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Using marteloscope in selection forestry – Study case from 'Pokojná hora' (Czech Republic)

Jan Kadavý[1], *Jana Kneiflová*[2], *Michal Kneifl*[1], *Barbora Uherková*[1]*

[1]*Department of Forest Management and Applied Geoinformatics, Faculty of Forestry and Wood Technology, Mendel University in Brno, Brno, Czech Republic*
[2]*University Enterprise Masaryk Forest in Křtiny, Křtiny, Czech Republic*

**Corresponding author: barbora.uherkova@mendelu.cz*

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Abstract: In today's forestry practices, integrated management is the prevailing approach. One method gaining traction is retention forestry, where certain trees, known as biotope trees providing microhabitats (TreMs), are preserved during harvesting operations. This article delves into hands-on training for marking interventions using marteloscope plots, focusing specifically on 'Pokojná hora,' a 1-hectare plot situated in the southeast of the Czech Republic. Field surveys were conducted using FieldMap technology, capturing essential data for all trees: coordinates, species, diameter, height, and health status. Additionally, details such as wood quality, economic value, microhabitats, and habitat value were documented for each tree. Forestry engineering students virtually mapped out interventions on the marteloscope plot, testing 11 solution variants across 2 scenarios to strike a balance between economic goals and biodiversity conservation. The plot hosts 155 microsites, predominantly on *Fagus sylvatica* (common beech) with 108 microsites. The likelihood of TreMs increases with tree diameter, while the correlation between a tree's economic value and its diameter was confirmed. Optimal management suggests maintaining 10 habitat trees per ha to reconcile economic and ecological objectives during harvesting operations. In essence, we contend that the adoption of retention forestry practices coupled with marteloscope training can play a pivotal role in arresting biodiversity decline within forest ecosystems.

Keywords: continuous cover forestry; ecological value; economic value; optimisation; tree microhabitat; virtual tree selection

In European temperate managed forests, there has been a long-term decline in biodiversity (Dauber et al. 2003; Bohn, Huth 2017; Mölder et al. 2021; Pötzelsberger et al. 2021; Duflot et al. 2022). One way to address this issue is by altering the forest management system through the implementation of nature conservation elements using integrative management approaches (Kraus, Krumm 2013). One such approach could be the use of a system known as retention forestry. This involves an integrated conservation approach where structures crucial for biodiversity, including trees providing microhabitats (TreMs), are intentionally retained during forest harvesting (Gustafsson et al. 2020). However, these trees may also have high economic value, and their preservation may result in economic losses. The selection of these trees requires finding a compromise between wood production and biodiversity conservation. This is particularly relevant in the context of close-to-nature for-

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estry (Continuous Cover Forestry, CCF), where the selection process occurs at the level of individual trees before harvesting, making it a crucial managerial decision. The choice of trees involves decisions about compromises between forest demands – preserving habitats or wood production (Kraus et al. 2018).

Biotope trees are typically considered as living standing trees with specific significance for fauna and flora, carrying so-called microhabitats (microsites), such as cavities, injuries and wounds, dead wood in the tree canopy, epiphytes, and nests (Kraus et al. 2016; Larrieu et al. 2018). Biotope trees are crucial drivers of biodiversity in forests and important components of the functional network of elements in old-growth forests. However, in managed forests, they are often rare or even absent. Silviculture systematically removes 'defective' trees with low economic value, which commonly includes trees hosting microhabitats or trees with high potential for their development (Vandekerkhove et al. 2013). The selection of trees, including the retention of biotope trees, is a key silvicultural activity as it determines the future appearance of the forest and the functions it will be able to fulfil. It is a time-consuming process, additionally incurring significant costs. Scientific literature has not dedicated much attention to the selection of trees as an individual or social decision-making process. Nevertheless, several studies have been published on this topic, focusing on the impact of the expertise of selected professional groups on decision-making in tree selection (Pommerening et al. 2015; Spinelli et al. 2016; Vítková et al. 2016; Pommerening et al. 2018; Cosyns et al. 2019; Cosyns et al. 2020; Joa et al. 2020).

Understanding and effectively implementing retention forestry in Central European temperate forests is deemed vital for enhancing the education of future foresters, as prolonged application of a management strategy tends to result in less frequent alterations (Vítková et al. 2016). Practical training in marking interventions on marteloscope plots can help bridge this gap (Kraus et al. 2018).

Marteloscope plots closely resemble standard research plots, where data on all or a subset of trees within a defined area are collected, including trunk diameter at breast height, tree height, species, Cartesian coordinates, and optionally additional qualitative traits such as wood quality and microhabitats (TreMs). Each tree is numbered for identification purposes and to link individual trees to measurements. Marteloscopes serve as practical training grounds for marking interventions based on predefined instructions and goals (Pommerening et al. 2015). This training method is employed in various European countries, the United States, and Canada, with potential applications in some Asian and South American regions, although obtaining relevant information from these areas can be challenging.

The hypotheses considered in this article are as follows:

(*i*) The tree's diameter at breast height (*DBH*) correlates with microhabitat occurrence;

(*ii*) In a stand managed for over 40 years as a selection forest (CCF), retaining biotope trees balances economic and ecological values effectively;

(*iii*) Training in marking biotope trees enhances forestry students' comprehension, enabling the exploration of solutions that reconcile economic and biodiversity needs.

The article describes a standard task and the results of training students in marking interventions in a selection forest (CCF) with the aim of finding an optimal strategy for integrative management through the retention of biotope trees. The area of selection forests and forests managed long-term with selection principles, also known as continuous cover forestry (CCF), amounts to approximately 39 million ha in Europe, representing around 30% of forested areas. In the Czech Republic, selection forestry is, unfortunately, so far practised on approximately less than 1% of the total forest area (Mason et al. 2022).

The novelty and the goal of the article lie in combining economic and ecological perspectives through retention forestry, including an evaluation of collected data and different scenarios on a marteloscope plot.

MATERIAL AND METHODS

Study area – marteloscope 'Pokojná hora'. Marteloscope 'Pokojná hora' covers an area of 1 ha (100 m × 100 m). It is located within the territory of the Training Forest Enterprise Masaryk Forest Křtiny, Czech Republic (Figure 1). The plot GPS location is 49°19'59.059"N, 16°41'38.841"E. The average elevation is 490 m a.s.l., the average annual precipitation is approximately 660 mm, and the average annual temperature is 6.6 °C. The soils are classified as Luvisols and Cambisols. The area corresponds to the herb-rich beech forests – L 5.1 biotope (EEA 2006; Chytrý 2013) or specifically the

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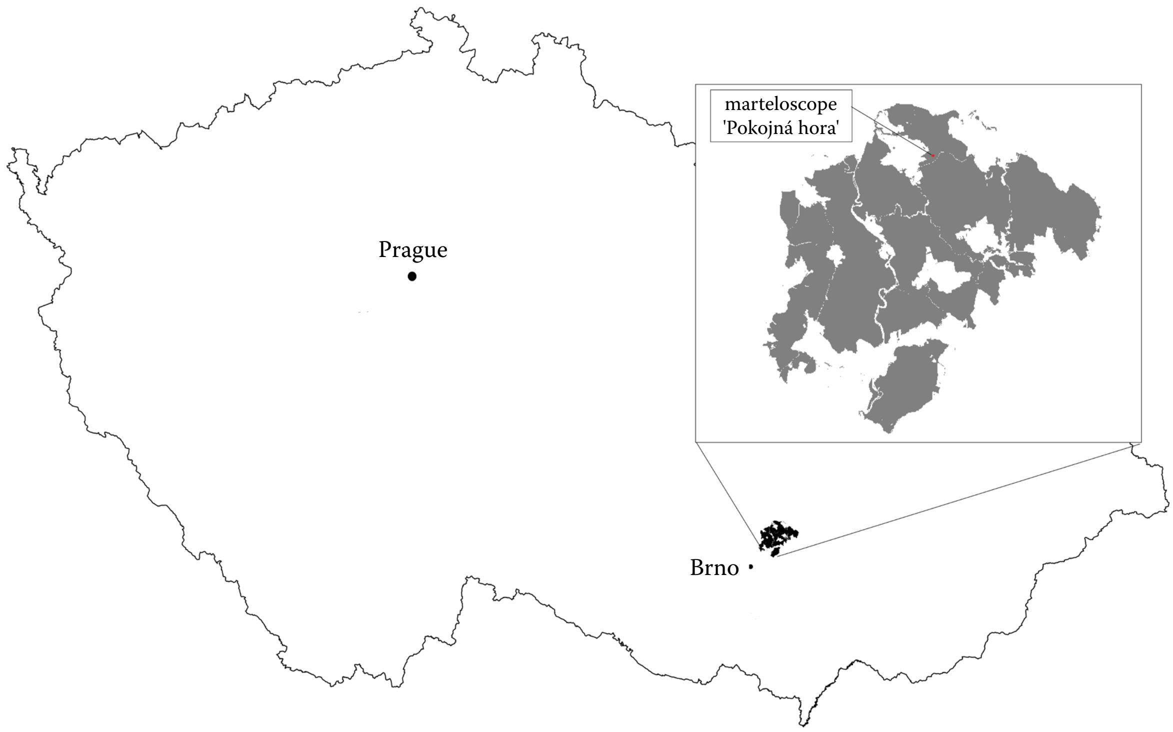

Figure 1. Location of the marteloscope study plot 'Pokojná hora'

Asperulo-Fagetum beech forests – 9130 according to Natura 2000 (EEA 2006). The surrounding forest stands (approximately 150 ha) have been managed as selection forests (CCF) since 1983. The area is part of the European Network of Marteloscopes facilitated by the European Forest Institute.

Data collection. All trees with a diameter at breast height (*DBH*) greater than 8 cm were inventoried using FieldMap technology (http://www.fieldmap.cz). For each tree, in addition to their coordinates, the species, diameter, height, and health condition were recorded. Health status was assessed as follows: healthy individual, dry branches at the base of the crown, dry branches in the crown, dry crown. A local forester estimated the wood quality of each tree, and the economic value (measured in CZK) was calculated based on volumes of up to five quality classes (A–D or F – fuel) multiplied by local wood prices.

Microhabitats (TreMs) were assessed based on their type, size, and developmental stage using the tree microhabitat catalogue (Kraus et al. 2016). The habitat value of the tree (measured in habitat points) was calculated as a composite index based on (*i*) the type and number of TreMs on a particular tree, (*ii*) their rarity, and (*iii*) the time required for specific TreMs to develop (Kraus et al. 2018).

Forestry engineering students virtually practised marking interventions in the selection forest using the marteloscope plot to balance economic and biodiversity concerns. Divided into eleven groups of 3–6 members, they explored two scenarios and tested eleven solution variants for virtual harvest marking. Their task involved individually marking trees, with specific criteria such as tree health, trunk shape, and maturity. When marking virtual harvest, they had to respect the following criteria: tree health, trunk shape, tree maturity (harvest *DBH* for *Abies alba* Mill., *Picea abies* (L.) H. Karst., *Fagus sylvatica* = 45 cm) and structural support. Table 1 shows the specifications of the scenarios and variants applied in the experiment.

The training took place on November 16 and December 15, 2023. For this purpose, students used the I + Trainer application (Android, Version 0.7.9.9 beta, 2023; http://iplus.efi.int/software-store.html) installed on mobile devices. The actual marking procedure took approximately 1.5 h, followed by a joint discussion between students and teachers for about 0.5 h.

Data analysis. The data analysis focused on two main goals: (*i*) to find the optimal selection of trees on the marteloscope plot to balance the economic and ecological value of the virtually harvested trees and those

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Table 1. Specifications of scenarios and variants applied in the experiment

Scenario	Variant	Biotope trees retained
S1 – total volume of all marked trees (both biotope and harvested) ≈ 100 m^3	V5	5
	V10	10
	V15	15
	V20	20
	V25	25
	V30	30
S2 – total volume of only trees marked for harvest ≈ 100 m^3	V5	5
	V10	10
	V15	15
	V20	20
	V30	30

retained in the stand, and (*ii*) to define the relationship between dependent variables (economic and ecological value, the probability of TreM occurrence, and assortments of quality classes A, B, and C) and the diameter at breast height (*DBH*) of the tree. Quality class D or F (fuel), was not assessed due to its clear occurrence in all possible assessment cases (it was never labelled as a non-occurring variable).

To determine a scenario for retaining the optimal number of biotope trees (for balancing economic and ecological goals), multi-criteria programming was used. The goal of the task is to optimise several scalar objective functions on the set of feasible solutions. In general, the mathematical formulation of the task can be defined in Equation (1) and Equation (2) as follows:

Maximise $z_1 = c^1x$; $z_2 = c^2x$:

$$z_k = c^k x \tag{1}$$

under given conditions:

$$x \in X = \{x \in R^n \mid Ax \leq b, x \geq 0\} \tag{2}$$

where:

c^i, $i = 1, 2, ..., k$ – vector of value coefficients for the i^{th} objective function;
z – scalar objective function to be maximised;
x – decision variables (in this case scalar);
X – set of feasible solutions;
R^n – n^{th} dimensional real space (in this case $n = 1$);
A – coefficient;
b – constraint representing the upper bound.

Any feasible solution $x_p \in X$ is defined by a vector of criterion values ($c^1x^p, c^2x^p, ..., c^kx^p$). The objective of the linear programming problem was to find a compromise solution. The computation involved aggregating objective functions. This principle is based on evaluating the importance of criterion functions with weights $v_1, v_2, ..., v_k$, $\Sigma v_i = 1$. In the solution, criterion functions with the same weights were employed. Instead of addressing problems (1) and (2), we could thus solve this problem as defined by Equation (3):

Maximise:

$$z = \sum_{i=1}^{k} v_i c^i x \tag{3}$$

under the conditions given in Equation (2),

where:

v – weights.

To express the relationship between diameter at breast height and dependent variables, regression analysis (economic and ecological value) was used, or more specifically, logistic regression (probability – P occurrence of TreM and assortments of classes A, B, and C) according to the relationship shown in Equation (4):

$$P = \frac{1}{1 + e^{-\left(\beta_0 + \beta_1 x_1\right)}} \tag{4}$$

where:

P – probability;
e – natural logarithm base;
β_0 – bias or intercept term;
β_1 – coefficient for input (x).

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The data were analysed in the R programming language environment (R Core Team 2021; The jamovi project 2022).

RESULTS

Plot inventory. There is a total of 357 trees on the plot, with a basal area of 33 m^2 and a volume of 435 m^3. The dominant species is *F. sylvatica* (59%), while *Pinus sylvestris* L. is the least represented species (4%; Table 2). The plot contains 155 microsites (TreMs), with the majority found on *F. sylvatica* (108 microsites), constituting 70% of the total.

The diameter and height structure of trees on the plot is highly differentiated (Table 3). On average, the thickest and tallest species is *Larix decidua* Mill. (48.7 cm and 34.6 m, respectively), while the thinnest and shortest is *A. alba* (16.4 cm and 22.4 m, respectively). The greatest diameter and height variability, expressed by the standard deviation of the diameter, is exhibited by *A. alba* (± 16 cm and ± 9 cm, respectively). The main canopy layer is formed by *F. sylvatica* with an average height of 23 m. The differentiation of the diameter and height structure of the stand can be inferred using the range of inventory values. The largest height range is found in *F. sylvatica* (5–39 m) and *A. alba* (5–35 m), while the smallest height range occurs in *L. decidua* (30–40 m). Similarly, the largest diameter range is observed in *F. sylvatica* (8–63 cm) and *A. alba* (8–60 cm), but the smallest diameter range is found in *P. sylvestris* (36–54 cm). The largest measured diameter is recorded in *P. abies* (71 cm), and the tallest height of 40 m is found in both *L. decidua* and *P. abies*.

The probability of TreM increased with increasing tree diameter [*DBH* (χ^2 = 42.3; *df* = 1; $P \leq 0.001$; Figure 2)]. This is despite the fact that (*i*) the data come from a marteloscope located in a management forest, (*ii*) the forest has been converted to a selection forest (CCF) for at least 40 years,

Table 2. Stand data of the marteloscope

Species	*N* (pcs·ha^{-1})	*BA* (m^2·ha^{-1})	*V* (m^3·ha^{-1})	Share (% according to *BA*)	Microhabitats (TreMs; pcs·ha^{-1})
Abies alba	77	4.6	47.5	14.1	17
Fagus sylvatica	227	19.2	283.3	58.7	108
Larix decidua	30	5.7	65.7	17.4	23
Picea abies	14	1.9	23.1	5.8	3
Pinus sylvestris	9	1.3	15.4	4.0	4
Sum	357	32.7	435.0	100.0	155

BA – basal area; *N* – number of trees; *V* – volume; TreMs – biotope trees providing microhabitats

Table 3. Data on the diameter and height structure of trees in the marteloscope plot 'Pokojná hora'

Variable	Species	Mean	Median	*SD*	Minimum	Maximum
DBH (cm)	*Abies alba*	22.4	11.9	± 16.39	8.0	59.5
	Fagus sylvatica	29.5	29.5	± 14.32	8.0	63.0
	Larix decidua	48.7	49.0	± 5.33	38.5	59.5
	Picea abies	38.9	37.0	± 13.85	22.5	71.0
	Pinus sylvestris	42.0	40.5	± 5.41	36.0	54.0
Height (m)	*Abies alba*	16.4	11.8	± 9.27	4.7	35.1
	Fagus sylvatica	23.4	25.5	± 8.60	5.0	39.0
	Larix decidua	34.6	34.5	± 2.48	29.7	39.9
	Picea abies	27.5	26.2	± 7.50	15.5	40.0
	Pinus sylvestris	29.5	26.9	± 4.96	23.6	37.0

DBH – diameter at breast height; height – total tree height; *SD* – standard deviation

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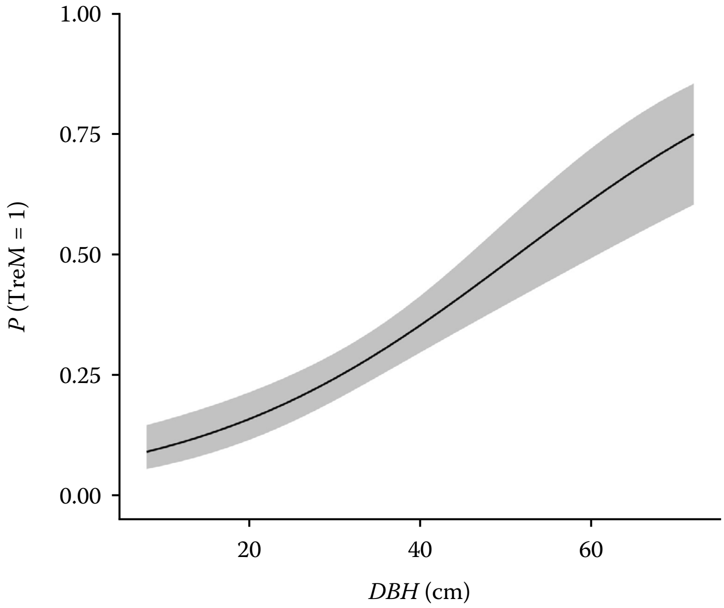

Figure 2. Representation of the probability (*P*) of TreM occurrence according to diameter at breast height on the marteloscope plot 'Pokojná hora'

DBH – diameter at breast height (cm); TreM – biotope trees providing microhabitat

and (*iii*) management activities have also regularly removed 'defective' trees, i.e. those most likely to carry TreMs.

Economic and ecological value. The total economic value of all trees in the plot (Table 4) in prices for the 4th quarter of 2023 reached CZK 1.083 thousand. *F. sylvatica* contributes 56% to this value. The highest average wood price per tree is achieved by *L. decidua* (CZK 9.7 thousand), while *A. alba* had the lowest (CZK 1 thousand).

The total ecological value, expressed by the point value of microsites (TreMs), was 2.2 thousand points. Of this value, 69% was generated by *F. sylvatica*. The highest average point value of microsites (TreMs) per tree was attained by *L. decidua* (8 points), while *A. alba* and *P. sylvestris* shared the lowest value (4 points).

There is a relationship between the economic value of a tree and its diameter (Figure 3; Loess – intercept: –2 821; slope *DBH*: 193; R^2 = 0.869). This fact is illustrated by the plots of the probability of occurrence of assortments of class A, B, and C according to the diameter of the trees (Figure 4A: χ^2 = 164; df = 1; $P \leq 0.001$; Figure 4B: χ^2 = 201; df = 1; $P \leq 0.001$; Figure 4C: χ^2 = 304; df = 1; $P \leq 0.001$). On the other hand, there is a large variation in ecological microhabitat (TreM) values according to tree diameters. This is also due to the fact that there is a large number of trees with zero ecological value due to applied selective manage-

Table 4. Economic and ecological values of trees in the marteloscope plot 'Pokojná hora'

Species	Economic value			Ecological value		
	total (CZK·ha^{-1})	relative share (%)	per tree (CZK·tree^{-1})	total (points·ha^{-1})	relative share (%)	per tree (points·tree^{-1})
Abies alba	80 221	7.4	1 042	337	14.9	4.0
Fagus sylvatica	604 126	55.8	2 661	1 562	68.9	7.0
Larix decidua	291 198	26.9	9 707	244	10.8	8.0
Picea abies	47 228	4.4	3 373	89	3.9	6.0
Pinus sylvestris	60 540	5.6	6 727	36	1.6	4.0
Sum	1 083 313	100.0	3 034	2 268	100.0	6.4

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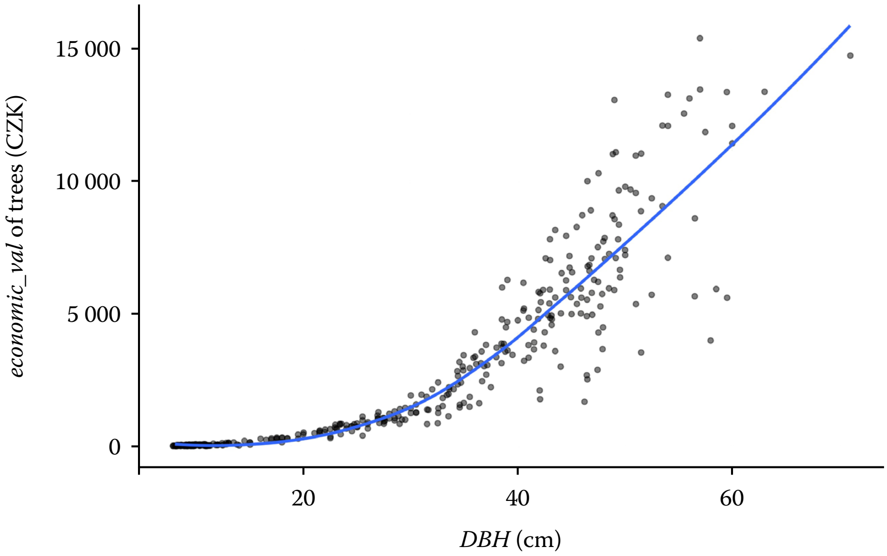

Figure 3. Display of economic values (*economic_val*) of trees according to their *DBH* (cm) on the marteloscope plot 'Pokojná hora'

Points – economic value of the tree (in CZK); regression line – interlacing of the point field (Loess); *DBH* – diameter at breast height

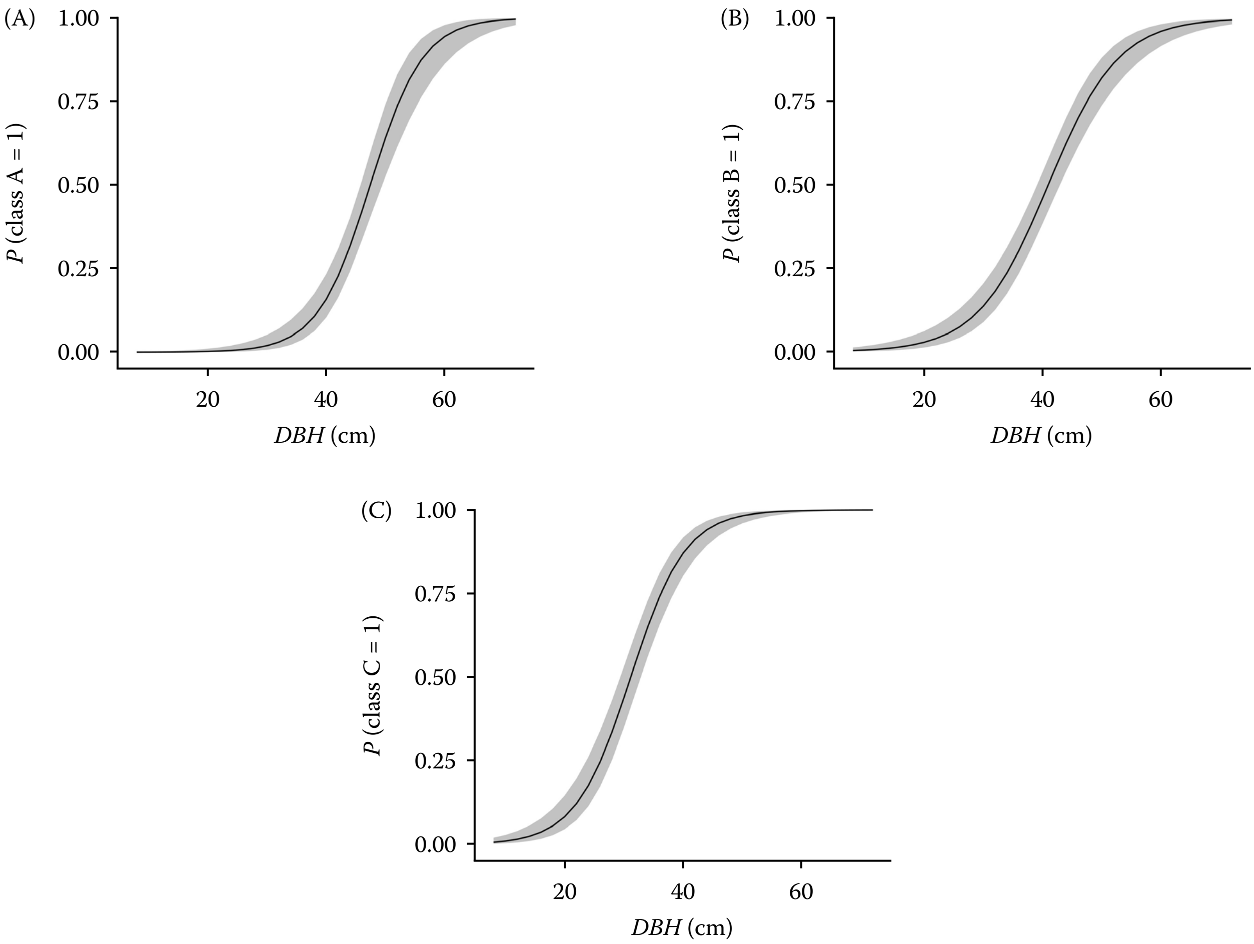

Figure 4. Representation of the probability (*P*) of occurrence of assortments of (A) class A, (B) class B, and (C) class C according to tree *DBH* (cm) on the marteloscope plot 'Pokojná hora'

DBH – diameter at breast height

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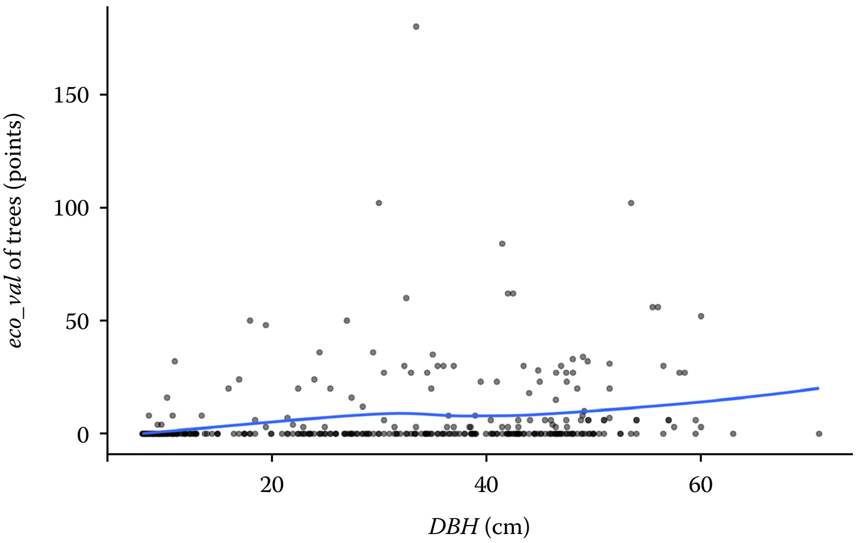

Figure 5. Display of ecological values (*eco_val*) of trees according to their diameter at breast height (*DBH*; cm) on the marteloscope plot 'Pokojná hora'

Points – ecological value of the tree (in number of points); regression line – interlacing of the point field (Loess)

ment, which preferentially removes 'defective' trees from the stand (Figure 5).

Forestry management scenarios. Two scenarios (S1 and S2) and 11 variants of the optimisation problem were evaluated (Table 5). The assessed variants included economic and ecological values for stand after harvest and the harvested trees. The optimisation computation considered all inputs of the variants, and the result is a proposed ranking based on the value of the objective function. The S2 scenario appears more promising, as four out of five of its variants are ranked in the top four positions according to the objective function. The highest-ranking variant (in terms of order) was S2-var10 (marked bold in Table 5), where virtually selecting 10 habitat trees per ha and simultaneously proposing the selection of trees for harvest in a total volume of 100 m^3 per ha. Ten habitat trees per ha appears to be optimal to balance both the economic and ecological aspects of harvest.

Table 5. Comparison of forestry management variants

Scenario-variant	Stand after harvest		Harvested trees		Objective function	Rank
	economic value (CZK·ha^{-1})	ecological value (points·ha^{-1})	economic value (CZK·ha^{-1})	ecological value (points·ha^{-1})		
S1-var5	879 613	2 109	203 700	159	0.71116	9
S1-var10	858 318	1 973	224 995	295	0.77296	5
S1-var15	886 412	2 036	196 901	232	0.73425	7
S1-var20	923 403	2 021	159 910	247	0.71931	8
S1-var25	962 555	2 101	120 758	167	0.66824	10
S1-var30	998 689	2 079	84 624	189	0.65635	11
S2-var5	850 934	1 989	232 379	279	0.77116	6
S2-var10	**823 097**	**1 754**	**260 216**	**514**	**0.87299**	**1**
S2-var15	802 093	1 893	281 220	375	0.83348	2
S2-var20	772 093	1 957	311 220	311	0.82652	3
S2-var30	834 471	1 953	248 842	315	0.79350	4

Bold – the highest-ranking variant (in terms of order)

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DISCUSSION

Identifying habitat trees: What makes a tree a habitat tree? Tree diameter serves as a key criterion for designating a biotope tree as a carrier of TreM. Research by various authors, including Johann and Schaich (2016), Asbeck et al. (2019), Paillet et al. (2019), Santopuoli et al. (2019), and Kozák et al. (2023), supports the trend of increased occurrence and abundance of TreM with larger tree diameters. Similar findings are observed on the 'Pokojná hora' marteloscope plot, as shown in Figure 2.

Retention forestry often involves the presence of large live trees, typically identified by their diameter at breast height (*DBH*). These trees typically surpass specific threshold values, such as *DBH* > 67.5 cm (Paillet et al. 2017) or *DBH* > 80 cm (Bobiec 1998; Großmann et al. 2023). While the first threshold was met at the 'Pokojná hora' marteloscope plot (*P. abies* – max. *DBH* 71 cm), the second threshold was not reached (Table 2). This can be explained by the current management practice of transitioning to selective forestry, which aims for a target *DBH* of 45 cm for *A. alba*, *P. abies*, and *F. sylvatica*.

Habitat trees are not solely defined by their diameter; other traits matter too. Scientific studies highlight factors such as TreM frequency in the stand (Cosyns et al. 2020), tree age and size (Kozák et al. 2023), tree vigour (Johann, Schaich 2016), as well as elevation and slope gradient (Kozák et al. 2023). However, while confirming the interchangeability of tree age and diameter, it is important not to overlook the positive impact of tree longevity on TreM richness, as emphasised by Kozák et al. (2023).

Combining economic and ecological principles. How many habitat trees per unit area is sufficient to reconcile the economic and ecological principles? There are several recommendations: 1–10 trees per ha (Gustafsson et al. 2020), 5–10 trees per ha (Asbeck et al. 2021), or aggregation in groups of about 15 trees per 3 ha (Bollmann, Braunisch 2013). The number of habitat trees must correspond to stand conditions and varies by region and forest ownership categories.

The ideal habitat tree has a high ecological and low economic value (Niedermann-Meier et al. 2010). To reconcile economic and ecological principles in marking, knowledge of the future evolution of TreM over time could probably help (Courbaud et al. 2017; Larrieu et al. 2018; Cosyns et al. 2020). Such information would be more helpful in deciding whether to retain a habitat tree, e.g. a rather thinner but ecologically preferred tree (e.g. hornbeam) or, conversely, a thicker but economically valuable tree (e.g. oak).

Cosyns et al. (2020) recommend using not only known economic indicators (e.g. costs, yields, stock growth, etc.) but also an ecological indicator based on the habitat value calculation. According to Cosyns et al. (2019), there are at least six explanations for the high variability in the habitat value calculation.

We assert that transitioning to forest management methods incorporating elements of nature conservation, such as retention forestry, is both economically and ecologically viable and aligns with the interests of the forestry conservation community. However, we acknowledge that our assessment lacks consideration of the time factor or projections for the future development of the assessed variables. Consequently, we propose that this area warrants further investigation in future research endeavours.

Integration of retention forestry. Recognising that integrating forest management and conservation through biotope tree retention in commercial forests may not fully maximise a site's potential for nature conservation across landscapes (Muys et al. 2022), we assert that its implementation and training on marteloscope plots can substantially aid in halting biodiversity decline in forests. This is crucial because only forests consistently maintaining biodiversity levels (relative to the norm) can remain vital and resilient to climate change.

While employing a retention approach in forests is not a standalone solution, it can contribute to fostering structurally diverse forests, which may exhibit greater resilience to various disturbances. We deem this significant, despite the absence of a universally accepted view regarding the role of forest structural diversity in climate change adaptation, as suggested by Dănescu et al. (2018).

CONCLUSION

In general, there is a mass decline in biodiversity in forests. Thus, the approach is to use integrative management methods; one option may be retention forestry. Retention forestry is a tool to maintain multifunctional forests and it is an integrated conservation approach where structures crucial for biodiversity, including trees providing microhabitats (TreMs), are intentionally retained during forest harvesting. Biotope trees are typically considered

https://doi.org/10.17221/29/2024-JFS

as living standing trees with specific significance for fauna and flora, carrying so-called microhabitats (micro-sites). So, the selection of trees, including the retention of biotope trees, is a key silvicultural activity. Practical training in marking interventions on marteloscope plots can be a good approach. Training in marking biotope trees contributes to a better understanding of the issue, helping to explore options for reconciling purely economic (forestry) and biodiversity (conservation) requirements.

The marteloscope plot 'Pokojná hora' contains 155 microsites, with the majority found on *F. sylvatica* (108 microsites). The probability of TreM increased with increasing tree diameter. The relationship between the economic value of a tree and its diameter was proofed. Following the examination of 2 harvesting scenarios and 11 solution variants, we found that maintaining 10 habitat trees per ha seems to be the optimal approach for achieving a balance between economic and ecological considerations in the harvest. All hypotheses of the paper were confirmed.

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