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Research on an effective artificial regeneration method for selected commercially important coniferous tree species on a large sanitation cut site situated in the Javorníky Mts., Western Carpathians

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Abstract: In response to the decline of Central European spruce monocultures driven by various factors, the Demonstration Object of Reconstruction of Spruce Forests (DORS) was established in Husárik locality, Javorníky Mts., northwestern Slovakia. The area includes the Husárik trial site, where the applicability and efficiency of different artificial regeneration methods are studied. The trial was established on a 24-ha area cleared following the outbreak of spruce bark beetles in 2011. Its altitude is 800 m a.s.l., aspect NW, slope 30%, the soil is Ranker on the soft flysch sandstone bedrock. Our study covered 4 conifers – Norway spruce (spruce), European larch (larch), silver fir (fir), and Douglas fir (doug fir). Each species was regenerated using 4 different approaches: planting of commercial bareroot transplants (BR), planting of container transplants (CON), direct seeding (DS) and vegetative cell seeding using seed shelters (VCS). Results concerning the nine-year development of transplants and seedlings, along with the calculation of cost-efficiency, are presented. As to the species, BR and CON transplants of spruce and larch reached the best survival and height. The DS larch was the most cost-efficient method of establishment of a successfully established plantation (survival > 50%; stem height > 2/3 of the weed height; ratio of damaged individuals < 50%) with a total cost of 2 372 EUR·ha^{-1}. On the contrary, the slow initial growth of fir and Douglas fir and their extensive damage resulted in the incomparably higher cost of establishment of their successfully established plantation, such as 4 980 EUR·ha^{-1} for five-years-old BR fir transplants. Our findings documented that current efforts related to the restoration of salvage-felled clearings remained difficult, especially in the case of introduction or reestablishment of coniferous tree species more vulnerable to open site conditions.

Keywords: artificial regeneration; bareroot plants; conifers; container plants; seeding; successfully established plantation

The beginning of the systematic establishment of coniferous monocultures in Central Europe dates back to the 19th century (Jansen et al. 2017) and forest stands dominated by Norway spruce have provided a valuable source of timber to the landowners for more than two hundred years (Seim et al. 2022).

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Recent effects of climate change, however, markedly hamper the vitality and status of these forest formations and have raised the question of their future management (Bolte et al. 2009). Although the restoration of significantly disturbed non-native coniferous forests in Central Europe primarily relies on the planting of deciduous tree species (Ammer et al. 2008; Vacek et al. 2021), coniferous tree species such as European larch, silver fir, Douglas fir and Norway spruce remain a reasonable option for enhancement of wood production in forests with suitable site and climate conditions (Kozak et al. 2013; Podrázský et al. 2016; Vitali et al. 2017; Čermák et al. 2021). In these conditions, however, the establishment of a satisfactorily stocked stand with the desirable tree species composition is becoming a challenging task. The abrupt decline of secondary forests accompanied by unexpectedly large areas in need of complete reforestation (Konôpka, Konôpka 2007; Kunca et al. 2015; Zahradník, Zahradníková 2019) challenge the production capacities for forest reproductive material due to the technical infrastructure as well as workforce limitations (Mlčoušek, Křístek 2021). Further complications are due to the restrictions related to the horizontal and vertical transfer of forest reproductive material (Repáč et al. 2017; Mlčoušek, Křístek 2021). In addition, considering the most commonly planted bareroot stocktype in Slovakia, satisfaction of fluctuating demand for reproductive material is also hampered by the length of cultivation period required for its production (Repáč et al. 2017; Bruchánik 2020).

Nevertheless, the development of methods enabling the production of forest tree species planting material of desirable quality within a reduced time period resulted in the conceptualisation of procedures and techniques that were capable of producing morphologically well-developed transplants within one or two growing seasons (Landis et al. 2010; Mattsson et al. 2010; Zahradník et al. 2018). Besides a shorter period required for the cultivation of container transplants compared to bareroot ones, container transplants also have other benefits, including a lower risk of root system damage, lower vulnerability to growth shock, and better survival and growth after planting (Leugner et al. 2009; Grossnickle, El-Kassaby 2016). On the other hand, the shortened cultivation cycle of planting material in container nurseries has also constraints related to lower flexibility of equipment demanding technology (area of greenhouses with regulated water and nutrient regime, storage places, cultivation trays etc.), which may fail to satisfy unexpected demands of large salvage felled areas (Landis et al. 2010; Mlčoušek, Křístek 2021).

However, artificial establishment of target tree species on salvage or clear-felled areas does not have to be necessarily realised through the planting of nursery-grown transplants (Palma et al. 2015; Grossnickle, Ivetić 2017). Reforestation methods, including recruitment of individuals from seeds directly sown into the substrate or mineral soil of a reforested site, represent an immediately available alternative to the conventionally used planting of transplants (Erefur et al. 2008; Grossnickle, Ivetić 2017; Repáč et al. 2017). Additionally, a recent modification of standard direct seeding of seeds into the mineral soil, with the placement of seeds into a seed shelter made of plastic tube (vegetation cell) filled with substrate and installed in a seeding hole, is under investigation with promising preliminary results (Tučeková 2015).

Regarding described artificial regeneration methods (bareroot transplants, container transplants, direct seeding), landowners may see that they have a wide choice of alternatives, any one of which could result in a satisfactorily stocked stand within a reasonable time (Leugner et al. 2009; Grossnickle, El-Kassaby 2016; Grossnickle, Ivetić 2017). However, each course of action has its probability of success and the forester on the ground must use his experience and informed judgment in predicting the probabilities (Sychra, Mauer 2013; Repáč et al. 2017, 2021; Suraweera et al. 2023). It is at this point that economic analysis can help by providing cost estimates for the separate jobs involved and, by the use of valuation techniques, indicating the relative value of several alternatives (McClay 1955). In Slovakia, the output of artificial regeneration is represented by a successfully established plantation with characteristics governed by the legal act (Notice No. 453/2006, § 26, Section 1 a–e of the Ministry of Agriculture of the Slovak Republic related to forest management and protection). According to the legal act effective in Slovakia, outplanted transplants and seedlings should have 5 to 7 years of age to meet the required characteristics of a successfully established plantation. However, many studies dealing with the assessment of artificial regeneration practices cover only a few initial post-planting years. In spite of presentation of important

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scientific findings, they do not usually provide enough information related to their cost-effectiveness (e.g. Sychra, Mauer 2013; Repáč et al. 2021). The data needed for proper economic calculations and cost-effectiveness comparison of assessed artificial regeneration methods can be obtained only from long-term studies with a measured period exceeding at least 7 years (e.g. McDonald 1991; Harrington et al. 2003; Hyttonen, Jylha 2008; Kuneš et al. 2013; Cole et al. 2018).

Extensive decline of coniferous monocultures in the Beskydy Mts. in Slovakia, driven mainly by biotic agents, bark beetles (*Scolytidae*) and honey fungus (*Armillaria* sp.), which started after 2002 led to the formation of large cleaned areas after sanitary cuttings (Tučeková, Longauerová 2008; Sitková, Šebeň 2012). In 2009, reforestation programs implemented on these sites emerged into the establishment of Demonstration Object of Reconstruction of Spruce Forests (DORS) as a part of the project 'Demonstration object of conversion of dying spruce forests into ecologically more stable multifunctional ecosystems' (Sitková, Šebeň 2012). In the conditions of the DORS Husárik, an acute need for the acquirement of an extraordinary amount of successfully established plantations of commercially important tree species within the legally permissible period initiated also the investigation of a variety of artificial regeneration options, including plantations of bareroot and container transplants as well as direct seeding procedures. The main aim of this study was to find out the most efficient method of establishment of four successfully established plantations with commercially important coniferous tree species meeting the criteria governed by Notice No. 453/2006 (survival, level of damage, minimal stem height) in conditions of the Husárik trial plot.

MATERIAL AND METHODS

Study site. The Husárik trial plot was established as part of the 'Demonstration object of conversion of dying spruce forests into ecologically more stable multifunctional ecosystems' (DORS Husárik) on a 24-ha salvage felled area situated in the Outer Western Carpathians, Javorníky Mts., northern Slovakia, 49°24'47''N, 18°46'10''E (Figure 1). Before the establishment of the trial plot, the site had been overgrown with 80-years-old spruce monoculture with an average diameter at breast height of 35 cm and a height of 30 m, stocking 0.8, stand volume 650 $m^3 \cdot ha^{-1}$, rotation period 110 years and target tree species composition at the end of stand restoration: beech 40%, spruce 30%, larch 20%, ash/maple 10%. The beginning of the spruce monoculture decline on the trial plot due to bark beetle infestation was registered in 2007 and the last remnants of stands were harvested in 2010. The trial plot was established in 2011.

The mean altitude of the Husárik trial plot is 800 m a.s.l., aspect NW, slope 30%. The site was classified as *Abieto-Fagetum* forest type (Hančinský 1972). The soil of the trial plot is silt loam (30% sand, 60% silt, 10% clay) Cambisol with a high content (> 40%) of rock fragments (> 2 mm) and an acidic pH (pH_{H_2O} 4.9). The underlying bedrock is composed of sandstones (FAO 2015).

(A) (B)

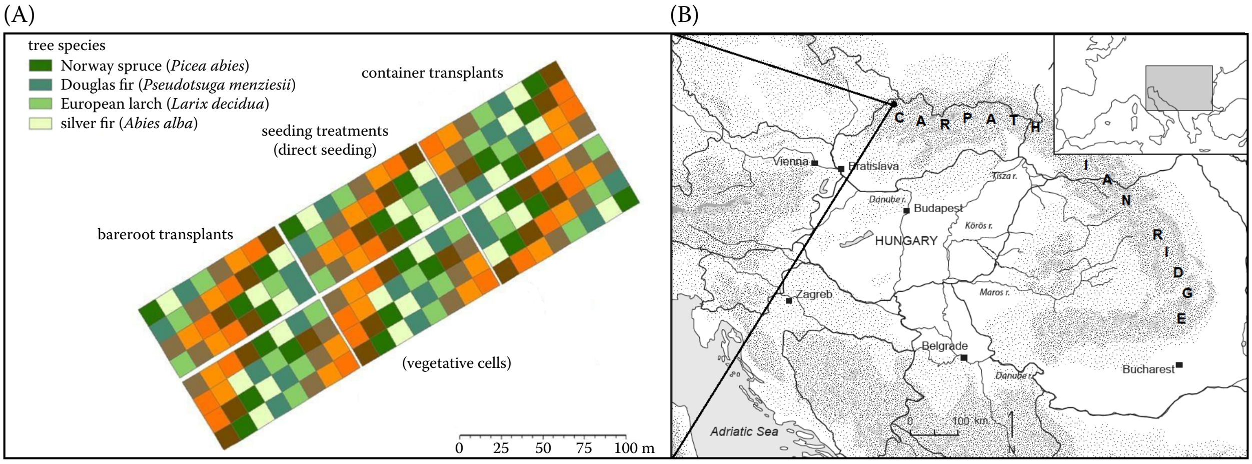

Figure 1. (A) Arrangement and (B) localisation of the Husárik trial plot in the Outer Western Carpathians, Javorníky Mts., Western Carpathians

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Table 1. Annual/growing season mean air temperature and annual/growing season precipitation totals over early five consecutive years after the establishment of the Husárik trial plot, Javorníky Mts., Western Carpathians

Year	Air temperature (°C)		Precipitation (mm)	
	annual	growing season	annual	growing season
2011	7.5	14.0	689	495
2012	7.4	14.4	800	420
2013	7.3	13.5	770	524
2014	8.8	13.6	972	692
2015	9.1	14.4	656	348

Long-term (1981–2010) mean annual/growing season air temperature at the study site reached 6.3 °C/12.4 °C and mean annual/growing season precipitation totals were 895/535 mm (Slovak Hydrometeorological Institute 2020). The period of the trial plot monitoring, including the early five years after its establishment, can be characterised by a gradual increase of mean annual/growing season air temperature and a decreasing amount of annual as well as growing season precipitation totals that reached the highest amplitudes in 2015 (Table 1).

Experimental design. Forest reproductive material of 4 commercially important coniferous tree species, including Norway spruce (spruce), silver fir (fir), European larch (larch) and Douglas fir (doug fir), was introduced into the trial plot using 4 different artificial regeneration methods: (*i*) planting of bareroot transplants (BR), (*ii*) planting of container transplants (CON), (*iii*) seeding of seeds into the growing substrate-enriched mineral soil (DS), (*iv*) seeding of seeds into the vegetative cells (VCS).

Planting of BR and CON as well as seeding of seeds (DS, VCS) was carried out on manually prepared spots of 30 cm × 30 cm in size distributed on square subplots (12 m × 12 m) at regular spacing for spruce and larch 2.0 m × 2.0 m, for fir and doug fir 1.5 m × 1.5 m (Figure 1). In total, the arrangement of the trial plot into the subplots of 12 m × 12 m in size for each tree species (4) × artificial regeneration method (4) combination repeated 8 times resulted in 3 200 planted seedlings and almost 12 000 seeded seeds on the area of 13 824 m^2 (Figure 1, Table 2).

Forest reproductive material. Spruce, larch, fir and doug fir seeds used in this study for the

Table 2. Seeds and transplants characteristics of spruce, larch, fir, and doug fir introduced by different artificial regeneration methods into the Husárik trial plot, Javorníky Mts., Western Carpathians

Seeds			
Tree species	germination (%)	germination energy (%)	National Registry code
Spruce	80	25	pab01554NO-485
Larch	30	10	lde13545DK-002
Fir	42*	NA	aal03424ZA-089
Doug fir	64*	NA	pme11413BS-001

transplants		
Tree species	cultivation regime, stem height/root collar diameter	total number of outplanted saplings
Spruce	BR 2 + 2 (35.5 cm/4.6 mm), CON 1 + 0 (15.2 cm/2.9 mm) 38.9 cm/5.6 mm	BR 288, CON 288
Larch	BR 2 + 0 (33.0 cm/4.5 mm), CON 1 + 0 (22.0 cm/3.0 mm) 38.9 cm/5.6 mm	BR 288, CON 288
Fir	BR 3 + 2 (33.5 cm/5.9 mm), CON 2 + 0 (15.2 cm/2.9 mm)	BR 512, CON 512
Doug fir	BR 2 + 1 (23.5 cm/4.0 mm), CON 2 + 0 (15.5 cm/3.1 mm)	BR 512, CON 512

* For fir and Douglas fir, the values refer to the viability tests; BR – bareroot; CON – containerised; NA – not available

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cultivation of transplants within planting treatments (BR, CON) as well as within seeding treatments (DS, VCS) were collected in the corresponding certified source of forest reproductive material and provenance region. Seed samples of each examined tree species used in this study were subjected to the analysis of elementary qualitative characteristics in the accredited laboratory (Table 2). BR and CON transplants (Table 2) of the investigated tree species were obtained from commercial production of the forest nursery of the State Forest Enterprise of the Slovak Republic (49°06'27''N, 19°44'54''E; altitude 830 m a.s.l.).

Artificial regeneration methods and post-planting care. Seeding of seeds (DS, VCS) and planting of transplants (BR, CON) was conducted on spots distributed at regular spacing on square subplots (12 m × 12 m). Planting as well as seeding spots (30 cm × 30 cm) were mechanically prepared by removal of the raw humus layer. Planting of BR and CON transplants was carried out manually into the holes of adequate size dug with a hoe. For DS seeding treatment, the manually dug out hole ($l \times w \times h$ = 10 cm × 10 cm × 10 cm) was filled with an approximately 8 cm thick layer of substrate, then seeded with 4 to 8 seeds (4 seeds of spruce; 8 seeds of larch and fir; 5 seeds of doug fir) and covered with a 1.5 cm to 2.0 cm thick layer of mineral soil. For VCS seeding treatment, the vegetative cell (plastic tube) was mounted into the manually dug out hole ($l \times w \times h$ = 10 cm × 10 cm × 8 cm), then filled with an approximately 6 cm thick layer of substrate, then seeded with 4 to 8 seeds (4 seeds of spruce; 8 seeds of larch and fir; 5 seeds of doug fir) and covered with a 1.5 cm to 2.0 cm thick layer of a substrate and perlite mixture.

In the year of the trial plot establishment, the forest floor was covered by remnants of forest herbaceous plants (e.g. *Vaccinium myrtyllus*, *Oxalis acetosella*) irregularly dispersed over the site. Over further consecutive years, various grasses (predominantly *Calamagrostis* sp.) and pioneer tree species (birch, rowan, sallow) started to occur, and they gradually became abundant on the trial plot. Five years after the trial plot establishment, the whole trial plot was occupied by competing vegetation (mainly monocotyledonous grasses). Post-planting care interventions included weed and pioneer tree species control and protection against game. Weed, as well as individuals of pioneer tree species growing within a 30-cm radius around the aboveground part of every established individual, were removed manually with a grass hook in July in each growing season. Individuals of pioneer tree species growing out of a 30-cm radius were cut out with a hand saw or axe every time they started to mechanically suppress or when they reached the 1.5-fold height of the examined individuals. The part of the DORS Husárik with the trial plot was fenced by a chain wire (height 2 m; mesh size 50 mm × 50 mm). The total fenced area was 5.12 ha. After repeated disruption of the installed fence by ungulates in the first year, individual protection of transplants and seedlings by the application of chemical repellents against game browsing to the leading bud and shoot was done after the end of each growing season.

Assessment of experimental material, economic calculation and statistics. The results presented in this study summarise nine consecutive years of the trial plot assessment after its establishment. For seeding treatments (DS, VCS) the seeding spot occupation rate was related to the ratio of spots occupied by at least one vital germinated seedling from the total number of established spots. For transplants, the survival rate was estimated as the ratio of vital transplants from the total number of planted transplants separately for BR and CON. The level of damage (dry leading shoot, shoot and bud browsing, weed suppression, other mechanical damage like missing leading shoot, broken stem) was estimated as the ratio of damaged individuals to the total number of living ones.

Assessment of morphological parameters included: stem height (*H*) and height increment (*Hi*). *Hi* was measured directly in the field as the length of the terminal shoot produced by the assessed individual. For treatments and tree species with the share of damaged individuals from living seedlings/transplants not exceeding 50%, an assessment of morphological parameters was carried out strictly on undamaged individuals. For treatments and tree species with the share of damaged individuals from living seedlings/transplants exceeding 50%, an assessment of morphological parameters was carried out also on damaged individuals. When the average *H* of tree species individuals within the assessed artificial regeneration method exceeded the threshold *H* related to 2/3 of *H* of surrounding herbaceous plants (estimated *H* threshold was 120 cm), further evaluation related to the fulfilment of successfully established plantation criteria as well as simple cost-effectiveness analysis were carried

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out. Criteria related to the assessment of the status of successfully established plantation included (Notice No. 453/2006): (*i*) the average height of planted tree species individuals exceeds the threshold *H* related to 2/3 of the height of surrounding herbaceous plants, (*ii*) planted tree species individuals are evenly distributed and occupy at least 50% of the reforested area, (*iii*) the ratio of damaged individuals from the total number of survived tree species individuals does not exceed 50%. For every tree species × artificial regeneration method combination, the cost-effectiveness referred to all expenses related to the achievement of the successfully established plantation. The structure of costs consisted of planting stock acquisition, outplanting labour and post-planting care interventions (weeding, protection against game). The required amount of forest reproductive material for each tree species reflects the recommended minimum number indexed in the National Standards (STN 48 2210 Silviculture. Artificial regeneration of the forest and post planting care interventions). The price of planting stock of the investigated tree species, as well as material and labour required for trial plot establishment and maintenance (outplanting, seeding, post-planting care interventions), were derived from the current publicly available price lists in the Slovak Republic. A detailed description of cost structure and information related to exact expenses can be found in Table S1 in the Electronic Supplementary Material (ESM).

Data on annual survival and *Hi* of each tree species were analysed by one-way analysis of variance (ANOVA) followed by Tukey's studentised range test (HSD). Prior to analysis, data were tested for normality using standard graphical approaches. Arcsin transformation was applied to the percentage data in order to correct non-normal distribution. Because of uncertainty of the comparison of tree species with different growth properties and individuals of different ages and morphological and physiological quality raised by a selected group of artificial regeneration methods, the significance of differences between BR and CON transplants, DS and VCS seedling *H* was examined by two-sample *t*-test for difference of means. Statistical analyses were performed using STATISTICA (Version 12, 2013).

RESULTS

Spruce. Nine years after the trial plot establishment, survival of spruce transplants and seeding spot occupation rate of seedlings constituted by different artificial regeneration methods were BR 75%, CON 74%, DS 42%, and VCS 67%. The largest decline in survival of transplants and seeding spot occupation rate of seedlings was recorded within the early five years. The significantly better survival of CON as compared to BR recorded one year after planting showed a temporal trend that was gradually equalised over the next period of the trial plot assessment (Table 3; Figure 2). For germinated seedlings, vegetative cells provided better conditions for seed germination and resulted in significantly higher values of the seeding spot occupation rate of VCS than in DS. Individuals established by VCS kept a significantly higher seeding spot occupation rate than DS also over the next period of trial plot assessment (Table 3; Figure 2). The last inventory confirmed the successful achievement of survival criteria reported for the successfully established plantation with BR, CON transplants and VCS seedlings (Figure 2).

Nine years after the trial plot establishment, *H* of spruce transplants and seedlings constituted by different artificial regeneration methods

Table 3. Analysis of variance (*F* and *P* values) of the effect of the artificial regeneration method on survival/seeding spot occupation rate and height increment (*Hi*) of seedlings and transplants of selected coniferous tree species after the 1st, 5th, 7th, and 9th year after the establishment of the Husárik trial plot, Javorníky Mts., Western Carpathians

Year	Spruce				Larch				Fir				Doug fir			
	survival		*Hi*		survival		*Hi*		survival		*Hi*		survival		*Hi*	
	F	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*	*F*	*P*
1st year	3.2	0.048	4.3	0.032	9.4	0.021	3.8	0.044	14.9	0.003	3.6	0.047	16.4	0.002	0.9	0.321
5th year	3.2	0.042	5.2	0.024	8.7	0.045	5.2	0.021	14.1	0.007	4.6	0.019	22.8	0.001	3.9	0.043
7th year	7.3	0.009	6.5	0.012	9.9	0.009	5.8	0.039	15.8	0.002	4.3	0.024	15.4	0.002	5.8	0.017
9th year	6.4	0.011	9.8	0.009	12.7	0.015	3.2	0.042	14.5	0.007	5.7	0.011	16.7	0.003	7.1	0.009

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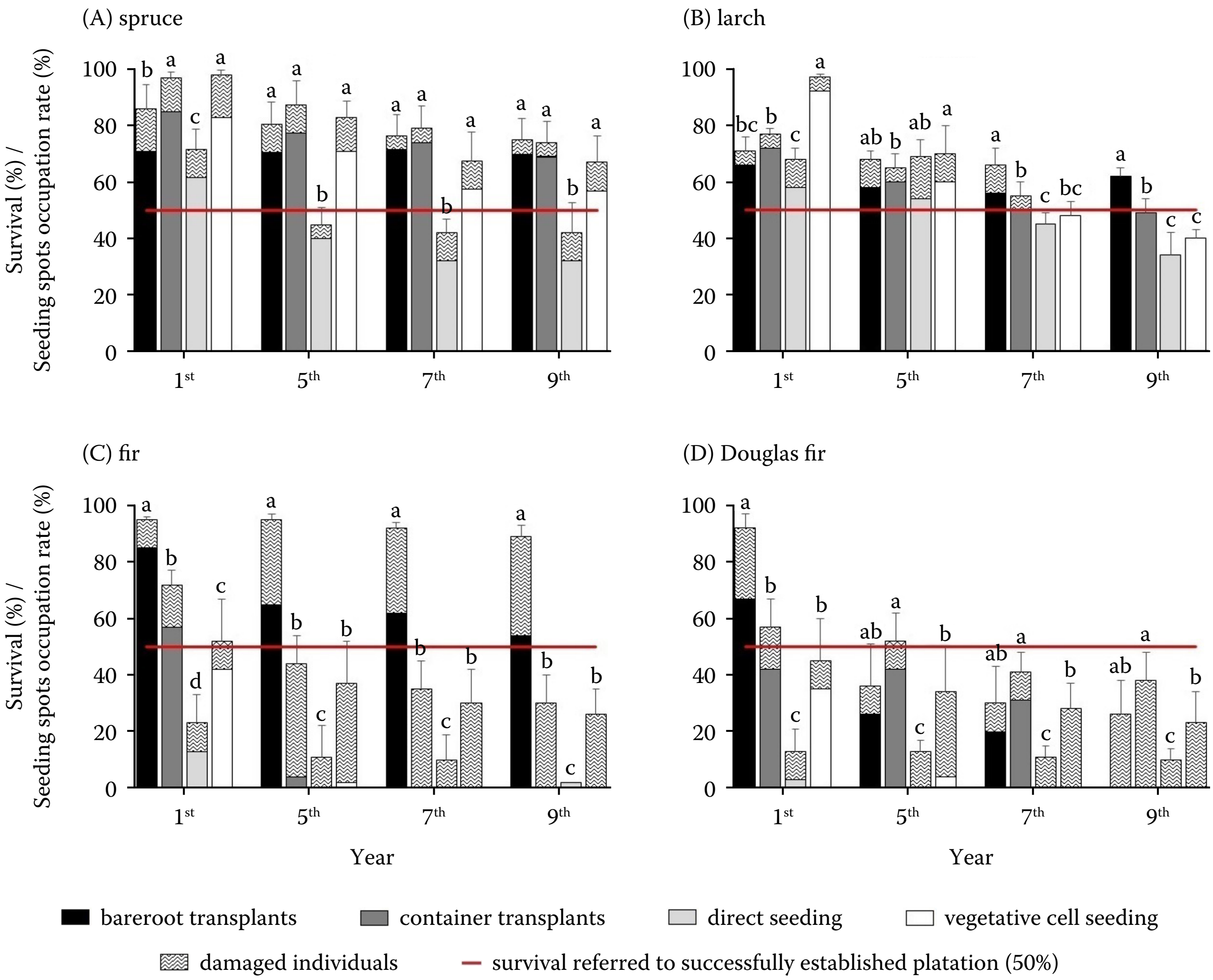

Figure 2. Mean (± standard deviation) 1st, 5th, 7th, and 9th year survival[1] and seeding spots occupation rate[1] of four coniferous tree species established by different artificial regeneration methods on the Husárik trial plot, Javorníky Mts., Western Carpathians

a–c – within each of the tree species and selected year, means followed by the same letter are not significantly different (P < 0.05); [1] shares of damaged trees are shown within the upper part of the respective columns

was BR 355 cm, CON 235 cm, DS 160 cm, and VCS 156 cm (Figure 3). Significant acceleration of the *Hi* of BR over CON transplants recorded in the 5th year after planting resulted in the significant growth dominance of BR over CON transplants over the next years (Table 3; Figures 3 and 4). The achievement of the stem height criteria reported for the successfully established plantation was recorded for BR transplants five years after planting and for CON transplants six years after planting, for DS and VCS seedlings eight years after seeding (Figure 3).

Larch. Nine years after the trial plot establishment, survival of larch transplants and seeding spot occupation rate of seedlings constituted by different artificial regeneration methods were BR 62%, CON 49%, DS 34%, and VCS 40%. A marked decrease in larch transplant survival with 71% BR and 77% CON survived transplants was recorded already after the first growing season. For CON, the gradual decrease continued and resulted in a significantly lower survival than in BR nine years after planting. For germinated seedlings, the significantly higher seeding spot occupation rate recorded for VCS (97%) than for DS (68%) showed only a temporal trend (Table 3; Figure 2). The last assessment of survival confirmed the fulfilment of survival criteria reported for the successfully established plantation only for BR and CON transplants (Figure 2). Nine years after the trial plot es-

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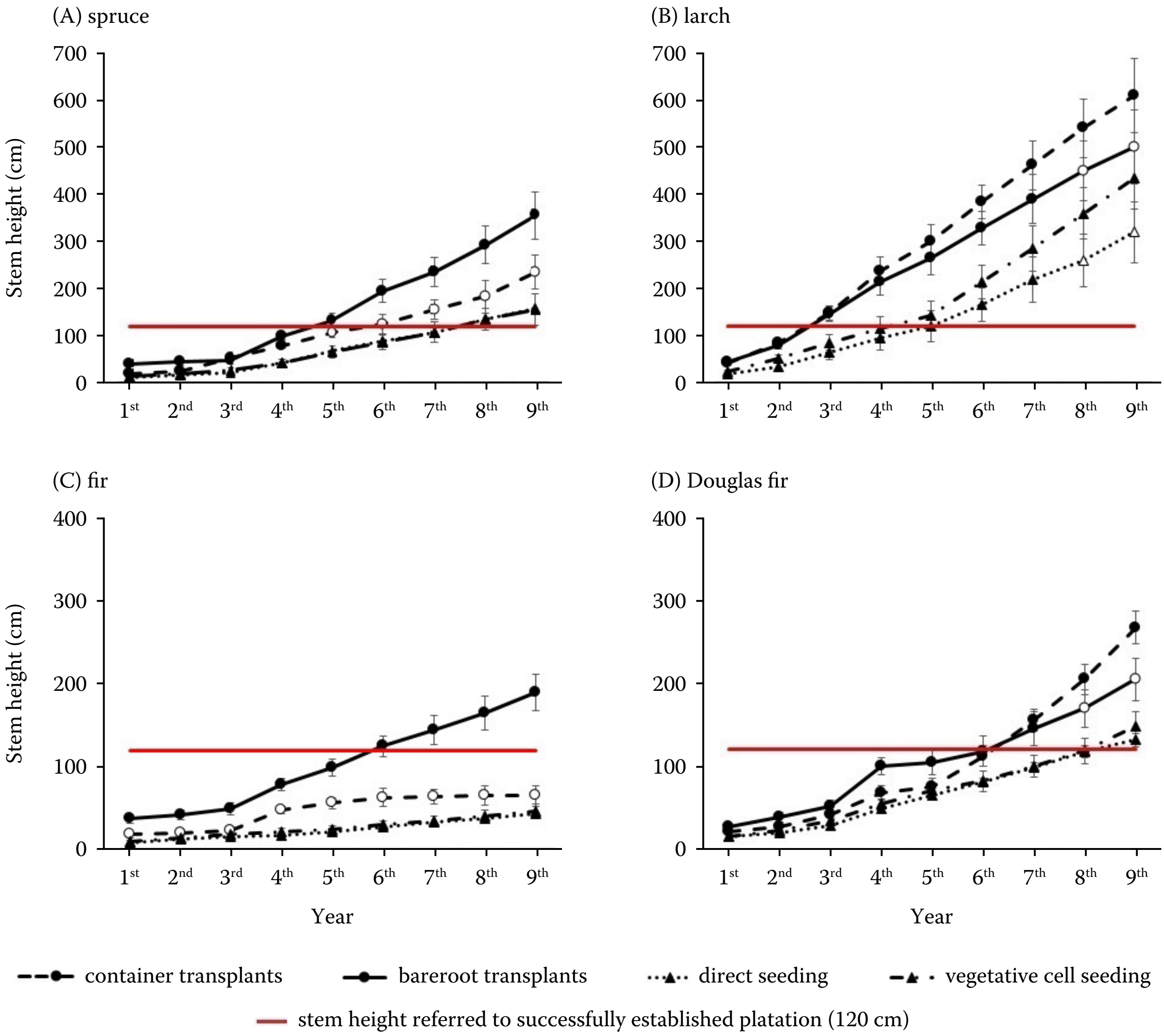

Figure 3. Mean (± standard deviation) stem height[1] of four coniferous tree species established by different artificial regeneration methods over nine consecutive years on the Husárik trial plot, Javorníky Mts., Western Carpathians

For each tree species and selected year, means marked by symbols (dots/triangles) of different colours are significantly different ($P < 0.05$); [1] for treatments and tree species with a share of damaged seedlings/transplants not exceeding 50%, the assessment of morphological parameters was carried out strictly on undamaged individuals, while for treatments and tree species with a share of damaged individuals exceeding 50%, damaged individuals were also measured

tablishment, *H* of larch transplants and seedlings constituted by different artificial regeneration methods was BR 500 cm, CON 610 cm, DS 320 cm, and VCS 435 cm. For outplanted transplants, a significantly higher *H* of CON than BR transplants was recorded after the 8th and 9th year after planting (Figure 3). VCS reached a significantly higher *H* than DS seedlings after the 8th and 9th year after seeding. Achievement of stem height criteria reported for the successfully established plantation was recorded for BR and CON transplants three years after planting, for DS and VCS seedlings five years after seeding (Figure 3).

Fir. Nine years after the trial plot establishment, survival of fir transplants and seeding spot occupation rate of seedlings constituted by different artificial regeneration methods were BR 89%, CON 30%, DS 2%, and VCS 26%. The largest decrease in the survival and seeding spot occupation rate with 95% BR, 72% CON, 23% DS, and 52% VCS was already recorded after the first growing season. CON exhibited a significantly lower survival than

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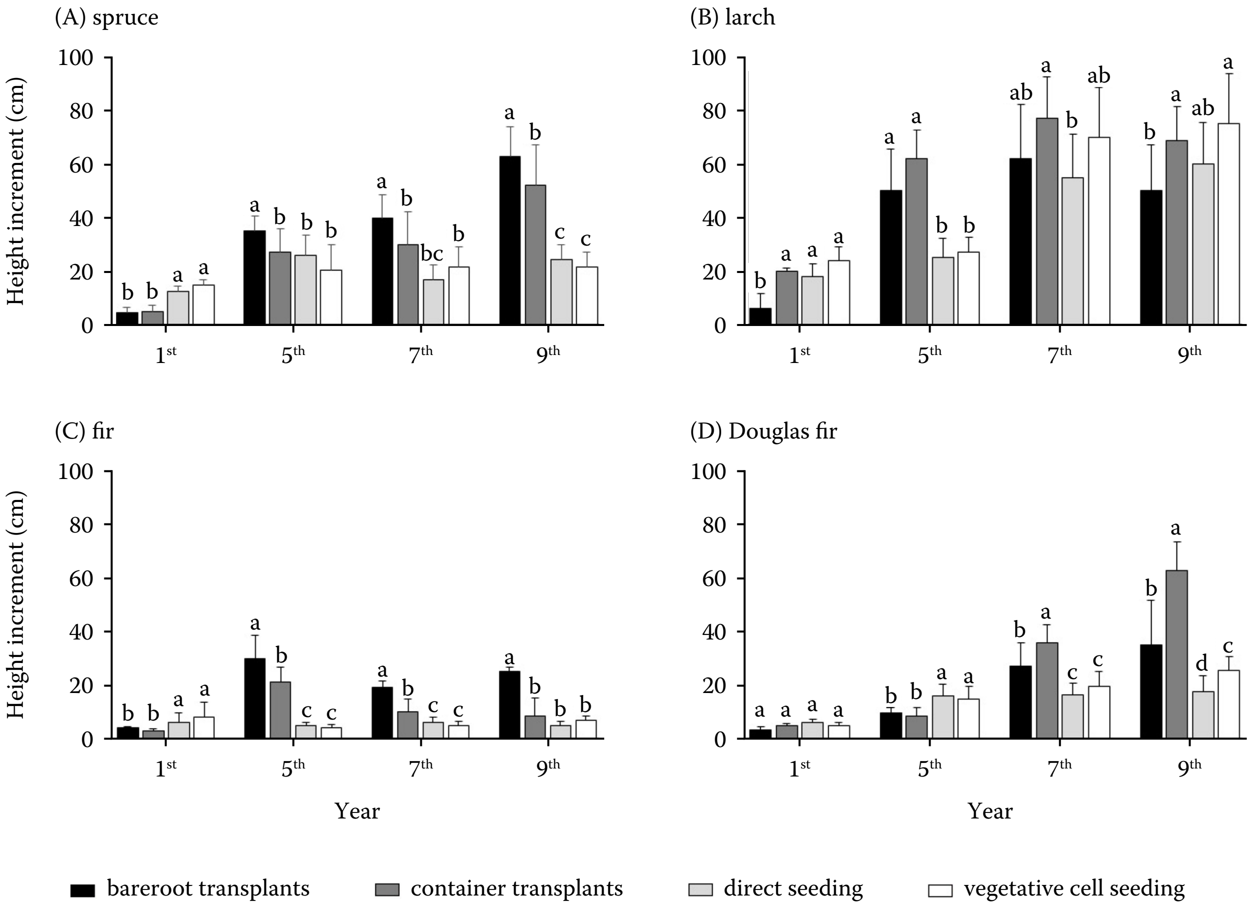

Figure 4. Mean (± standard deviation) 1st, 5th, 7th, and 9th height increment[1] of four coniferous tree species established by different artificial regeneration methods on the Husárik trial plot, Javorníky Mts., Western Carpathians

a–d – for each tree species and selected year, means followed by the same letter are not significantly different ($P < 0.05$); [1] for treatments and tree species with a share of damaged seedlings/transplants not exceeding 50%, the assessment of morphological parameters was carried out strictly for undamaged individuals, while for treatments and tree species with a share of damaged individuals exceeding 50%, damaged individuals were also measured

BR transplants within each of the assessed years (Table 3; Figure 2). VCS reached a significantly higher seeding spot occupation rate than DS within each of the assessed years. Regardless of the assessed artificial regeneration method, an excessive ratio, ranging from 11% (BR in 1st year) to 100% (CON, DS, VCS in 7th and 9th year), of damaged individuals by ungulates was registered (Figure 2).

Nine years after the trial plot establishment, *H* of fir transplants and seedlings constituted by different artificial regeneration methods was BR 190 cm, CON 65 cm, DS 43 cm, and VCS 47 cm. BR kept their significant growth advance over CON within each of the assessed years (Figure 3). *H* of seedlings germinated within seeding treatments was markedly diminished. Nine years after the establishment, *H* of fir VCS and DS seedlings did not exceed 50 cm (Figure 3). Achievement of stem height criteria reported for the successfully established plantation was recorded only for BR transplants six years after planting.

Doug fir. Nine years after the trial plot establishment, the survival of doug fir transplants and seeding spot occupation rate of seedlings constituted by different artificial regeneration methods were BR 26%, CON 38%, DS 10%, and VCS 23%. Significantly better first-year survival of BR than in CON transplants showed only a temporal trend (Table 3; Figure 2). Seedlings germinated within VCS reached a significantly higher seeding spot occupation rate than DS within each of the assessed years (Figure 2). Regardless of the assessed artificial regeneration method, an excessive ratio of damaged doug fir individuals from living ones

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by ungulates, ranging from 19% (CON in 5th year) to 100% (BR, CON, DS, VCS in 9th year), was registered (Figure 2). For doug fir, the last assessment of survival did not confirm the successful achievement of survival criteria reported for the successfully established plantation for any of the assessed artificial regeneration methods (Figure 3).

Nine years after the trial plot establishment, *H* of doug fir transplants and seedlings constituted by different artificial regeneration methods was BR 205 cm, CON 268 cm, DS 132 cm, and VCS 148 cm. CON transplants reached significantly higher *H* than BR transplants in the 8th and 9th year after planting. Except for the last measurement conducted in the 9th year, a significant difference between *H* of seedlings grown in DS or VCS was found during the monitored period. The achievement of the stem height criteria reported for the successfully established plantation was recorded for BR and CON transplants seven years after planting, for DS and VCS seedlings nine years after seeding (Figure 3).

Cost-effectiveness of establishment of 1 ha of a successfully established plantation. Successful achievement of the successfully established plantation criteria was recorded for spruce BR, CON, VCS; larch BR, CON, DS, VCS; and fir BR individuals. The lowest costs related to the establishment of 1 ha of successfully established plantation were estimated for larch, followed by spruce and the highest for fir. The average costs required for the establishment of 1 ha of successfully established plantation of larch were 16% lower than for spruce and 50% lower than for fir. For larch, the least expensive method of artificial regeneration was DS, followed by BR, CON, and VCS. The difference between the cheapest (DS) and the most expensive method (CON) of artificial regeneration for larch reached 7%. For spruce, the least expensive method of artificial regeneration providing the successfully established plantation was BR, followed by VCS and CON. The difference between the cheapest (DS) and the most expensive method (CON) of artificial regeneration for spruce reached 9% (Figure 5). Expenses

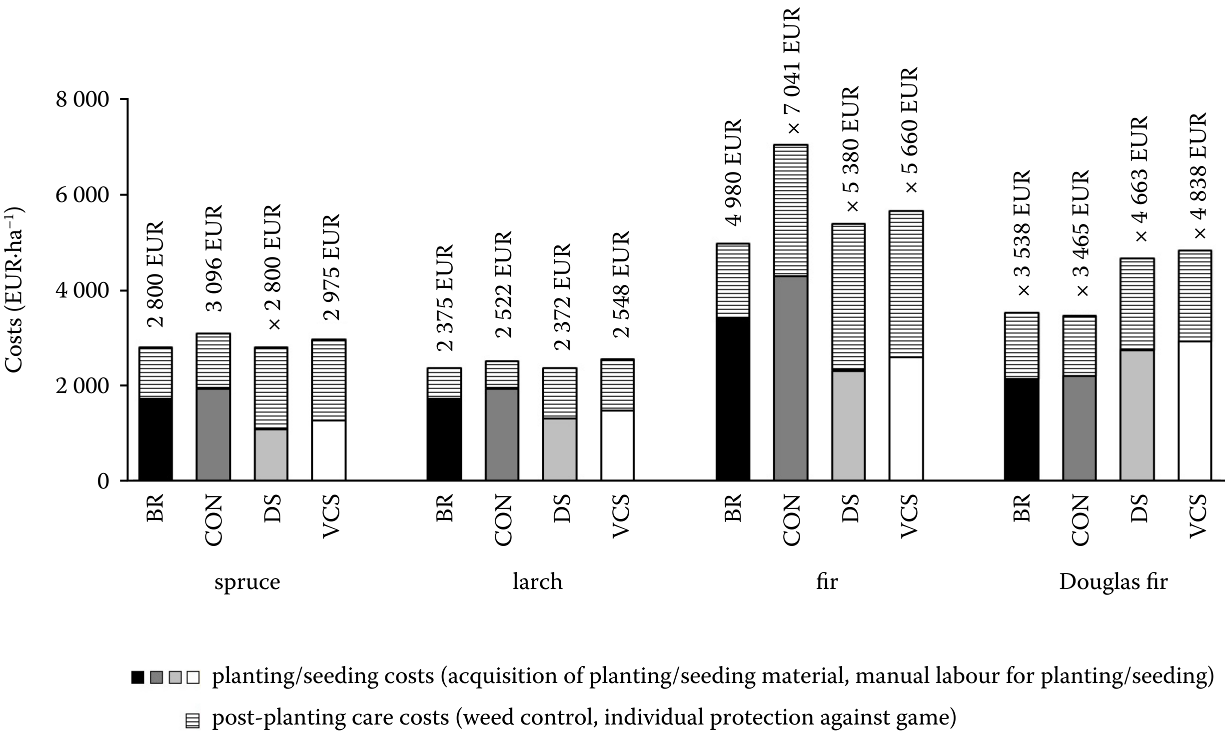

Figure 5. Total costs spent on the accomplishment of a successfully established plantation of four coniferous tree species raised by different artificial regeneration methods on the Husárik trial plot, Javorníky Mts., Western Carpathians

Examined tree species × artificial regeneration method combinations represented by columns and marked by cross failed to meet the essential criteria of a successfully established plantation and need to be re-established; a detailed description of the calculation of costs can be found in Table S1 in the Electronic Supplementary Material (ESM); BR – bareroot transplants; CON – container transplants; DS – direct seeding; VCS – vegetative cell seeding

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related to the establishment and maintenance of fir CON, DS, VCS and doug fir BR, CON, DS, VCS over the monitored period are not definitive and do not include costs related to the partial reestablishment of plantations (Figure 5).

DISCUSSION

In this study, conventional planting of BR transplants ensured the successful establishment of spruce, larch and fir. Better field performance of CON over BR discussed and manifested in many studies (Leugner et al. 2009; Grossnickle, El-Kassaby 2016 and references therein) has been observed in this study only for CON larch and CON spruce. Better initial survival of CON of the selected tree species recorded in our study could probably be related to the crucial feature of CON, well-developed root system concentrated within the root plug that provides favourable conditions for the growth of new roots, as well as residues of water and mineral nutrients from a nursery cultivation period that are further available also under field conditions (McKay 1997; Idris et al. 2004; Leugner et al. 2009; Grossnickle, El-Kassaby 2016). For larch, the beneficial effect of CON over BR tended to be more obvious in this study. In spite of the marked initial size gap between two-year-old BR and one-year-old CON transplants of larch, CON reached a significantly higher *H* than BR nine years after planting. McDonald (1991) and Grossnickle (2005) suggested that for tree species forming a distinctive taproot during juvenile growth stages, including e.g. larch, preference of CON over BR might be more beneficiary also for another reason. The crucial feature of CON stock type enables cultivated transplants to develop the root system in a more natural shape without any radical adjustments (undercutting and lifting of BR transplants). However, an excessive growth rate of larch transplants, together with a slight omission of silvicultural interventions (thinning), resulted in decreased static stability and survival decline over the last inventories (7^{th} and 9^{th} year). Tall and thin trunks of larch started to suffer from heavy snow which bent and later also started to uproot less stable individuals. Moreover, unfavourable soil profile characteristics (high content of rock, shallow depth) of the study site probably also contributed to the decreased static stability of larch trees.

Leugner et al. (2009) observed that in the conditions of an experimental site in the Krkonoše Mts., the initial significance of differences in *H* and root collar diameter between spruce smaller two-years-old CON and larger three-years-old BR might equalise within less than a two-year period. On the other hand, the size gap between spruce one-year-old CON and four-years-old BR transplants as well as fir two-years-old CON and five-years-old BR transplants planted in our study was probably too large and caused that the beneficiary effect of CON over BR showed only a temporal trend (e.g. better spruce first-year survival of CON than BR). Hytönen and Jylhä (2008) as well as Repáč et al. (2021) observed that once larger-sized spruce BR transplants overcome planting shock and become established, larger biomass of assimilatory organs, roots and other structures enables them to accumulate more supplies required for growth and then produce a larger biomass increment. In our trial, the last measurement revealed similar survival of BR and CON transplants in spruce but significant growth advance of BR (355 cm), having the aboveground part larger by more than 100 cm over CON (235 cm) transplants. For fir, differences were still more apparent. In spite of the excessive ratio of damaged fir individuals, BR transplants with an average survival reaching 89% and an average *H* of 190 cm markedly outperform CON transplants with an average survival of 30% and an average *H* not exceeding 65 cm nine years after planting. Additionally, the excessive intensity of damage had a detrimental effect also on doug fir plantations that failed to fulfil the criteria corresponding to the successfully established plantation. For both tree species in this study, a key assumption of accomplishment of the successfully established plantation was to escape from the browsing threatened zone as quickly as possible. Unfortunately, smaller-sized two-year-old CON transplants suffering from repeated browsing formed a bushy habitus with multiple stems and failed to accomplish this task. Bernard et al. (2017) documented that the intensive foraging preference of fir by deer on unfenced plots in the Vosges Mts. reduced the survival of fir juveniles two to five times and average *H* ten times, which led to a tree species composition shift in favour of spruce. For the successful promotion of fir regeneration, Bernard et al. (2017) recommended excluding the deer for at least a ten-year period. In our study, cohorts of damaged tree species individuals were part of the larger fenced area (5.12 ha).

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Nevertheless, it was out of our capacity to maintain the impenetrability of the fence for deer that most often lifted it up and crawled under it mainly in places of small terrain depressions. Furthermore, despite the recommendations (Pepper 1992; STN 48 2210), the height of the used fence (2 m) also turned out to be insufficient, as the red deer was able to jump even this high. Thus, individual protection through the application of chemical repellents had to be used. In spite of this intervention, deer continued to damage transplants and seedlings of both fir and doug fir. Regarding our experience, we would recommend fencing smaller areas and using a higher fence than is proposed (Pepper 1992; Häsler, Senn 2012; STN 48 2210).

In this study, the establishment of investigated coniferous tree species through direct seeding methods has been successful only for VCS spruce, DS and VCS larch. For spruce and larch the first-year seeding spot occupation rate ranging from 98% (VCS spruce) to 62% (DS spruce), as well as the ability to produce *H* of nursery-grown seedlings of corresponding age (Slávik 2005; Vaario et al. 2009) created basic assumptions for further development of seedlings raised within these treatments. In spite of the size gap between planted transplants and germinated seedlings, spruce and larch seedlings overcame the threshold *H* (120 cm) determined for the successfully established plantation five (larch) and seven (spruce) years after the trial plot establishment. However, artificial regeneration practices based on direct seeding of seeds markedly depend also on the seed parameters of employed tree species (Erefur et al. 2008; Grossnickle, Ivetić 2017; Huth et al. 2017). Fir as well as doug fir represent tree species with seed dormancy that protects seeds from germination in unfavourable conditions (Grossnickle 2000; Dobrowolska et al. 2017; Robakowski et al. 2021). Nevertheless, for these tree species it is an additional variable that affects the success of direct seeding artificial regeneration methods. In spite of the employment of pre-stratified fir and doug fir seeds in our study, as well as the placement of a higher number of seeds on the seeding spot, the first-year seeding spot occupation rate recorded for both tree species ranged only from 52% (fir VCS) to 13% (doug fir DS). Further development of germinated fir and doug fir seedlings was markedly influenced by their inability to efficiently compete with weed for growing space, basic resources (nutrients, water) and similarly to planted transplants, with intensive damage caused by the game.

A simple economic analysis conducted in this study revealed that the most cost-efficient method of accomplishment of 1 ha successfully established plantation of selected coniferous tree species was DS larch and the least efficient BR fir. In this study, the costs required for the establishment of a BR fir plantation are slightly lower than those presented by Suraweera et al. (2023) because of the omission of transport and fence costs in the calculation. Similarly to Suraweera et al. (2023), the most expensive inputs of the regeneration methods based upon the planting of transplants that consumed almost 80% of estimated costs have been planting material and labour. According to Grossnickle and Ivetić (2017), the replacement of planting material by seeds should lead to a marked reduction of artificial regeneration expensiveness. In our study, the lowest expensiveness of seeding compared to the planting method and delivering the successfully established plantation was demonstrated only for DS larch. An additional step within VCS treatment, the installation of a seed shelter (vegetative cell) increased the costs so that they surpassed the costs estimated for the successfully established plantation of BR transplants. On the other hand, an obvious size gap between planted transplants and germinated seedlings highlighted by Grossnickle and Ivetić (2017) and observed also in our study extended the period of required post-planting care interventions (weeding, protection against game) and, in some cases, it probably contributed to a failure of direct seeding methods and the need for partial reestablishment of the regenerated sites (e.g. DS, VCS fir and doug fir in this study).

CONCLUSION

The most successful artificial regeneration method delivering the successfully established plantation of assessed coniferous tree species in this study was outplanting of BR transplants. BR spruce, larch and fir met the criteria (survival, stem height, share of damaged individuals from living ones) of a successfully established plantation within a three- to six-year period after the Husárik trial plot establishment. BR transplants have been outperformed by CON transplants in terms of growth only in larch subplots. The partial disadvantage of CON compared to BR transplants in this study might probably be related to the smaller initial dimensions that prolonged the post-planting care intervention period necessary for all the evaluated tree species. In spite of the declared better planting shock tolerance and a lower recommended normative number of planted individuals per ha, the planting of CON transplants represented the least efficient artificial regeneration method of native conifers in this study.

The methods of direct seeding examined in this study provided the successfully established plantation only on spruce and larch subplots. For fir and doug fir, the gradual initial growth, as well as the excessive level of damage observed on seedlings and transplants of both tree species, had a marked negative impact on their development within all assessed treatments. However, the first-year seeding spot occupation rate exceeding 90% for spruce and larch VCS seedlings, as well as the lowest costs of 1 ha of the successfully established plantation calculated for DS larch, suggest the potential reasonability of these methods in artificial regeneration applications.

However, further investigation is needed to authenticate these results also for other sites situated in mountainous areas of Central Europe.

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