where the project principles and outcomes are presented and discussed. The diversification project is regularly presented to the students of university programs focused on forestry and environmental sciences through fieldtrips to the Jizera Mountains, as well as at classroom lectures. Further discussions with the students and practitioners give the authors of the project important feedback.

Message for decision makers

The total area of the clear-felled tracts in the Jizera Mountains amounted to 12,000 ha at the end of the 1980s. These tracts have been replanted. On the upper plateau, spruce stands predominate, accompanied by dwarf pine. However, the proportion of silver fir and broadleaves, such as beech, maple, birch, and rowan, should be increased. Without diversification, the local forest ecosystems will be significantly more vulnerable to abiotic and biotic stresses resulting from climate change.

The proportion of the underplanted or interplanted broadleaves and silver fir in the target species composition of a diversified forest does not necessarily have to be high. The whole area of the centers and corridors, if these are distributed within the proposed spatial system (Figure 3), does not have to be particularly large to produce the required diversification effect.

The project is now in the stage of research verification and operational assessment mostly in the area of 1 forest district (Jizerka) in the central part of the Jizera Mountains. If the verification is successful, the diversification scheme could be expanded to the other forest districts on the upper plateau.

A rough economic calculation suggests that creation of a system of diversification components (with areal proportion of 10%) covering the whole Czech part of the upper plateau would require approximately US$ 29 million within 20 years of implementation (calculated rate of inflation of 3.5%). The state forests cannot completely cover such a high cost, but a number of grants could be available (eg from EU funds).

Conclusions

The system of centers and corridors with growing broadleaf trees and silver fir on the upper plateau of the Jizera Mountains suggests that the strategy described is a promising approach to diversifying the spruce forests of the mountains in terms of age, structure, and species composition. This holds true, especially if the system of diversification centers is combined with tending of the existing spruce stands. The bare-rooted saplings of broadleaves complement standard common-sized seedlings, especially on weed-infested sites, or sites prone to ground frosts during growing season. The saplings must be stabilized either by support poles or placed in plastic shelters to avoid deformation caused by snow. Broadleaves and fir must be protected from browsing by hoofed game. The overall long-term success of diversification also depends on the reduction of overstocked populations of hoofed game (red and roe deer). Our approach could be applied to diversifying the coniferous forests of other formerly air-polluted areas, such as the Krušné hory (Ore) Mountains or the Krkonoše (Giant) Mountains.

ACKNOWLEDGMENTS

We would like to express our gratitude to Vratislav Balcar (Forestry and Game Management Research Institute Jíloviště–Strnady) and Petr Navrátil (Forest Management Institute, Brandýs nad Labem) for valuable comments and research on which the project capitalized. Our thanks are addressed to Jitka Šišáková and Rick Manore for proofreading the manuscript. The activities described in the paper were supported by the Ministry of Agriculture of the Czech Republic (projects NAZV QH92087 and QK1920328), Forests of the Czech Republic, state enterprise, Nature Conservation Agency of the Czech Republic (PLA Administration Jizerské hory), and the Czech University of Life Science in Prague (Project No. A_19_24). The paper was prepared also in the frame of activities covered by the unit 1.01.05, Mountain forest management, of the IUFRO.

REFERENCES

Aarnio T, Martikainen PJ. 1995. Mineralization of C and N and nitrification in Scots pine forest soil treated with nitrogen fertilizers containing different proportions of urea its slow-releasing derivate, ureaformaldehyde. *Soil Biology and Biochemistry* 27(10):1325–1331.
Akselsson C, Ardö J, Sverdrup H. 2004. Critical loads of acidity for forest soils and relationship to forest decline in the northern Czech Republic. *Environmental Monitoring and Assessment* 98:363–379.
Baláš M, Kuneš I, Šrenk M, Koňasová T. 2011. Time requirements and work standards related to planting of bare-rooted saplings of broadleaves on mountain sites [in Czech with English abstract and summary]. *Zprávy Lesnického Výzkumu* 56(3):235–243.
Balcar V. 2001. Some experience of European birch (*Betula pendula* Roth) and Carpathian birch (*Betula carpatica* W. et K.) planted on the ridge part of the Jizerské hory Mts. *Journal of Forest Science* 47(Special Issue):150–155.
Balcar V, Kacálek D. 2008a. European beech planted into spruce stands exposed to climatic stresses in mountain areas. *Austrian Journal of Forest Science* 125(1):127–138.
Balcar V, Kacálek D. 2008b. Growth and health state of silver fir (*Abies alba* Mill.) in the ridge area of the Jizerské hory Mts. *Journal of Forest Science* 54(11):509–518.
Balcar V, Kacálek D, Kuneš I. 2009. Scotch elm (*Ulmus glabra* Huds.) plantations prosperity in ridge part of the Jizerské hory Mts [in Czech with English abstract and summary]. *Zprávy Lesnického Výzkumu* 54(Special Issue):3–8.
Balcar V, Kacálek D, Kuneš I, Dušek D. 2011. Effect of soil liming on European beech (*Fagus sylvatica* L.) and sycamore maple (*Acer pseudoplatanus* L.) plantations. *Folia Forestalia Polonica, Series A* 53(2):85–92.
Balcar V, Podrázský V. 1995. Vitality improvement of forest tree plantations by application of milled rocks on calamity clearcuts in the Jizerské Mts [in Czech with English abstract and summary]. *Zprávy Lesnického Výzkumu* 40(3–4):44–49.
Borůvka L, Mládková L, Drábek O. 2005. Factors controlling spatial distribution of soil acidification and Al forms in forest soils. *Journal of Inorganic Biochemistry* 99:1796–1806.
Burda P, Nárovcová J, Nárovec V, Kuneš I, Baláš M, Machovič I. 2015. Technology for production of new generation semisaplings and saplings of broadleaves in forest nurseries—Summary of certified technology. *In:* Houšková K, Černý J, editors. *Proceedings of Central European Silviculture*. Brno, Czech Republic: Mendel University in Brno, pp 9–18.
CBD [Convention on Biological Diversity]. 2012. Introduction. www.cbd.int/intro/; accessed on 18 September 2020.
Flousek J. 1999. Field vole (*Microtus agrestis*) and forest management in Giant Mts [in Czech with English abstract]. *In:* Slodičák M, editor. *Regeneration and Stabilisation of Mountain Forests*. Jíloviště–Strnady, Czech Republic: Výzkumný ústav lesního hospodářství a myslivosti (VÚLHM), pp 49–53.
Gloser V, Gloser J. 2000. Nitrogen and base cation uptake in seedlings of *Acer pseudoplatanus* and *Calamagrostis villosa* exposed to an acidified environment. *Plant and Soil* 226(1):71–77.
Guo Q, Fei S, Potter KM, Liebhold AM, Wen J. 2019. Tree diversity regulates forest pest invasion. *Proceedings of the National Academy of Sciences* 116(15):7382–7386.
Hisano M, Chen HYH, Searle EB, Reich PB. 2019. Species-rich boreal forests grew more and suffered less mortality than species-poor forests under the environmental change of the past half-century. *Ecology Letters* 22(6):999–1008.
Hrkal Z, Burda J, Fottová D, Hrkalová M, Nováková H, Novotná E. 2012. Groundwater quality development in area suffering from long term impact of acid atmospheric deposition—The role of forest cover in Czech Republic case study. *In:* Voudouris K, editor. *Water Quality Monitoring and Assessment*. Shanghai, China: InTech, pp 561–584.
Hrkal Z, Prchalová H, Fottová D. 2006. Trends in impact of acidification on groundwater bodies in the Czech Republic; an estimation of atmospheric deposition at the horizon 2015. *Journal of Atmospheric Chemistry* 53:1–12.
Hurni H, von Dach SW, Zimmermann A, Wachs T. 2009. Editorial. *Mountain Research and Development* 29:3–4.
Jahns T, Ewen H, Kaltwasser H. 2003. Biodegradability of urea-aldehyde condensation products. *Journal of Polymers and the Environment* 11(4):155–159.
Jahns T, Kaltwasser H. 2000. Mechanism of microbial degradation of slow-release fertilizers. *Journal of Polymers and the Environment* 8(1):11–16.
Jahns T, Schepp R, Siersdorfer C, Kaltwasser H. 1999. Biodegradation of slow-release fertilizers (methyleneureas) in soil. *Journal of Environmental Polymer Degradation* 7(2):75–82.

Kamler J, Homolka M, Barancekova M, Krojerova-Prokesova J. 2010. Reduction of herbivore density as a tool for reduction of herbivore browsing on palatable tree species. *European Journal of Forest Research* 129(2):155–162.
Karpaš R, Hušek J, editors. 2014. *The Jizera Mts. 3: About the Forests, Wood and Nature Conservation* [in Czech]. Liberec, Czech Republic: Nakladatelství RK.
Kolář T, Čermák P, Oulehle F, Trnka M, Štěpánek P, Cudlín P, Hruška J, Büntgen U, Rybníček M. 2015. Pollution control enhanced spruce growth in the "Black Triangle" near the Czech–Polish border. *Science of the Total Environment* 538:703–711.
Křeček J, Hořická Z. 2001. Degradation and recovery of mountain watersheds: The Jizera Mountains, Czech Republic. *Unasylva* 52(207):43–49.
Křeček J, Nováková J, Hořická Z. 2010. Ellenberg's indicator in water resources control: The Jizera Mountains, Czech Republic. *Ecological Engineering* 36(9): 1112–1117.
Kuneš I, Baláš M, Koňasová T, Špulák O, Balcar V, Bednářová Millerová K, Kacálek D, Jakl M, Zahradník D, et al. 2014. Biomass of speckled alder on an air-polluted mountain site and its response to fertilization. *Environmental Management* 54(6):1421–1433.
Kuneš I, Baláš M, Koňasová T, Zahradník D, Balcar V, Špulák O, Kacálek D, Jakl M, Jaklová Dytrtová J. 2012. Cultivation of speckled alder under harsh mountain conditions. *Journal of Forest Science* 58(5):234–244.
Kuneš I, Baláš M, Špulák O, Kacálek D, Balcar V, Šesták J, Millerová K. 2011. Nutritional status of Norway spruce as an information source for decision whether to fertilize the broadleaves and silver fir introduced to coniferous stands [in Czech with English abstract and summary]. *Zprávy Lesnického Výzkumu* 56(Special Issue):36–43.
Kuneš I, Baláš M, Zahradník D, Nováková O, Gallo J, Nárovcová J, Drury M. 2014. Role of planting stock size and fertilizing in initial growth performance of rowan (*Sorbus aucuparia* L.) reforestation in a mountain frost hollow. *Forest Systems* 23(2):273–288.
Kuneš I, Balcar V, Zahradník D. 2007. Influence of a planting hole application of dolomitic limestone powder and basalt grit on the growth of Carpathian birch (*Betula carpatica* W. et K.) and soil chemistry in the air-polluted Jizerské hory Mts. *Journal of Forest Science* 53(11):505–515.
Lomský B, Šrámek V, Novotný R. 2011. Changes in the air pollution load in the Jizera Mts.: Effects on the health status and mineral nutrition of the young Norway spruce stands. *European Journal of Forest Research* 131:757–771.
Mauer O, Palátová E. 2011. Root system development of European beech (*Fagus sylvatica* L.) after different site preparation in the air-polluted area of the Krušné hory Mts. *Beskydy* 4(2):147–160.
Miller GR, Kinnaird JW, Cummins RP. 1982. Liability of saplings to browsing on a red deer range in the Scottish Highlands. *Journal of Applied Ecology* 19:941–951.
Miller HG. 1981. Forest fertilization: Some guiding concepts. *Forestry* 54(2):157–167.
Pavlů L, Borůvka L, Nikodem A, Rohošková M, Penížek V. 2007. Altitude and forest type effects on soils in the Jizera mountains region. *Soil and Water Research* 2(2):35–44.
Podrázský V, Moravčík P. 1992. Biomass and nutrients accumulation in mountain ash stands located near Pomezní boudy in Krkonoše Mts [in Czech with English summary]. *Opera Corcontica* 29:123–137.
Pyšek P. 1993. What do we know about *Calamagrostis villosa*? A review of the species behaviour in secondary habitats. *Preslia* 65(4):289–384.
Simončič T, Bončina A, Jarni K, Klopčič M. 2019. Assessment of the long-term impact of deer on understory vegetation in mixed temperate forests. *Journal of Vegetation Science* 30(1):108–120.
Slodičák M, editor. 2005. *Forestry Management in the Jizerské hory Mts* [in Czech with English abstract and summary]. Hradec Králové and Jíloviště–Strnady, Czech Republic: Lesy České republiky and Výzkumný ústav lesního hospodářství a myslivosti (VÚLHM).
Slodičák M, Novák J. 2008. Nutrients in the aboveground biomass of substitute tree species stand with respect to thinning–blue spruce (*Picea pungens* Engelm.). *Journal of Forest Science* 54(3):85–91.
Špulák O. 2011. Acclimatization of European beech (*Fagus sylvatica* L.) leaves first year after planting into different light conditions of young spruce stand. *Folia Forestalia Polonica, Series A* 53(2):104–113.
Špulák O, Kacálek D. 2016. Below-canopy and topsoil temperatures in young Norway spruce and Carpathian birch stands compared to gaps in the mountains. *Journal of Forest Science* 62(10):441–451.
Špulák O, Kacálek D, Balcar V. 2019. Seven spruce species on a mountain site—Performance, foliar nutrients, and forest floor properties in stands 20 years old. *iForest—Biogeosciences and Forestry* 12(1):106–113.
Vacek, S. 2003. *Mountain Forests of the Czech Republic*. Prague, Czech Republic: Ministry of Agriculture of the Czech Republic.
van Beeck Calkoen STS, Leigh-Moy K, Cromsigt JPGM, Spong G, Lebeau LC, Heurich M. 2019. The blame game: Using eDNA to identify species-specific tree browsing by red deer (*Cervus elaphus*) and roe deer (*Capreolus capreolus*) in a temperate forest. *Forest Ecology and Management* 451:117483.
Vašát R, Pavlů L, Borůvka L, Drábek O, Nikodem A. 2013. Mapping the topsoil pH and humus quality of forest soils in the North Bohemian Jizerské hory Mts. Region with ordinary, universal, and regression kriging: Cross-validation comparison. *Soil and Water Research* 8(3):97–104.

Supplemental material

FIGURE S1 The Jizera Mountains in the early 1990s.
FIGURE S2 Rowan plantation in a diversification center.
FIGURE S3 Broadleaf development in a plantation.
FIGURE S4 Silver firs in one of the diversification centers.
FIGURE S5 Diversification center with European beech.
FIGURE S6 A microcenter and an interplanting corridor.
FIGURE S7 Polyvinylchloride (PVC) grafting tape fastening a sapling to a support pole.
FIGURE S8 Installation of support poles in a newly established diversification center.
FIGURE S9 Fencing construction for game-proof exclosures.

Found at: https://doi.org/10.1659/MRD-JOURNAL-D-19-00059.1.S1.