https://doi.org/10.17221/56/2024-JFS

Economic parameters of the natural forest regeneration in changing conditions – A case study

Stanislav Novotný, Josef Gallo, Vilém Podrázský*

Department of Silviculture, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague, Prague, Czech Republic

**Corresponding author: gallo@fld.czu.cz*

Citation: Novotný S., Gallo J., Podrázský V. (2024): Economic parameters of the natural forest regeneration in changing conditions – A case study. J. For. Sci., 70: 529–538.

Abstract: Natural regeneration is a crucial factor in improving the economy of forest estates. The presented study analysed the economic parameters of three different approaches to forest regeneration: (*i*) artificial regeneration with Norway spruce, (*ii*) a 25% admixture of soil-improving and stabilising species (SSTS), and (*iii*) natural regeneration. The expenses for these specific operations related to individual regeneration methods were derived. These variants were investigated before the bark beetle calamity (2014) and after the outbreak (2023) for management sets (MS) 531, 551, 571, and 591, i.e. for acidic, nutrient-rich, gleyed, and waterlogged sites of higher elevations. In all cases, natural regeneration decreased expenses by approximately 2 000 EUR·ha^{-1} (50 000 CZK·ha^{-1}) to 6 000 EUR·ha^{-1} (150 000 CZK·ha^{-1}). The 25% admixture of SSTS increased the expenses. The proportion of natural regeneration subsequently decreased due to the bark beetle calamity from roughly 40% to 10% in recent years, which is comparable with the Czech Republic as a whole.

Keywords: admixture; bark beetle calamity; economic efficiency; Norway spruce

The Bohemian-Moravian Highlands (Českomoravská vrchovina) is an area most affected by the recent bark beetle calamity which led to a large-scale disintegration of forest stands and the need for a rational, rapid, but future-oriented regeneration and cultivation (Remeš, Pulkrab 2024). As a result of this development, the Czech Republic belongs to regions with a considerably altered species composition (MoA 2023). Not only in the Czech Republic but also on a European scale, there has been a decline in the proportion of broadleaved trees from 66% to 33% and a change in the function of forest ecosystems (Kenk, Guehne 2001; Parviainen 2005; O'Hara 2016). In addition, the proportion of salvage logging is also increasing (CSO 2023). Currently, there is a growing demand to modify the structure and function of forests within the landscape (Bednář, Bína 2023).

Forest regeneration is a critical phase of forest management, where the species composition and subsequent vitality and productivity of the forest ecosystem are fundamentally determined (Clark et al. 1999; Poleno et al. 2011). Artificial regeneration is still beneficial especially in case of the aim of changing species composition (Gallo et al. 2018, 2020b). The genetic material for artificial regeneration must meet the forestry requirements for growth, production, and quality (Poleno 1997; Šindelář et al. 2006). In the past two decades, we have observed a shift from a clear-cutting sys-

Supported by the Technology Agency of the Czech Republic (grant No. SS01020189). The paper was elaborated using the facilities at Truba Research Station [Forests of the Czech University of Life Sciences Prague (Lesy ČZU) and Department of Silviculture, Faculty of Forestry and Wood Sciences, Czech University of Life Sciences Prague] in Kostelec nad Černými lesy.

https://doi.org/10.17221/56/2024-JFS

tem to a nature-oriented, or 'near-natural' (Poleno et al. 2009; Remeš, Pulkrab 2024) forest management in European countries. It is part of a broader trend of forest adaptation to climate change (Hagerman, Pelai 2018; Frischbier et al. 2019; Gallo et al. 2020a; Vacek et al. 2020a). This trend is supported by data from the Czech Republic. The share of natural regeneration increased gradually from 16% in 2000 to 28% in 2013. The following years showed a slight decrease due to calamities. In 2022, the natural regeneration share reached 23%. The overall course of natural forest regeneration takes longer than artificial regeneration; natural regeneration starts with well-timed stand preparation, followed by the fructification of seed trees, and it ends after reaching the young growth stage. All these processes must follow a natural, uninterrupted sequence (Vacek et al. 1995). Shelterwood management combines several management concepts and is based on small-area shelterwood cutting, which, in the first phase, starts with light intervention to create favourable soil and light conditions. This management method is sometimes referred to as 'halfway' between the clear-cutting and the selection-cutting system (Poleno et al. 2009).

In this context, the main objective of the forest owners and state forestry policy is to manage forests based on the principles of sustainable development while maintaining the economic efficiency of management – a cornerstone of sustainable forest management (Baláš et al. 2024). The fundamental prerequisites include the maximum use of natural regeneration and ensuring the proportion of soil-improving and stabilising tree species (SSTS) or appropriate species composition (Remeš, Pulkrab 2024). Our study aims to contribute to the evaluation of the bark beetle calamity impact on the economics of forest regeneration, both natural and artificial, with different proportions of SSTS on a model example of a private forest estate.

MATERIAL AND METHODS

Study area. For the model comparison of forest restoration costs after salvage logging in spruce stands, we selected a private-property forest management unit (FMU) Prylovi, which belongs to the natural forest area (NFA) No. 16 – Bohemian-Moravian Highlands (Českomoravská vrchovina). It lies in the Pacov Uplands (Pacovská vrchovina) with an undulating relief and an altitude from 535 m a.s.l. in the northeastern part to 690 m a.s.l. below the Stražiště Hill in the southeast. Geomorphologically, the area is part of the Bohemian Massif, characterised by deep metamorphosed basement rock. The parent bedrock composition is raw gneiss and light quartzite interbedded with granite. In the Stražiště location, quartzites and quartzitic gneiss prevail. The predominant soil type is oligotrophic strongly acidic brown soil – forest site type complex (FSTC) 5K and mesotrophic moderately acidic brown soil (FSTC 5S), while on waterlogged sites, it is submontane pseudogley (5P), and stagnic mesotrophic brown soil (6O). The average annual temperature ranges between 6–7 °C. The growing season lasts 140–150 days, and the total average annual precipitation is 650–700 mm, of which 400 mm is in the growing season. In terms of forestry typology, the predominant FSTC are 5K – *Abieto-Fagetum acidophilum* 50.44%, 5S – *Abieto-Fagetum oligo-mesotrophicum* 18.28%, 5I – *Abieto-Fagetum illimerosum acidophilum* 10.80%, 6O – *Piceeto-Abietum variohumidum mesotrophicum* 8.08%, and 5H – *Abieto-Fagetum illimerosum mesotrophicum* 7.91% (Viewegh 2003). The Prylovi FMU property is heavily dominated by conifers. Norway spruce is the main commercial tree species, complemented by larch and pine, with an area share of 94–98%. Most stands were classified in phenotypic class 'C' (stands of average quality). None of the stands were classified as 'D' (poor quality). This is supported by the original inclusion of part of the FMU in the spruce gene pool. Currently, several parts of the stand are classified as phenotypic class 'B' (high-quality stands), which are recognised for seed collection. These are stands of spruce, larch, and Douglas fir at a rotation age with above-average standing volume and extensive regeneration, especially of spruce. Currently, there is a massive regeneration of larch from reserved trees in salvage-logged areas. In managing these stands, the emphasis is being placed on the transition from clear-cutting to a more natural shelterwood system.

For the forest regeneration cost analysis, the target management sets (TMS) with the highest representation were chosen. The spring as well as autumn reforestation have the same costs, not distinguished.

TMS 53 – acidic habitats at higher altitudes are characterised by acidic subsoils with moderately deep soils. These are exemplary conditions for the natural regeneration of the forest, which can be en-

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hanced by different variants of small-area shelterwood cutting. Artificial regeneration can be used to add soil-improving and stabilising tree species.

TMS 55 – nutrient-rich habitats at higher altitudes include rich and lush habitats. The soil is deep in richer subsoils. The conditions allow for above-average timber production in addition to the development of vigorous forest weeds. From the point of view of natural regeneration, it is a challenge to find a balance of light conditions with shelterwood cutting when shade-loving trees are already regenerating under the parent stand but without the weeds. Where natural regeneration cannot be achieved, artificial regeneration must be utilised.

TMS 57 – stagnic habitats at higher altitudes with wet to waterlogged soils; these may include both poor and nutrient-rich subsoils. There is a higher threat of windthrows, weed overgrowing, and, most often, the blackberry shrubs. Regeneration here is chiefly natural, with an emphasis on small-area shelterwood cutting. Beforehand, gaps with, for example, silver fir, can be established in the restored stands.

TMS 59 – habitats permanently affected by water of the upper and middle altitudes include waterlogged, peaty, and peat soils. Due to the high ground water table, trees suffer from shallow root systems and are susceptible to wind damage. Therefore, restoration is recommended to start as soon as possible and proceed very slowly, with an emphasis on natural regeneration in the form of shelterwood cutting. In the case of artificial regeneration on such sites, it is necessary to account for a higher mortality of seedlings despite taking amelioration measures (Novotný, Šišák 2016).

Data acquisition and processing. In the first phase of the research, the company's economic data were analysed, especially the cost items for natural and artificial forest regeneration by bare-rooted planting material, with different representations of SSTS, in 2009–2014 and 2022–2023. For this purpose, data from the annual harvesting and reforestation/regeneration reports were used. The data on the size of the restored areas are taken from the forest management plan (FMP) using InterSoft (Version 12.1, 2023) and located using GPS coordinates. Total costs are calculated per 1 ha. Where artificial planting material is used, the price of each seedling is calculated, including the cost of planting. This item then is recalculated per the number of trees for reforestation of 1 ha. The artificial regeneration hectarage for spruce is set at 5 000 pcs·ha^{-1}, while for beech and oak it is 10 000 pcs·ha^{-1}. Costs for the labour equipment depreciation are also included in the calculation, while overheads and administrative expenses, such as the costs of transporting the seedlings to the salvage-logged sites, inspection, and receipt of the operations, are not included. In artificial regeneration, bare-rooted planting material from the company's forest nursery is predominately used. It is collected according to the actual need, so there is no delay between pick-up and planting. Therefore, the losses are minimal – comparable to container-grown seedling use. On the other hand, when dealing with the smaller percentage of purchased bare-rooted seedlings, which undergo longer transport and storage times, the losses can be more significant. The damage can be particularly evident in the case of unsuitable climatic conditions for the chemical treatment of conifer seedlings. Costs have been quantified for all the operations from soil preparation through established forest cover to the first tending intervention, where artificial and natural regeneration will be balanced depending on the number of individuals. The total area of artificial regeneration studied in all of the MSs from 2009–2014 is 18.1 ha, and from 2022–2023 it is 71.64 ha. Since the representation of tree species in the restored sites varies, the following three restoration options were selected and calculated:

(*i*) Clear-cut with artificial spruce regeneration, without SSTS;
(*ii*) Clear-cut with artificial spruce regeneration, with an SSTS share of 25%;
(*iii*) Natural, without a specified proportion of SSTS.

In all of the MSs, the proportion of natural and artificial regeneration has been measured from 2009. Since 2012, there has been a significant increase in the volume of work carried out by harvester technology, which replaced the traditional prevailing technology – a manual chainsaw and universal wheel tractor. The results of the restoration method in the period under study at the FMU were also used to compare the development in the entire Czech Republic. For this purpose, data from the Reports on the State of the Forest and Forest Management of the Czech Republic in 2013–2022 (MoA 2022) were utilised.

RESULTS

The results are presented in Tables 1–4 per primary management sets (MS) and in Figure 1, which summarises all costs in EUR.

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MS 531 – acidic habitats at higher altitudes have ideal conditions for natural regeneration of spruce and other tree species. Conditions for natural regeneration in this MS should be exploited as much as possible, even on salvage-logged sites. Artificial regeneration in this habitat type can start with some time lag if natural regeneration does not take hold. If the proportion of SSTS is maintained at 25%, the natural regeneration in 2023 from the study area revealed a cost savings of 6 219 EUR·ha^{-1} (155 478 CZK·ha^{-1}) compared to artificial regeneration. Between 2014 and 2023, this amount increased by 2 701 EUR·ha^{-1} (67 514 CZK·ha^{-1}) (Table 1).

TMS 551 – the management of nutrient-rich habitats at high altitudes is associated with the issue of vigorous forest weeds, which have been observed on salvage-logged sites and at the beginning of shelterwood cutting. Therefore, chemical soil preparation is implemented here to protect against weeds. In some locations, the interventions need to be performed repeatedly. Where natural regeneration is not well established, it makes economic sense to resort to the artificial variant. For this reason, these sites should be reforested by artificial planting, preferably in sites more suitable for natural regeneration. If the proportion of SSTS is maintained at 25% in 2024, the cost savings of natural regeneration in the study area amount to 6 932 EUR·ha^{-1} (173 311 CZK·ha^{-1}) compared to artificial regeneration. Between 2014 and 2023, this amount increased by 3 054 EUR·ha^{-1} (76 338 CZK·ha^{-1}) (Table 2).

TMS 571 – the management of stagnic habitats at higher altitudes has similar conditions as acidic habitats. Therefore, the costs of both natural and artificial forest regeneration are comparable. On the nutrient-rich subsoil of this set, brambles spread fast, which leads to increased costs for chemical weed control. A 2% solution application of the selective systemic herbicide Garlon shows relatively good results. Fir is recommended as the most suitable SSTS in this habitat and management set and should be preferable over beech. With an SSTS share of 25%, natural regeneration brings cost savings of 6 414 EUR·ha^{-1} (160 358 CZK·ha^{-1}) compared to artificial regeneration. Between 2014 and 2023, this amount increased by 2 336 EUR·ha^{-1} (58 394 CZK·ha^{-1}) (Table 3).

TMS 591 – the management of waterlogged habitats at higher and middle altitudes shows higher losses of seedlings during artificial regeneration in years with standard precipitation. Despite regular maintenance of the drainage ditches, the loss has reached 10%. The water balance adjustment in these habitats should include the construction of water reservoirs to improve the retention capacity of the landscape, slow down surface water

Table 1. Direct costs of reforestation, including the first thinning in 2014/2023: Prices for MS 531 by reforestation variant in EUR·ha^{-1} (CZK·ha^{-1})

Operations	(*i*) Artificial regeneration Norway spruce		(*ii*) Artificial regeneration Norway spruce + 25% SSTS		(*iii*) Natural regeneration	
	2014	2023	2014	2023	2014	2023
Planting – establishment	2 000 (50 000)	3 100 (77 500)	2 410 (60 250)	3 865 (96 625)	0 (0)	0 (0)
Weeding	660 (16 500)	1 080 (27 000)	701 (17 531)	1 170 (29 250)	0 (0)	0 (0)
Chemical protection/weeds	359 (8 970)	540 (13 500)	382 (9 543)	585 (14 620)	0 (0)	0 (0)
Chemical protection/insects	40 (1 000)	62 (1 550)	30 (750)	43 (1 085)	0 (0)	0 (0)
Fencing	0 (0)	0 (0)	800 (20 000)	1 000 (25 000)	0 (0)	0 (0)
Repellent application	581 (14 520)	821 (20 530)	436 (10 890)	616 (15 398)	0 (0)	0 (0)
Schematic treatment	0 (0)	0 (0)	0 (0)	0 (0)	480 (12 000)	800 (20 000)
First thinning	280 (7 000)	460 (11 500)	280 (7 000)	460 (11 500)	480 (12 000)	720 (18 000)
Total	3 920 (97 990)	6 083 (152 080)	5 039 (125 964)	7 739 (193 478)	960 (24 000)	1 520 (38 000)
Difference to natural regeneration	2 960 (73 990)	6 063 (151 580)	4 079 (101 964)	6 219 (155 478)	–	–
Difference to natural regeneration between 2023 and 2014	3 103 (77 590)		2 701 (67 514)		560 (14 000)	

MS – management set; SSTS – soil-improving and stabilising tree species

https://doi.org/10.17221/56/2024-JFS

Table 2. Direct costs of reforestation, including the first thinning in 2014/2023: Prices for TMS 551 by reforestation variant in EUR·ha^{-1} (CZK·ha^{-1})

Operations	(*i*) Artificial regeneration Norway spruce				(*ii*) Artificial regeneration Norway spruce + 25% SSTS				(*iii*) Natural regeneration			
	2014		2023		2014		2023		2014		2023	
Planting – establishment	2 000	(50 000)	3 100	(77 500)	2 410	(60 250)	3 865	(96 625)	0	(0)	0	(0)
Weeding	880	(22 000)	1 600	(40 000)	935	(23 375)	1 700	(42 500)	0	(0)	0	(0)
Chemical protection/weeds	478	(11 960)	720	(18 000)	508	(12 708)	765	(19 125)	200	(5 000)	240	(6 000)
Chemical protection/insects	40	(1 000)	62	(1 550)	30	(750)	47	(1 163)	0	(0)	0	(0)
Fencing	0	(0)	0	(0)	800	(20 000)	1 000	(25 000)	0	(0)	0	(0)
Repellent application	581	(14 520)	821	(20 530)	436	(10 890)	616	(15 398)	0	(0)	0	(0)
Schematic treatment	0	(0)	0	(0)	0	(0)	0	(0)	480	(12 000)	800	(20 000)
First thinning	280	(7 000)	460	(11 500)	280	(7 000)	460	(11 500)	480	(12 000)	720	(18 000)
Total	4 259	(106 480)	6 763	(169 080)	5 399	(134 973)	8 452	(211 311)	1 160	(29 000)	1 560	(39 000)
Difference to natural regeneration	3 099	(77 480)	5 203	(130 080)	4 239	(105 973)	6 932	(173 311)	–		–	
Difference to natural regeneration between 2023 and 2014	2 504 (62 600)				3 054 (76 338)				400 (10 000)			

SSTS – soil-improving and stabilising tree species; TMS – target management set

runoff, and increase biodiversity. In recent years, their importance as water storage in case of fire has also increased. Alder tolerates sites with stagnant groundwater and can be used in reforestation. The lower profitability of this tree species is partly offset by the reduced silvicultural costs. Due to the carrying capacity of the terrain, harvesting should be carried out when there are lower groundwater levels, possibly in winter, when the topsoil will freeze, minimising the damage.

Table 3. Direct costs of reforestation, including the first thinning in 2014/2023: Prices for the TMS 571 by reforestation variant in EUR·ha^{-1} (CZK·ha^{-1})

Operations	(*i*) Artificial regeneration Norway spruce				(*ii*) Artificial regeneration Norway spruce + 25% SSTS				(*iii*) Natural regeneration			
	2014		2023		2014		2023		2014		2023	
Planting – establishment	2 000	(50 000)	3 100	(77 500)	2 410	(60 250)	3 865	(96 625)	0	(0)	0	(0)
Weeding	660	(16 500)	1 080	(27 000)	701	(17 531)	1 170	(29 250)	0	(0)	0	(0)
Chemical protection/weeds	359	(8 970)	720	(18 000)	382	(9 543)	780	(19 500)	0	(0)	0	(0)
Chemical protection/insects	40	(1 000)	62	(1 550)	30	(750)	43	(1 085)	0	(0)	0	(0)
Fencing	0	(0)	0	(0)	800	(20 000)	1 000	(25 000)	0	(0)	0	(0)
Repellent application	581	(14 520)	821	(20 530)	436	(10 890)	616	(15 398)	0	(0)	0	(0)
Schematic treatment	0	(0)	0	(0)	0	(0)	0	(0)	480	(12 000)	800	(20 000)
First thinning	280	(7 000)	460	(11 500)	280	(7 000)	460	(11 500)	480	(12 000)	720	(18 000)
Total	3 920	(97 990)	6 243	(156 080)	5 039	(125 964)	7 935	(198 385)	960	(24 000)	1 520	(38 000)
Difference to natural regeneration	2 960	(73 990)	4 723	(118 080)	4 079	(101 964)	6 414	(160 358)	–		–	
Difference to natural regeneration between 2023 and 2014	1 764 (44 090)				2 336 (58 394)				560 (14 000)			

SSTS – soil-improving and stabilising tree species; TMS – target management set

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Table 4. Direct costs of forest regeneration, including the first thinning in 2014: Prices for the TMS 591 by regeneration variant in EUR·ha^{-1} (CZK·ha^{-1})

Operations	(*i*) Artificial regeneration Norway spruce		(*ii*) Artificial regeneration Norway spruce + 25% SSTS		(*iii*) Natural regeneration	
	2014	2023	2014	2023	2014	2023
Planting – establishment	2 200 (55 000)	3 410 (85 250)	2 651 (66 275)	4 252 (106 288)	0 (0)	0 (0)
Weeding	660 (16 500)	1 080 (27 000)	701 (17 531)	1 170 (29 250)	0 (0)	0 (0)
Chemical protection/weeds	359 (8 970)	540 (13 500)	382 (9 543)	585 (14 620)	0 (0)	0 (0)
Chemical protection/insects	40 (1 000)	62 (1 550)	30 (750)	43 (1 085)	0 (0)	0 (0)
Fencing	0 (0)	0 (0)	800 (20 000)	1 000 (25 000)	0 (0)	0 (0)
Repellent application	639 (15 972)	821 (20 530)	479 (11 979)	616 (15 398)	0 (0)	0 (0)
Schematic treatment	0 (0)	0 (0)	0 (0)	0 (0)	480 (12 000)	800 (20 000)
First thinning	280 (7 000)	460 (11 500)	280 (7 000)	460 (11 500)	480 (12 000)	720 (18 000)
Total	4 178 (104 442)	6 373 (159 330)	5 323 (133 078)	8 126 (203 141)	960 (24 000)	1 520 (38 000)
Difference to natural regeneration	3 218 (80 443)	4 853 (121 330)	4 363 (109 078)	6 606 (165 141)	–	–
Difference to natural regeneration between 2023 and 2014	1 635 (40 887)		2 243 (56 063)		560 (14 000)	

SSTS – soil-improving and stabilising tree species; TMS – target management set

At an SSTS share of 25%, natural regeneration incurs a saving of 6 606 EUR·ha^{-1} (165 141 CZK·ha^{-1}) in the study area compared to artificial regeneration. Between 2014 and 2023, this amount increased by 2 243 EUR·ha^{-1} (56 063 CZK·ha^{-1}) (Table 4).

Financial comparison of direct costs per variant is summarised in Figure 1. For all management sets, the incorporation of natural regeneration reduced the final reforestation costs. At the same time, the use of SSTS [variant (*ii*)] increased the

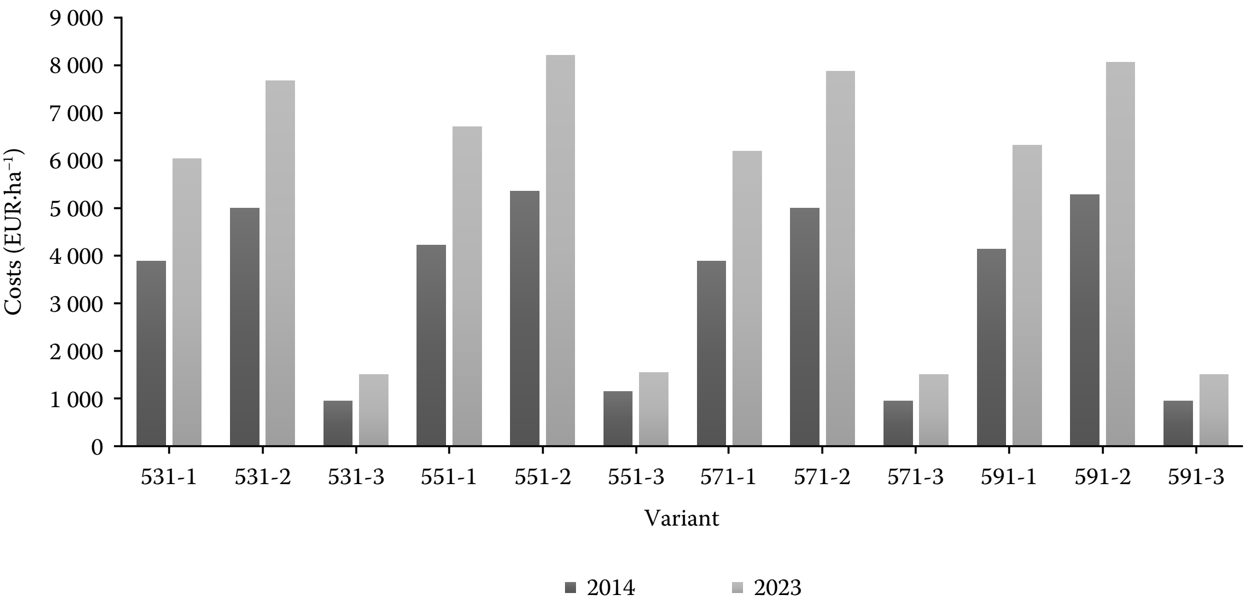

Figure 1. Financial comparison of direct costs per variant (three methods of forest regeneration including first thinning for particular management sets) in 2014 and 2023: Prices (in EUR·ha^{-1}) at four management units (531, 551, 571, and 591) at the Prylovi property

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Table 5. Percentage of natural and artificial regeneration on the analysed property in 2009–2014 and 2022–2023

Year	Area (ha)	Artificial regeneration (%)	Natural regeneration (%)
2009*	1.13	100	0
2010*	3.47	90	10
2011	8.33	75	25
2012	5.13	52	48
2013	6.42	59	41
2014	3.24	55	45
2022	27.92	91	9
2023	43.73	90	10

*Natural regeneration shares in 2009–2010 were affected by wind calamities Kyrill and Emma, which occurred in previous years

costs in comparison to both artificial and natural regeneration [variants (*i*) and (*iii*), respectively].

The proportion of natural regeneration was relatively high within the studied property (Table 5). Before the bark beetle calamity, it had reached a steady trend of above 40%. This was due to suitable natural conditions of the overall management concept.

DISCUSSION

Economic studies always face various limitations. First, it is the consequences of the dynamic development of the forest production's economic parameters, which can change during a short period of time. Another is the close relationship to the specific local conditions and current situation. However, with some degree of generalisation, the studies are valuable for management practice strategies. To some extent, our study resembles the approach of Knoke (2009), although it is less comprehensive, limited to only part of the management cycle (regeneration and development up to the first thinning) and does not compare two forest properties that differ only in the application of the management method. Our study compares similar practices over two distinct time horizons under the same comparative approach. Therefore, it can be used for broader model-based evaluations (Hanewinkel 2002; Šišák et al. 2017; Remeš, Pulkrab 2024).

Analyses proved that for almost every management set, based on chief commercial tree species, suitable SSTS or admixed species can be selected that increase both the quantity and quality of production (Podrázský 2005; Podrázský et al. 2009; Podrázský, Kupka 2011; Remeš et al. 2020). This is reflected in the current legislation (Regulation No. 298/2018 Coll.). In the presented case, larch and Douglas fir can complement spruce stands and thus increase their diversity, stability, and production (Mondek, Baláš 2019; Remeš et al. 2020; Mondek et al. 2021). Broader species composition is also relevant in the context of ongoing climate change as the use of spruce will encounter habitat limits due to its high sensitivity to environmental changes (Kupčák et al. 2019; Remeš, Pulkrab 2024).

In our study, we selected an adapted method (Hannewinkel 2002) similar to other relevant studies (Remeš, Pulkrab 2024) that model the economic results of the management principle based on specific data within a single forest property/management unit. This differs from the method presented by Knoke (2009), which assumes a comparison between two properties in similar habitat and socio-economic conditions. Even in the phase of harvesting and the technologies used, economically positive results can be achieved (Remeš, Pulkrab 2024).

The economic data on regeneration and harvesting have been tracked since 2008. Harvester machinery is predominately used in regenerative cuts. As the proportion of harvesting methods increases, it brings significant cost savings in harvesting and the efficiency of the whole shelterwood management increases (Remeš et al. 2011; Schütz 2011; Šafařík et al. 2022; Manner, Ersson 2023). In achieving these goals, high demands must be placed on both the adherence to technological procedures and the skill of the workers (Novotný, Šišák 2016). The concept of using harvester technology in shelterwood management started on the studied property in 2007 and currently represents a sum of the volume of planned and salvage harvests carried out by harvesters of more than 90%. The beginning of the bark beetle calamity was observed in the monitored area on the management sets influenced by water, where the groundwater table dropped, and the stands with shallow root systems subsequently suffered from water scarcity. These stressed stands were affected first. If the damage caused by abiotic factors to these sites is also considered, the rotation period should be shorter as part of the risk reduction (Korená Hillayová et al. 2022). These sites face a significant change in both temperature and

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moisture conditions when the stands have been thinned. In addressing the issue of water management in stands and to reduce risks, more frequent interventions with lower intensity should be implemented in future, even at the expense of reducing the economic efficiency of harvesting (Novotný, Šišák 2016). The highest increase in forest protection costs occurred in stands with higher management intensity. The findings show that the highest costs were for weed control, followed by game-induced damage protection, and the lowest costs were calculated for insect pest control. Contrarily, Pulkrab et al. (2011) report the highest costs over the stand growing period for game damage, followed by weed control costs, and the lowest costs for insect pest control.

The proportion of natural regeneration on the monitored property is relatively high – apart from the calamity years – due to suitable conditions, especially in acidic environments which offer ideal habitats for natural regeneration, not only of spruce but also of other tree species. The influence of harvesting technology on successful natural regeneration and protection of natural young growth proves to be crucial (Novotný, Šišák 2016). For this purpose, harvesters are used, following manual chainsaw pre-harvesting. This method guarantees minimal harvesting damage to the growth established under the shelter of the parent stand. However, in most cases, natural regeneration cannot be successfully ensured over the entire stand area, so it is necessary to replenish the property under study with bare-rooted planting material. The use of suitable SSTS to increase the stability and production of forest stands is proposed (Podrázský 2005; Remeš, Pulkrab 2024). Several factors contributed to the bark beetle calamity in the Czech Republic. Initially, it was the continuous increase in the rotation age, which has risen by 22.5 years since 1930. It significantly exacerbates the risks associated with over-aged stands, which are, of course, more susceptible to the effects of harmful biotic and abiotic factors. In habitats threatened by a lack of precipitation, the age of regeneration should fall below 80 years, which is a limit currently mandated by law. It is particularly noteworthy that the necessity to cut down and peel the infested trees, burn the bark and quickly remove the wood from the forest had already been issued in a decree of the Prague Governorate from 1835 (Nožička 1957).

The natural regeneration of the spruce undergrowth on the property is relatively abundant, so the damage caused by deer is insignificant. The situation is considerably different for other species of forest trees with a lower overall share, where the game pressure is enormous and substantially limits nature-friendly management on the property. Maples and firs show the highest degree of damage by browsing and fraying (Vacek et al. 2020b; Vančura et al. 2020). These tree species cannot be reasonably naturally restored without systematic hunting pressure.

In Central Europe, spruce was primarily a tree species of mountain areas, where it usually formed the upper boundary of the forest. It also occurred naturally at lower altitudes, for example, the Sázava spruce ecotype at 400–500 m a.s.l. (Pokorný 1955; Vančura et al. 2020). Due to the high quality of its wood, spruce was planted in all vegetation altitudinal zones, often in monocultures. The tree species representation suggests that the property is pure spruce management with an admixture of larch at higher elevations on the acidic habitats of management sets (MS) 531, nutrient-rich habitats of MS 551, water-enriched habitats of MS 571, and waterlogged habitats of MS 591. The production optimum for its cultivation can be found on the presented sites (Průša 2001). From the spectrum of damaging factors, only wind caused more pronounced damage to the monitored property in the past. Even during hurricane Kyrill, the volume of salvage felling did not exceed the annual standard. Until the large-scale bark beetle calamity, the salvage-felled bark beetle-infested timber had represented only 0.1–0.2 $m^3 \cdot ha^{-1}$, with an average stock of 565 $m^3 \cdot ha^{-1}$. Thus, spruce is expected to be adequately represented in the future and with proportionate economic effects (Remeš, Pulkrab 2022, 2024). In salvage felling clearings, artificial reforestation, including SSTS, should be performed in a short time frame, including the use of tree species that are only marginally present in the original stands and cannot be expected to regenerate naturally. The trend towards the use of natural regeneration and suitable soil-improving tree species guarantees the effective cultivation of stable and diversified forest stands (Podrázský 2005; Remeš, Pulkrab 2024). Such trends, especially in natural regeneration, are confirmed also by foreign studies from Sweden (Löf et al. 2021), Poland (Długosiewicz et al. 2019), and even earlier from Switzerland (Bürgi, Schuler 2003).

https://doi.org/10.17221/56/2024-JFS

CONCLUSION

The presented study demonstrated the suitability of more nature-friendly methods for increasing the economic efficiency of forest management. The employment of natural regeneration is a critical factor in economic efficiency. Changes in economic conditions in 2014–2023 have substantially contributed to different economic parameters of forest management. However, the established trends provide sufficient preconditions for economically efficient management along with the preservation of stable forest ecosystems. The cornerstone is the maximum use of natural regeneration, the choice of suitable species composition, and the optimisation of regeneration processes and the subsequent tending, harvesting, and utilisation of the timber.

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Received: August 8, 2024
Accepted: August 28, 2024
Published online: October 23, 2024