Human Tree-Selection Behaviour in Continuous Cover Forestry
Insights from Marteloscope Exercises

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Abstract

Continuous Cover Forestry (CCF) has gained increasing attention as a forest management approach aimed at balancing timber production with biodiversity conservation and promoting resilient forestry. Central to CCF is the selection of individual trees for retention or removal, a process that is inherently shaped by human decision-making. This thesis investigates human tree-selection behaviour by using previous knowledge and material from marteloscope exercises, with the objective of improving the understanding of agreement, conformity and the ecological–economic trade-offs involved in CCF-related decisions.

Data from a peer-reviewed publication were analysed in this paper. The data came from a previously conducted marteloscope exercise involving forestry students, where a "trainer" had marked habitat trees as a baseline prior to the exercise. Tree-selection behaviour was analysed using a combination of agreement metrics, conformity indices, logistic regression and spatial indicators, including tree size, dominance, species mingling and location diversity. These methods enabled a detailed assessment of both individual and group-level decision-making patterns across habitat-tree selection and removal scenarios. The results revealed consistently low agreement among participants, confirming findings from previous studies. However, conformity analyses demonstrated that meaningful collective tendencies existed despite low agreement. Distinct decision-making profiles emerged among participant groups, even within a relatively homogeneous educational context. The trainer's selections were characterised by a strong preference for large, dominant trees in mixed-species neighbourhoods and spatially dispersed configurations, reflecting ecologically informed decision-making. In contrast, several student groups exhibited weaker sensitivity to structural and spatial attributes or prioritised economic outcomes, particularly in removal decisions. Overall, the findings indicate that low agreement is an inherent feature of CCF decision-making rather than a deficiency, reflecting the plurality of valid management pathways. Marteloscope exercises are shown to be valuable tools for both research and training, offering insights into human behaviour, trade-offs and uncertainty in forest management. Enhancing transparency and incorporating behavioural feedback into training may support more consistent and ecologically robust implementation of CCF.

Keywords: Continuous cover forestry, CCF, human tree-selection behaviour, marteloscope, agreement, conformity, habitat-tree, tree-related microhabitat

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Abbreviations

Abbreviation	Description
CCF	Continuous cover forestry
RFM	Rotation forest management
DBH	Diameter at breast height
TreMs	Tree-related microhabitats
EFI	European Forest Institute
HT	Tree height

1. Introduction

The quality of European forest ecosystems is in decline, threatening the well-being and economy of societies (EEA, 2024). Land development, agricultural activities and conventional forestry, also known as rotational forest management (RFM), are listed as the key factors responsible for this decline (Ibid.). During the past five centuries, expanding industrial demands and changes in land use have led to a continuous reduction in old-growth forest areas worldwide (Gray et al., 2023). These forests are recognised for their substantial ecological value, primarily due to the high abundance of deadwood and habitat trees, which typically emerge during late successional stages (Martin et al., 2021). Gray et al. (2023) argue that the definition of an old-growth forest lies at the intersection of ecology, policy and values. Displaying an additional dimension of the societal scope on forests and their management.

Overview of forest management history
The concept of sustainable forestry emerged in 18th-century Germany (Andersson, 2015). It spread throughout Europe due to the scientifically based, continuous timber supply and revenue stream promised by this management (Hölzl, 2010). At the time, sustainable forestry meant harvestable timber in a steady supply for industries, all else disregarded (ibid). It is possible that the word sustainability embraces other things today. When commenting on the words of an astute Ecuadorian, Hölzl (2010) concludes in his final statement:

> We might deduct that sustainability has been a bargain from the beginning that was as scientific as it was charged with meaning, class bias and ecological lopsidedness. Acknowledging the historicity and the culture of the environment may be a good starting point for further negotiation (Hölzl 2010).

Clear-cut-based RFM invented in Germany remains the status quo in northern Europe and across the boreal forest ecosystem (Vestin et al., 2020). The principal argument used to promote RFM is its purported capacity to replicate the natural disturbance regime historically associated with stand-replacing fires (Berglund & Kuuluvainen, 2021; Kuuluvainen, 2009). The notion that stand-replacing fires were the dominant agent of natural forest dynamics in boreal forest ecosystems is being disputed. Recent studies suggest that the norm was a less severe and more complex disturbance regime, composed of low-intensity fires, wind, fungi and insect outbreaks, creating a structurally diverse uneven-aged forest mosaic (Berglund & Kuuluvainen, 2021; Kuuluvainen, 2009; Kuuluvainen & Aakala, 2011).

Continuous cover forestry (CCF) is based on ecological principles and offers improvements for sustaining ecosystem services while satisfying the needs of various stakeholders at the same time (Kruse et al., 2023; Pommerening, 2023; Turckheim 2006). It may be considered an accurate description of sustainable forestry practices; however, the present text deliberately avoids the term sustainability, as its interpretation is highly context dependent (Hölzl, 2010). The definition of CCF management exhibits variation across practitioners. Nevertheless, one consistent and defining feature is the abandonment of large-scale, clear-felling operations as a constant attribute (Pommerening et al., 2025). CCF can be viewed as an umbrella term for the plethora of management alternatives where large-scale clear-felling is excluded. Some of these management alternatives include close-to-nature forest management, single selection forestry, group selection forestry, Qualification-Dimension (QD), ecological forestry, irregular shelterwood, and coppice with standards.

The new EU forest strategy for 2030 advocates that Europe should move away from same-age, mono-species and clear-cut forest management and promotes CCF to create forests that are more resilient to devastating disturbances like extreme weather, fires, pests and pathogens, which are expected to become more frequent in the future (European Commission, 2021).

Kruse et al. (2023) stated that one reason CCF is not implemented to its full potential in Sweden is due to a lack of methodological know-how. Thus, proposing a need for a national benchmark for CCF training requirements. Other European countries have also encountered obstacles in promoting CCF. Obstacles like proper training of forest personnel, fear of losing control by people in charge, heterogeneity of harvested products to the industry and mechanical progress (Turckheim 2006).

CCF have been around since the latter half of the 19th century, with local variations and objectives (Pommerening & Murphy 2004). The popularity of CCF has waxed and waned with the past historic events and the following social attitude (Pommerening & Murphy, 2004; O`Hara, 2002). CCF became popular in Sweden during the 20th century as a reaction to the established RFM, when ideas of close-to-nature forest management flourished, clashing with the current status quo (Andersson, 2015).

RFM gained a foothold and became the widespread standard in European forest management (Hölzl. 2010). Mechanical advances have led to homogenization of forest stands and larger clear-cuts, trading unstable stands, increased silvicultural cost, site damages and loss of ecosystem services for a larger profit (Turckheim, 2006).

To stop the cyclic popularity of CCF and make its use widespread and consistent through the test of time. Future advances need to be based on scientific findings within a holistic frame of reference. CCF is currently gaining renewed

attention in response to increasing demands for a more feasible forest management, in light of the current global challenges (Ekholm et al., 2023; Kruse et al., 2023; Pommerening & Murphy 2004; Pommerening 2024)

Marteloscopes

In the middle of the 20th century, scientists in Europe started to question and investigate the selection behaviour of forest workers (Pommerening 2024). Whether the forestry workers were consistent with other workers in their management decisions. At the end of the 20th century, Max Bruciamacchie and colleagues realised the potential to base training and education on thinning inventories (ibid). Resulting in field courses, marking trees to collect data that would be analysed using specialised spreadsheet software. To promote this new didactic tool, the group of scientists named this research plot the marteloscope.

Since its origin, marteloscopes have become an increasingly popular application for training, education and research (Kadavý et al., 2024; Kruse et al., 2023; Poore, 2011; Soucy et al., 2016). Training and education can be applied to everyone, from novices to seasoned forestry professionals in marteloscopes. Studies have revealed that participants from those two backgrounds perform markedly differently (Bravo-Oviedo et al. 2020; Vítková et al. 2016). Experienced forest workers often display a bias based on their preceding theories. Instead of adapting to the ecosystem-based management instructions. At the same time, test persons without previous experience are more receptive to the instructions. Resulting in the recommendation that experienced forestry workers would need persuasion and training in CCF management to a higher degree, compared to the less experienced participators (Vítková et al. 2016).

The word marteloscope comes from the composition of the two words "martelage" and "skopein". Martelage is French, meaning "tree selection", and skopein comes from the Greek language, meaning "to look" (EFI, 2025).

A marteloscope is, in its essence, a forest research plot. But instead of mainly measuring growth rates, the marteloscopes' focus is primarily on forestry training and research in human tree selection behaviour (Pommerening & Grabarnik, 2019). Human tree selection behaviour is a novel research direction where ecology, natural science and social science intersect (Pommerening, 2015). It refers to the relationship between the two main factors in the marteloscope, humans and trees. Human tree selection behaviour embraces everything from selecting trees in a thinning operation to the decision of which tree would be suitable to picnic under (Pommerening & Grabarnik, 2019). Data collected in marteloscope exercises can reveal how human predisposition and preferences interplay with the attributes of a tree.

A marteloscope aiming to research human tree selection behaviour should ideally have an area of 100 × 100 m contain 150 – 500 trees with a mixture of

species and size distribution (Pommerening & Grabarnik, 2019). These plot properties serve the purpose of being small enough for long-term research and big enough for test persons to complete the exercise within a reasonable time. The area should not be overly crowded, allowing multiple participants to conduct the exercise simultaneously without the risk of influencing one another (ibid). An advantageous characteristic of a marteloscope is the presence of thinning urgency, which emerges when thinning interventions are postponed. This condition is considered preferable, as it broadens the range of selection possibilities and minimises the likelihood that participants will encounter constraints in their decision-making during the exercise (ibid).

A marking sheet serves as a meta-tool within the marteloscope exercise, facilitating systematic data collection and constructing a crucial role of the analysis in human tree selection behaviour. Its design should be tailored to the purpose of the experiment and have no considerable influence on the test person's marking behaviour. A marking sheet can be as simple as a sheet of paper or a tablet using a software application with the correct instructions. The instructions should be tailored to the purpose of the experiment in a way that is easy to follow while being precise in terms of the objective. It is preferred that participants work individually in the marteloscope when researching human tree selection behaviour (ibid). This approach minimises the risk of participants influencing each other's selection behaviour during the exercise.

All trees included in the marteloscope should fulfil a lower diameter at breast height (DBH) threshold and be marked with a unique identity number, visible from opposite directions. DBH, height and volume are surveyed. Coordinates for each tree are registered in an ideal situation. Apart from these preferred traits, all thinkable data can be collected and registered within a marteloscope.

Human tree selection behaviour

Human tree-selection behaviour represents a complex field of research, shaped by the diversity of both forest ecosystems and societal contexts. Existing studies have generated a broad spectrum of findings, revealing numerous interacting factors and processes that require further disentanglement to achieve a more comprehensive understanding (Pommerening et al. 2018).

Agreement between test persons in marteloscope exercises are often low compared to other scientific fields (Pommerening et al. 2015; Pommerening et al. 2018; Vítková et al. 2016). A study by Pommerening et al. (2018) analysed data from 36 marteloscopes in Britain and found that even with good education, instructions and training, high levels of agreement among participants were unattainable. In 4 out of 36 cases, poor agreement occurred; slight (14) and fair (17) agreement were the most common results. However, a certain lack of agreement proved to be a good starting point for more detailed analysis. It was

found that rating and marking bar charts (see Section 2.2.3) offered valuable information on active and passive selection processes. Active rating behaviour refers to the participants' rating behaviour. Passive rating behaviour focuses on the attributes of the tree indicated by the number of participants selecting a given tree. These two processes interact in complicated ways, making it difficult to characterise their collective fallout by means of simple statistics (Pommerening et al. 2018). Furthermore, it was found that the mean conformity number (see Section 2.2.1) can serve as a surrogate for the agreement measure, Fleiss' kappa (see Section 2.2.2).

By reviewing logistic regression models based on binary selection data, it is possible to visualise selection behaviour traits (Pommerening & Grabarnik 2019). Selection traits, like whether a participant has been influenced by e.g. DBH or species. i.e. Expressed by increasing selection probability with increasing stem diameter. Or as the tree selection probability decreases with decreasing stem diameter, showing tendencies reflecting a thinning from below (ibid).

In a thinning experiment in Austria, Ebenhard & Haasenauer (2020) investigated selection methods and how they affect the future of Norway spruce stands. The analysis aimed to investigate whether selection behaviour and its outcome differ between forest managers and harvester drivers. This was done by comparing four different selection methods (foresters, harvesters, random selection and control) and how the future stand developed through a forest growth model. The study revealed that 70% of trees selected by the forest managers were identical to the selection of the harvester drivers. It was concluded that no difference between the selection methods of the two groups could be found after a 50-year simulation by the growth model analysis.

Participants in marteloscope exercises are, first and foremost, individuals shaped by their personal history, education, prior experiences, gender, age and other attributes. These factors collectively contribute to the complexity of human tree selection behaviour as a research field. Ultimately, such characteristics manifest as differing preferences in tree selection Joa et al. (2020) conducted a qualitative study on the decision-making in tree selection from four marteloscope exercises in Germany (Jägerhäuschen and Rosskopf, two exercises in each). The study aimed to explore how participants behave in their decision-making and reasoning, based on their background and profession. Participating groups consisted of conservationists, foresters and students from each branch of profession. Data was collected by participant observations and recorded group discussions. Their findings strengthen the notion that tree-selection behaviour is based on experience, professional routine and intuition. Not merely the result of a rational, cognitive weighing process.

Bravo-Oviedo et al. (2020) examined if sociodemographic variables (gender and age) and learned methods from formal studies (foresters and non-foresters)

influence marking decisions in a marteloscope experiment. The participants were tasked to conduct two separate thinning approaches (systemic and conventional) in the Northern Apennines in Italy. The study found that the ability to adhere to new methods is highly conditioned by previously obtained knowledge. Confirming that experienced foresters apply the conventional method they are comfortable with (Vítková et al., 2016; Joa et al., 2020). Agreement was low within and between the groups, with no difference depending on the silvicultural approach. However, gender revealed to be more influential on tree selection compared to age. The authors suggest that the low agreement in the study indicate that tree selection is highly personal and individual pathways can amount to the same silvicultural goal.

To date, agreement among raters in marteloscope exercises has consistently remained low (Bravo-Oviedo et al., 2020; Pommerening et al. 2015; Pommerening et al. 2018; Vítková et al. 2016). Whether this represents a substantive problem remains unclear, as different tree selection choices may ultimately lead to comparable outcomes (Bravo-Oviedo et al., 2020). Nevertheless, developing approaches to enhance agreement, strengthen decision-making and improve the understanding of human tree-selection behaviour through marteloscope exercises constitutes an important step in the further development of CCF and in increasing its accessibility to both the forestry sector and society. Pommerening et al. (2020) may have taken an important initial step in this direction through an interdisciplinary study that integrated political science with environmental forest science. The authors analysed data from 50 marteloscope experiments conducted across Great Britain by applying three proportional multi-winner voting rules commonly used in political science. In this framework, participants in the marteloscope exercises typically referred to as raters were conceptualized as voters, whereas the trees constituted the candidates. The findings indicate that proportional voting rules can yield improved representation compared with standard approval voting, particularly in situations where experts disagree in their selection of trees. Moreover, incorporating proportional rules into forestry decision-making may help reduce risk in cases where majority-based decisions prove unsuitable. This interdisciplinary approach demonstrates the potential for enhanced representativeness in tree-selection outcomes and highlights crowdsourcing as a promising avenue for advancing CCF management.

Another marteloscope study using theories from the realm of political science was published by John et al. (2024). The authors set out to investigate if marteloscope exercises could facilitate a space for information deliberation between foresters and climate activists. Two groups often found on opposing sides in the polarised forest debate. The study consisted of 30 participants (climate activists and non-activist students), the exercises was led by three local foresters over five exercises that took place in two marteloscopes located close to urban

areas in Germany. The findings support the potential of marteloscope exercises to foster information deliberation between the two groups. This meeting however, did not reproduce the traditional conflicts present between forestry and conservation actors. The authors pointed out, that knowledge hierarchy potentially presents a barrier for free communication in these settings. And suggests that if studied further it would be interesting to select participants from groups further out in the societal periphery.

A limitation of marteloscope exercises and related research is that they are time-consuming, logistically demanding and geographically dispersed, which complicates the establishment of global standards and the progress of urgently needed research. Balestra et al. (2025) set out to create a digital replica of a marteloscope, making a technical education tool for smart forest management. They managed to create a reliable digital 3D replica of a one-layered beech forest that is part of the official European Forest Institute (EFI) Integrate+ marteloscope network, located in the Apennines Mountain range in Central Italy. This was done by using a mobile laser scanner to extract fundamental forest parameters (DBH and total height) and software. The authors stated that virtual reality marteloscope twins like this one can become a permanent forestry tool, able to be updated and enhanced over time. With the potential of facilitating endless possibilities in marteloscope training for students and forestry workers, as well as data collection and enhancements in CCF management.

Habitat tree selection

The amount of deadwood and habitat trees are commonly used parameters to assess biodiversity in managed forests (Mueller & Butler, 2010; Asbeck et al., 2021). Habitat trees are trees with one or more distinguishable morphological features referred to as tree-related microhabitats (TreMs). Larrieu et al. (2018) defines TreMs as "a distinct, well delineated structure occurring on living or standing dead trees, that constitutes a particular and essential substrates or life site for species or species communities during at least a part of their life cycle to develop, feed, shelter or breed". There are at least 47 different TreMs described that have different morphological features (Butler et al., 2021). These features facilitate sheltering, breeding, hibernating and feeding for a plethora of forest associated species (ibid). The formation of TreMs is initiated by a diverse array of biotic and abiotic factors, many of which remain poorly documented (Larrieu et al., 2025).

Old-growth characteristics like high deadwood and TreM occurrence are often rare or even absent in managed forests, even those under CCF management (Kraus et al., 2016). The low TreMs occurrence in managed forests is attributed to the fact that forest managers traditionally viewed these occurrences as damages or defects and should be removed (Larrieu et al., 2018). Deadwood and habitat-

bearing trees constitute great importance for biodiversity, with numerous species directly or indirectly depending on these elements for survival (Kozák et al., 2023; Kraus et al., 2016). Therefore, trees possessing TreMs are considered important bearers of biodiversity and should be highly considered to sustain biodiversity, even in managed forests (Kraus et al., 2016). Protecting these habitat trees has been proven to be a cost-effective tool in biodiversity conservation (Kozák et al., 2023). By taking habitat trees and deadwood into consideration in forest management operations, it is possible to emulate the biodiversity state of natural or old-growth forest (Martin et al., 2021; Przepióra & Ciach, 2023).

The number of TreMs serves as suitable biodiversity indicator within forest ecosystems (Winter & Möller, 2008; Basile et al., 2020). Insufficient ecological consideration in favour of maximizing profit is one of the principal criticisms directed at RFM (Sing et al., 2018). As in all forms of forest management, trade-offs between economic and ecological objectives often occur (Felton et al., 2016). Within the framework of CCF, this trade-off situation becomes most evident during the decision-making process of determining whether a given tree should be retained or removed. In a study investigating trade-offs among silviculture trainers, district foresters and forestry students, Cosyns et al. (2018) found that participants consistently selected habitat trees of low economic value, although their selection behaviour varied according to their level of expertise. Silviculture trainers made the most consistent decisions, outperforming both district foresters and forestry students. The study concluded that habitat-tree selection is not self-evident and influenced by professional background and training.

Another study by Cosyns et al. (2019) examined the same trade-off between foresters and conservationists. They found that foresters retained a notable number of small hornbeams while the conservationists almost exclusively retained large oaks, at a high opportunity cost. This disagreement was associated with the apprehension of the opportunity cost related to tree retention. As well as their disagreement on how to value current TreMs. Like the situation in Cosyns et al. (2018), the groups did not agree and had incompatible interpretations of what defines a habitat-tree. The conclusion states that ecological elements in a forest require a value. So those values can be compared to the opportunity cost of a harvested tree when making forest interventions.

Human tree selection behaviour is an intricate, novel area of expertise. In need of global and national "benchmarks", training opportunities, exercises and further research (Cosyns et al. 2018; Cosyns et al. 2019; Kruse et al. Joa et al. 2020; Poor 2011; Susse et al., 2011; Soucy et al., 2016; Vítková et al. 2016).

1.1   Objectives of this master thesis

The primary objective of this master thesis is to investigate human tree-selection behaviour and CCF by analysing the results from a previous marteloscope exercise and by reviewing current literature on the subject. With the growing interest of CCF and ecosystem-based management practices, this study seeks to examine how participants approach the decision-making process involved in forest management within a marteloscope setting.

This will be achieved by comparing the results derived from this analysis to current literature. With the aspiration to contribute with a step in bridging the gap between theory and practice in forestry, providing actionable insights that benefit both the ecological health of forests and the economic sustainability of forest management systems.

2. Materials & Methods

2.1 Description of the experiment: Marteloscope 'Pokojná hora'

This thesis examines and conducts further analysis on a research study from the Czech Republic published by Kadavý et al. (2024). Were they set out to strike a balance between biodiversity conservation and economic goals in selection forestry through a marteloscope exercise. This analysis is based on data provided by Michal Kneifl, senior researcher at Mendel University in Brno, one of the authors from Kadavý et al. (2024). The marteloscope at a location referred to in Czech as 'Pokojná hora' is a part of the European Network of Marteloscopes, facilitated by the European Forest Institute. It covers an area of 1 ha (100 × 100 m) and is located northeast of the city of Brno (49°19'59.059"N, 16°41'38.841"E). Forest surrounding the marteloscope covers approximately 150 ha and has been managed according to CCF since 1983. Average elevation is 490 m a.s.l., average annual precipitation is approximately 600 mm and the annual temperature is 6.6 °C. Soils at the location are classified as luvisols and cambisols. Local vegetation is described as an herb-rich beech forest.

The marteloscope included 357 trees (> 8 cm stem diameter at 1.3 meters above ground level, referred to as DBH) with *Fagus sylvatica* L. (68.9%) as the dominant species. Other present tree species are: *Abies alba* Mill. (14.9%), *Larix decidua* Mill. (10.8%), *Picea abies* (L.) H. Karst. (3.9%) and *Pinus sylvestris* L. (1.6%). All 357 trees were surveyed, including coordinates, species, DBH, total height and tree health. Tree-related microhabitats (TreMs) were assessed according to the tree microhabitat catalogue by Kraus et al. (2016). The trees with TreMs identified, also known as habitat trees, were assigned ecological points calculated as an index based on the number, rarity and the time required to form the specific habitats for their development (Kraus et al. 2018). The assessment of wood quality for all trees was conducted by a local forest professional. Economic value was then calculated by multiplying the timber volume of each species and quality class by the corresponding local wood prices.
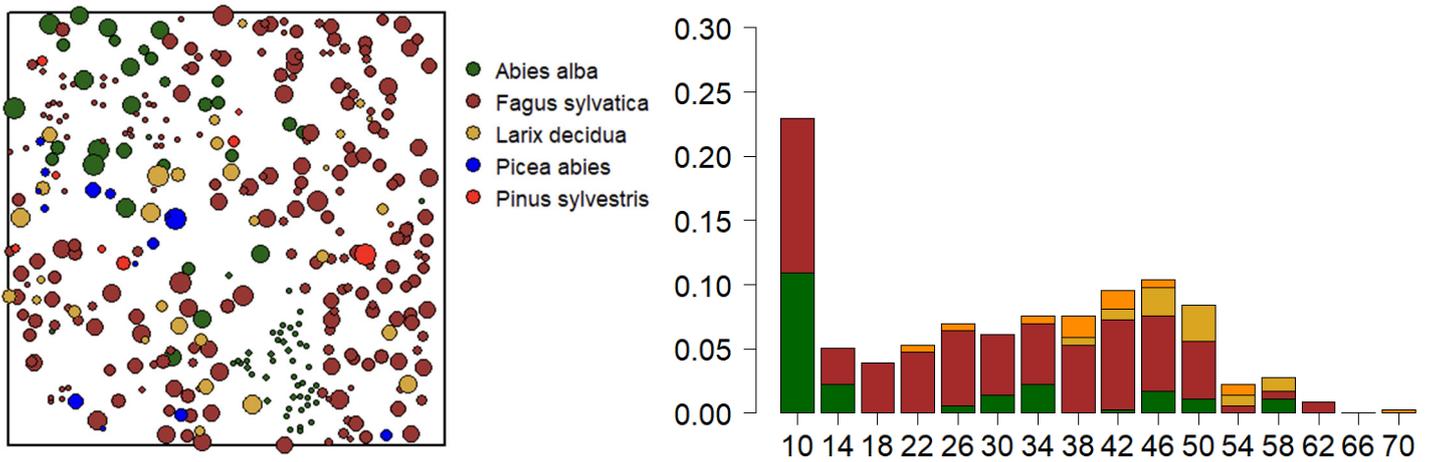
Figure 1. Tree dispersal map, dot-size according to DBH (left) and stacked DBH chart of all trees included in marteloscope 'Pokojná hora', DBH on x-axis and proportion on y-axis(right). Colour legend according to species applies to both figures.

Fig. 1 gives an initial indication of the species mixture, tree dispersal, DBH distribution and structure of the population. Forestry engineering students were divided into 11 groups with 3-6 members in each. These groups got assigned one of two scenarios to implement in the experiment. Virtual tree marking was performed using the I+ Trainer software installed on mobile computer devices. The exercise took place on November 16 and December 15, 2023. Students had to abide by certain criteria, such as tree health, trunk shape and tree maturity when marking the trees. Scenario 1 aimed to virtually mark a total volume equivalent to approximately 100 m³, consisting of both habitat trees and harvested trees. Scenario 2 aimed to mark the same volume, however, consisting only of trees marked to be harvested. This paper only analysed the results from scenario 1. Were 6 groups executed individual variants of the scenario, with the task of selecting a set number of habitat trees seen in Table 1.

Table 1. Explanation of the scenario 1 analysed in this thesis and the number of habitat trees to select assigned to each group according to Kadavý et al. (2024).

Scenario 1	Group (variant)	Habitat-trees selected
Total volume of all marked trees (both habitat trees and harvested) ≈ 100 m³	1	5
	2	10
	3	15
	4	20
	5	25
	6	30

2.1.1 Description of the experiment derived from data

The data received from the marteloscope experiment came in the form of a Microsoft Excel file and the analysis was carried out in R (2024.12.1). R scripts containing codes for each of the analysis was provided by the supervisor Arne Pommerening and altered by me to adjust for the result of the final analysis. In addition to what has previously been mentioned, the data included basal area, volume and the reason for the suggested action that led to a tree being marked by the groups. All variables were organised in columns, giving each tree an individual row.
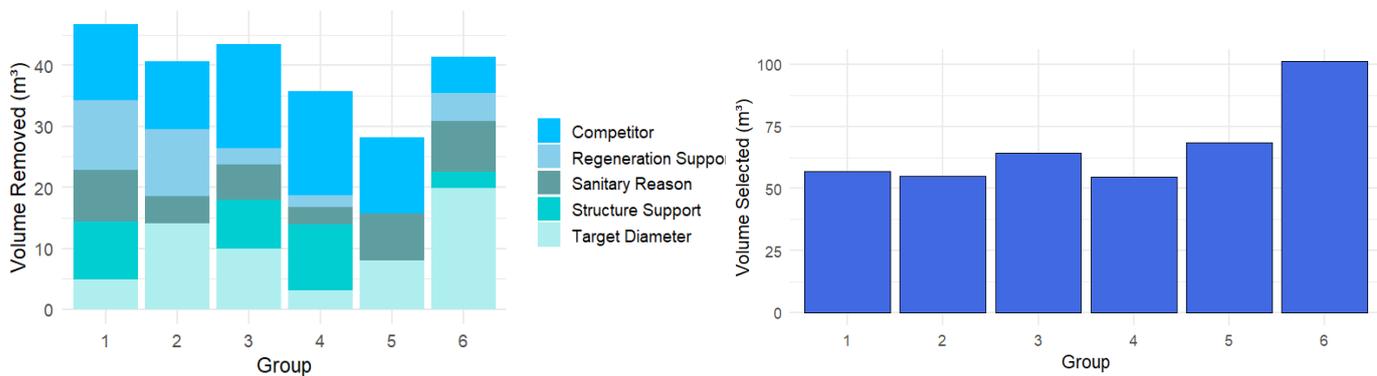
Figure 2. Barchart chowing total volume of marked trees to be removed by each group; colour coded according to stated reason (left). Bar chart showing the total volume of trees marked to be removed and habitat trees by each group (right).

TreMs had been surveyed in a separate event according to Kraus et al. (2018). Trees with one or more TreMs are referred to as habitat trees chosen by the "trainer" hereafter. All trees assessed as a habitat-tree received a **1** in the MS Excel worksheet and a **0** if not. The trainer marked a total of 98 trees. All trees were labelled with one of three explanations regarding the test person's choice, i.e. "no action", "retained" or "removed". All proposed actions received a short explanation corresponding to the action in the data as seen in Fig. 2. How each of the groups preformed in reaching the volume goal can be seen in Fig. 2 as well.

To analyse and compare the tree selection behaviour of the groups, information in the explanatory column was converted to binary data, i.e. if the desired action description = **1**, if not = **0** (e.g. "retained", yes = **1**, if not = **0**). My analysis investigated human tree selection behaviour by analysing the two different selection categories in the dataset, retained and removed. Since only group results were available, these were treated like individual persons' results in other studies.
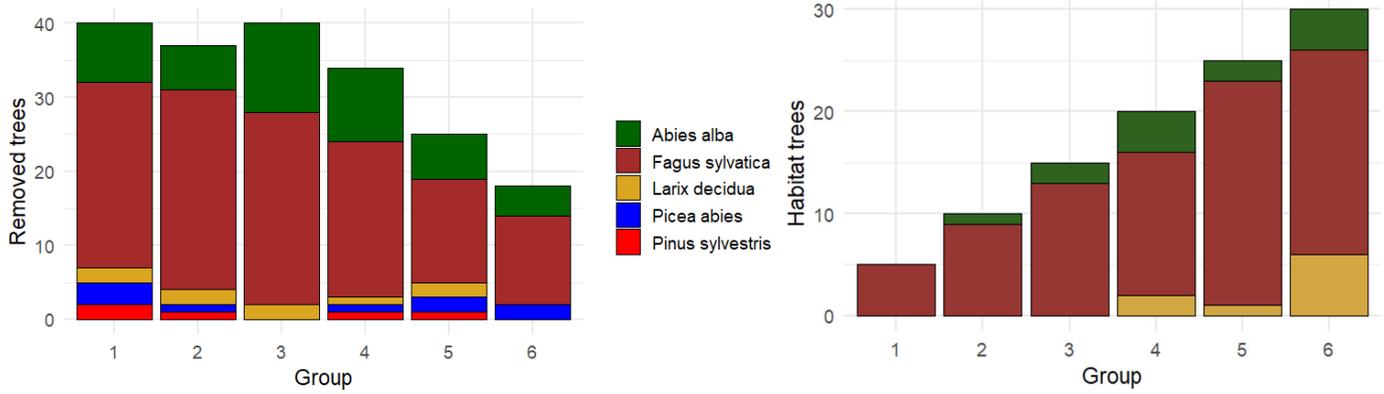
Figure 3. Bar chart showing the number of trees marked to be removed by each group, colour according to species (left). Bar chart showing the number of trees marked to be habitat trees by each group, colour according to species (right).

To provide an overview of the student groups' tree selection in both categories, Fig. 3 presents bar plots illustrating the number of trees selected and their species composition.

2.2   Analysis

2.2.1   Conformity numbers

Surowiecki (2004) introduced the wisdom of the crowd theory. The theory expects that a large crowd of independent individuals will collectively be closer to a true answer compared to an individual expert. Building on the premise that frequently selected trees may reflect a 'wisdom-of-the-crowd' effect, we quantify the extent to which individual participants conform to the overall selection tendencies of the group. Although this concept is related to inter-rater agreement, it captures a distinct behavioural dimension, namely the degree to which individual selections align with collective preferences. Following the approach of Stoyan et al. (2018b), conformity number c_i can be defined as:

$$c_i = \frac{1}{s_i} \sum_{j=1}^{n} 1 x_i (j) \cdot n_j \; for \; i = 1, 2, \dots, r. \tag{1}$$

Where c_i is the absolute conformity number, r is the number of test persons in the experiment, S_j is the number of trees selected by person i and n_j denote the number of times tree j is selected by all participants in the exercise. "$1\, x_i\,(j)$" is a function, equal to 1 if tree j is selected by test person i, 0 if not. c_i thus represents the mean number test persons selecting the same tree j as test person i. This gives an idea of how strong the selection behaviour of one test person complies with the tendency of the whole group.

2.2.2   Fleiss' kappa & Concordance index

Fleiss' kappa, $\kappa,$ is a numerical statistical characteristic for measuring the degree of agreement between participants when the number of test persons > 2 (Fleiss 1971; Fleiss et al. 2003). Fleiss' kappa is based on pairwise comparisons, with roots in one-way analysis of variance (Pommerening & Grabarnik 2019). κ usually takes values between 0 and 1, seen in Table 2. Despite measuring the degree of agreement, it does not provide information about individual behaviour of single raters (Stoyan et al 2018a; Stoyan et al 2018b). Fleiss' kappa can be expressed in various forms to highlight different aspects of nature (Pommerening & Grabarnik 2019). Eq. 2 is the expression used in this analysis.

$$\kappa = \frac{p_0 - p_e}{1 - p_e}, \tag{2}$$

p_0 is the observed proportion of agreement among participants and p_e is the expected proportion of ratings in agreement. How p_e is calculated can be found in Pommerening & Grabarnik (2019).

Table 2. Proposed interpretation of the Fleiss' kappa characteristic κ values by Stoyan et al. (2018b)

κ	Interpretation
< 0.10	Poor agreement
0.10-0.33	Slight agreement
0.33-0.50	Fair agreement
0.50-0.67	Moderate agreement
0.67-0.90	Substantial agreement
≥0.90	Almost perfect agreement

Zucchini and Gadow (1995) introduced a measure of agreement in human tree selection by calculating the absolute difference between the number of people marking and not marking each tree. Summarising these differences across all trees in a marteloscope gives the concordance measure C. Using the binomial probability function and the average number of trees marked, the expected concordance **EC** can be determined. Comparing C with **EC** yields the concordance index *I,* which is calculated as:

$$I = \frac{C - \mathbf{EC}}{C_{max} - \mathbf{EC}} \tag{3}$$

A positive value of *I* indicates agreement and the level of agreement increases with the value of *I*. If *I* = 0, that would suggest a lack of agreement among the test persons, i.e. all test persons selected trees randomly or unrelated to each other (Zucchini & Gadow 1995). Zucchini and Gadow (1995) additionally introduced the term *disagreement* in this context, if *I* were to take a negative value.

2.2.3   Rating & Marking bar charts

Rating and marking bar charts are a descriptive statistic which can provide useful information about the rating behaviour of the participants in a marteloscope exercise (Pommerening et al., 2018). An explicative way of examining this behaviour is formulating the rating as active and passive. The active behaviour refers to the participants or raters and how trees are selected, as some might mark many and others fewer trees (ibid). Passive rating behaviour refers to the attraction evoked by a tree, e.g. the number of marks given to a certain tree (ibid). In some cases, the decision of whether to mark a tree may be self-evident to all participants.

Active rating behaviour relates to the rating bar chart, which depicts the test person's action by showing how many trees the test person selected. The participants are then ranked according to the proportion of trees selected (P_n). The test persons are ranked on the abscissa and the proportion of trees on the ordinate, where each bar represents one participant (Pommerening & Grabarnik 2019).

Passive rating behaviour relates to the marking bar chart, by showing how many times a tree has been selected. An individual tree holds the possibility of being selected (i.e. marked) by all, some or none of the participants. Consequently, a single tree may receive a number of marks ranging from 0 to the total number of participants r involved in the exercise. Thus, there will be $r + 1$ bars on the abscissa, since some trees will not be selected by a single participant, denoted as P_0. On the ordinate, there is the proportion of trees marked "1". For example, in a hypothetical experiment with four participants, 1% of the trees received marks from all four participants, 5 % received three marks, 15% received two marks, 23% received one mark and 52% received zero marks. The bar illustrating zero marks P_0, can be seen as a kind of "pseudo" agreement (Pommerening et al., 2018). An implicit agreement exists that trees without markings can be regarded as being of no or low interest within the framework of the exercise. Such unselected trees may have been excluded due to reasons that were considered obvious by all participants. P_m illustrates the highest 20% class of the marking bar chart (ibid). In this example it would refer to the 1% of the trees which received a mark from all four participants. This characteristic indicates a strong level of agreement and can provide insights that Fleiss' kappa fails to capture under these circumstances (Pommerening et al., 2018; Pommerening & Grabarnik 2019).

2.2.4   Type of selection

As a general measure concerning the type of tree selection in commercial timber plantations, Kassier (1993) suggested the ratio of P_G and P_N:

$$B = \frac{\text{Proportion of the number of trees selected}}{\text{Proportion of basal area of selected trees}} = \frac{P_N}{P_G} \tag{4}$$

To investigate tree selection behaviour in a marteloscope exercise, the ratio in Eq.4 is altered as B_i, to account for the results of individual test persons (Kruse et al 2023):

$$B_i = \frac{P_i^N}{P_i^G} \tag{5}$$

In Eq. 5 B_i-ratio quantifies the tree selection type by comparing the number of trees selected by test person i with its cumulative size. If $B_i < 1$, the proportion of selected trees was lower than their corresponding share of the cumulative basal area and can be viewed as a preference for selecting large trees. If $B_i > 1$, the proportion of selected trees was higher than their corresponding share of the cumulative basal area, i.e. viewed as a preference for selecting smaller trees. If $B_i \approx 1$, this result indicates random tree selection or that tree size does not influence selection of the test person (Pommerening & Grabarnik 2019).

2.2.5   Slenderness (*h/d*-ratio)

Slenderness (Eq. 6), also described as *h/d* ratio is an allometric relationship derived from tree height and DBH that serves as a rough indicator of individual tree morphology and tree-stability (Pommerening & Grabarnik 2019).

$$h/d = \frac{\text{Tree heigth}}{DBH} \qquad (6)$$

Table 3 Interpretation of how the h/d ratio relates to tree-stability (Burschel and Huss 1997).

h/d ratio	Interpretation
>100	Very unstable
80 - 100	Unstable
< 80	Stable
<45	Open grown

The values in Table 3 particularly apply to species of trees with shallow root systems. The ratio can also be useful in understanding previous and future management operations (Abetz and Klädtke 2002; Pretzsch 1996). The *h/d* ratio thus becomes an important indicator to consider in human tree selection behaviour.

2.2.6   Tree selection probabilities

Tree selection probability is a key characteristic for understanding human tree-selection behaviour (Pommerening & Grabarnik, 2019). Logistic regression allows this probability to be related to multiple predictors, thereby facilitating an assessment of how these factors influence the likelihood of a tree being selected for a specific purpose.

$$P_i^{(S)} = \frac{e^{\beta_0 + \beta_1 \cdot d}}{1 + e^{\beta_0 + \beta_1 \cdot d}}, \tag{7}$$

In Eq. 7 $P_i^{(S)}$ is the probability that a tree is selected by test person i, β_0 and β_1 are model parameters and d the predictor variable. The predictor variable d may denote DBH; however, it can equally be substituted with any other variable of interest. Notably high or low values for the slope parameter β_1 indicate a strong influence on selection probability for that predictor variable. β_1 values close to, or 0 indicates very low or no influence on selection probability by this predictor variable.

2.2.7   Location diversity index (Clark & Evans, 1954)

Clark and Evans (1954) proposed aggregation index R' to characterise the distribution of living organisms. Applying this spatial measure of structure has proven useful in understanding forest growth (Bravo & Guerra 2002; Pretzsch 1995). This location diversity index compares the observed mean distance $\bar{r}$ between any tree in a pattern of trees in a forest and its nearest neighbour with the mean distance in a completely random spatial pattern (CSR), $\mathbf{E}r$. The given pattern of trees in a forest is thus the deciding factor of the mean observed distances (Pommerening & Grabarnik 2019).

$$R' = \frac{\bar{r}}{\mathbf{E}r} \text{ with } \mathbf{E}r = \frac{1}{2 \cdot \sqrt{\frac{N}{A}}} \tag{8}$$

In Eq. 8, N and A are the number of observed or selected trees in a marteloscope and its area. $R' > 1$ indicates a tendency towards a regular tree distribution, while $R' < 1$ indicates a tendency towards clustering. $R' \approx 1$ when mean observed distance and complete spatial randomness are roughly the same (ibid).

2.2.8   Species mingling

In CCF and forest conservation management, maintaining or promoting a specific mixture of tree species is often an important objective. The mingling index M_i is the mean heterospecific fraction of trees among the k nearest neighbours of the given tree i (Aguirre et al., 2003). This index provides information about the heterogeneity of the forest and can be used to assess participant selection behaviour in a marteloscope exercise. e.g. if a test person shows a preference to select a certain species for removal or as a habitat-tree. In this analysis, all trees within the marteloscope act as the typical point i once.

$$M_i = \frac{1}{k} \sum_{j=1}^{k} \mathbf{1}\left(m_i \neq m_j\right) \qquad (9)$$

In Eq. 9, m_i denotes the tree i and m_j denotes the species of the nearest neighbour j, with $j = 1\ldots, k$. The binary indicator function $\mathbf{1}(m_i \neq m_j)$ results in 1 if the tree and the nearest neighbour are of different species and 0 if they are the same (Pommerening & Grabarnik 2019). When applied in practice, this measure yields the empirical mingling distribution, derived from observed data. Low mingling "0", meaning that all four ($k = 4$) nearest neighbours are conspecific and high mingling "1", meaning that all four ($k = 4$) nearest neighbours are heterospecific (Becs et al., 2024).

3. Results

3.1 Conformity numbers

Conformity describes how closely an individual's tree-selection choices align with the overall selection tendencies of the group, rather than whether the same trees are selected by everyone. Unlike agreement measures, conformity captures alignment with collective preferences and reflects the idea of wisdom-of-the-crowd.

To evaluate conformity between participants and selection categories, conformity numbers were calculated for each group and for each category. Fig. 4 displays the results of all groups in the two selection categories: habitat-tree selection (4A) and trees selected for removal (Fig. 4B).

Conformity numbers for habitat-tree selection range between 1.1 (group 6) and 2.23 (group 3), with a mean conformity value of 1.8.
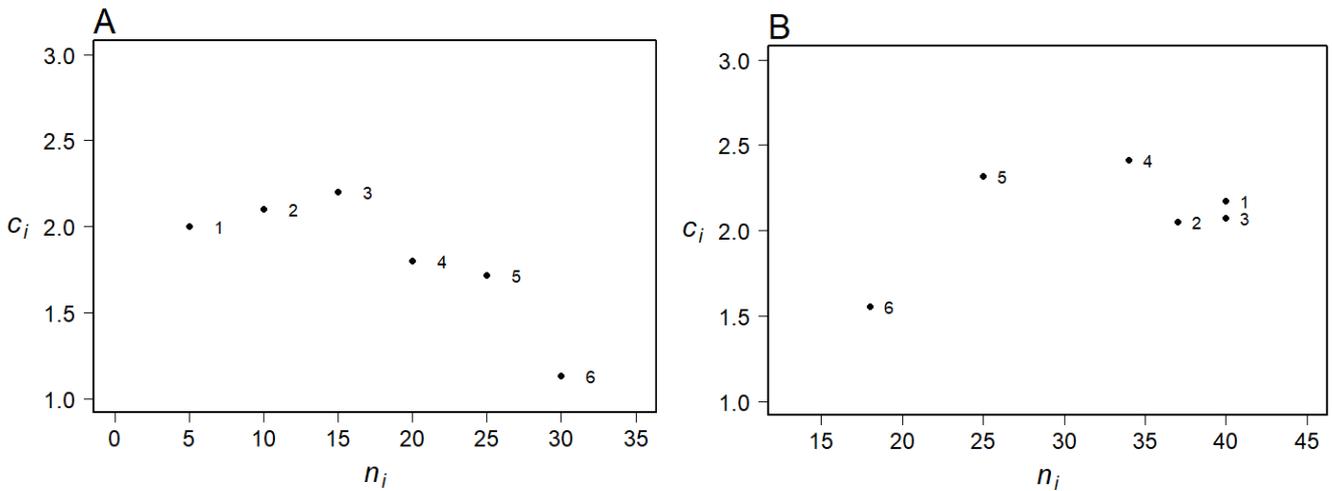
Figure 4. Scatterplot of the number of trees selected by each group n_i and conformity number c_i. Group number located right of corresponding point. Habitat-tree selection (A) and trees marked to be removed (B).

The groups were tasked with selecting different numbers of habitat trees, as clearly seen in how the groups are placed on the abscissa in Fig. 4A, the number of selected trees is suspected to influence the conformity scores as well. Conformity numbers for trees marked to be removed range between 1.56 (group 6) and 2.41 (group 4), with a mean value of 2.1. In this scenario, the number of trees selected is more uniform (Fig. 4B). Groups 1, 3, 2 and 4 are showing proof of a more active rating behaviour compared to groups 5 and 6.

Table 4. Conformity number for all participants and selection scenarios: Habitat-tree selection trainer included (TreM(T)), Habitat-tree selection (TreM) & trees selected for removal (Rem).

Group	c_i TreM(T)	c_i TreM	c_i Rem
1	2.4	2	2.18
2	2.3	2.1	2.05
3	2.53	2.23	2.08
4	2.2	1.75	2.41
5	2	1.7	2.32
6	2.03	1.1	1.56

Table 4 was produced to illustrate the conformity results for all participants and selection categories. The trainer was included when calculating the conformity numbers in the first column. This was done to display how conformity numbers are influenced by the marking of the trainer, as all the habitat trees should already have been marked at least once. This increased the conformity numbers for all groups as expected and the mean conformity value increased from 1.8 to 2.24.

3.2 Fleiss' kappa & concordance index

Fleiss' kappa was used to quantify inter-rater agreement, measuring the extent to which participants selected the same trees beyond what would be expected by chance. In contrast, the concordance index captures the degree to which participants show similar selection tendencies without requiring exact agreement on individual trees. Together, these measures allow agreement to be interpreted both in terms of strict consistency and broader alignment in selection behaviour. The Concordance Index I quantifies the pairwise agreement between the expected concordance and the observed. It reflects the degree of consensus with the standard.

The results in Table 5 reveal poor agreement in the first two selection categories and slight agreement in the last category according to the kappa values in Table 2. The concordance index results are close to zero in all selection categories. The result indicates that there is a lack of agreement between the groups in all selection categories.

Table 5. Fleiss' kappa values & concordance index for tree selection scenarios: Habitat-tree selection trainer included, habitat-tree selection & trees selected for removal.

	Trainer included	Trainer excluded	Trees removed
κ	0.067	0.093	0.150
I	0.017	0.019	0.079

Including the trainer in Table 5 provides an expert-based ecological reference, allowing conformity to be interpreted as alignment with experienced, ecologically informed tree-selection behaviour. Excluding the trainer generally increases conformity values, indicating that student groups are more similar to each other than to the trainer, and highlighting differences between peer-level decision-making and expert practice.

3.3   Rating & Marking bar charts

Rating bar charts

Rating bar charts are used to derive descriptive statistics, depicting the participant activity and ranking them accordingly. The charts in Fig.5 show the proportions of trees selected by a participant divided by the total number of trees (n_i/n). On the abscissa, participants are ranked according to the number of trees selected and on the ordinate, the proportion of trees selected P_n is illustrated.
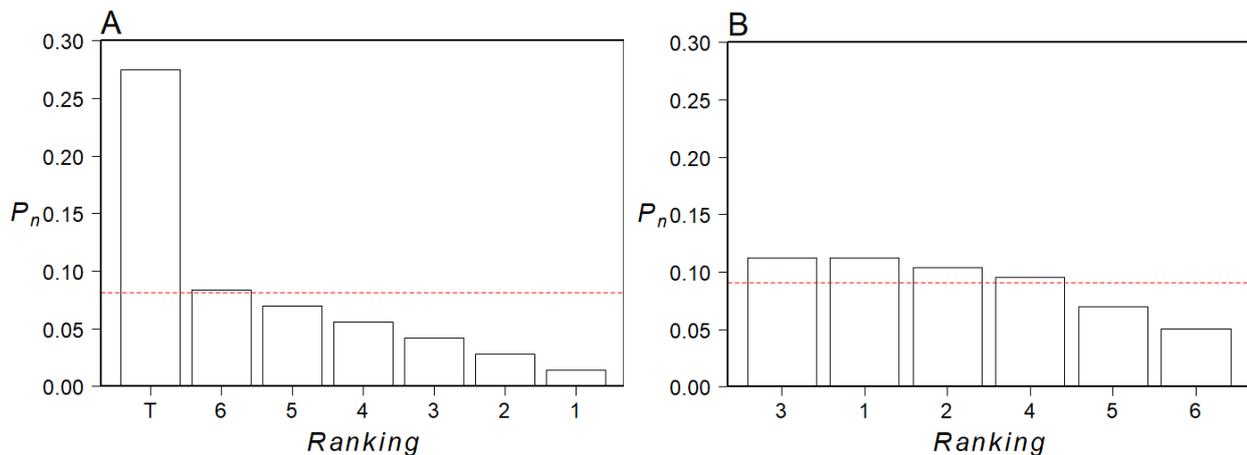
Figure 5. Rating bar charts, Proportion of trees (P_n) and groups ranked for habitat-tree selection (A) and trees selected to be removed (B). The participants are ranked according to who selected the largest proportion of trees in each category. The numbers represent the corresponding group; the trainer is represented by "T". The red dotted line indicates the reference according to the uniform distribution.

In Fig. 5A, which includes the trainer (T), the habitat-tree selection scenario reflects the predefined tasks, with rating activity clearly illustrating active selection behaviour. The rating bar charts effectively visualise these patterns in a pedagogical manner. In contrast, tree removal selections in Fig. 5B show a more uniform rating distribution among the four highest-ranked groups (3, 1, 2, and 4), while Groups 5 and 6 exhibit slightly lower rating activity. This pattern is likely related to the predefined requirement of selecting a fixed total harvest volume (seen in Fig. 2).

Marking bar charts

The marking bar charts in Fig. 6 portray the proportion of trees, marked or not, by the participants in three selection categories, i.e., proportions of marks per tree. On the abscissa, the bars represent the number of marks received; on the ordinate, the proportion of trees receiving this number of marks. The red curve indicates the reference according to random tree marking, derived from the binomial distribution. Under this line, tree marking behaviour can be considered as random.

In Fig. 6A, evidence of "pseudo agreement" can be seen ($P_0 = 0.62$). The only bar not reaching over the reference curve is the one representing trees marked once, indicating some form of agreement in this selection category.

Fig. 6B is where the highest P_0 characteristics can be found ($P_0 = 0.78$). This can be explained by the fact that these trees are most likely not an alternative, concerning habitat tree selection. The bar representing trees selected once are below the reference curve and the bar representing trees selected twice is situated on this line. All other bars reach over the random tree selection curve. Indicating agreement from the previous selection category.

Fig. 6C possesses a similar P_0 characteristic to Fig. 6A ($P_0 = 0.66$). The bar representing trees selected once is below the reference curve; the bar representing trees selected twice is situated on this line. The P_m characteristic ($P_m = 0,05$) is the lowest result of all selection categories. However, all other bars reach over the random tree selection curve, indicating some form of agreement in this selection category.
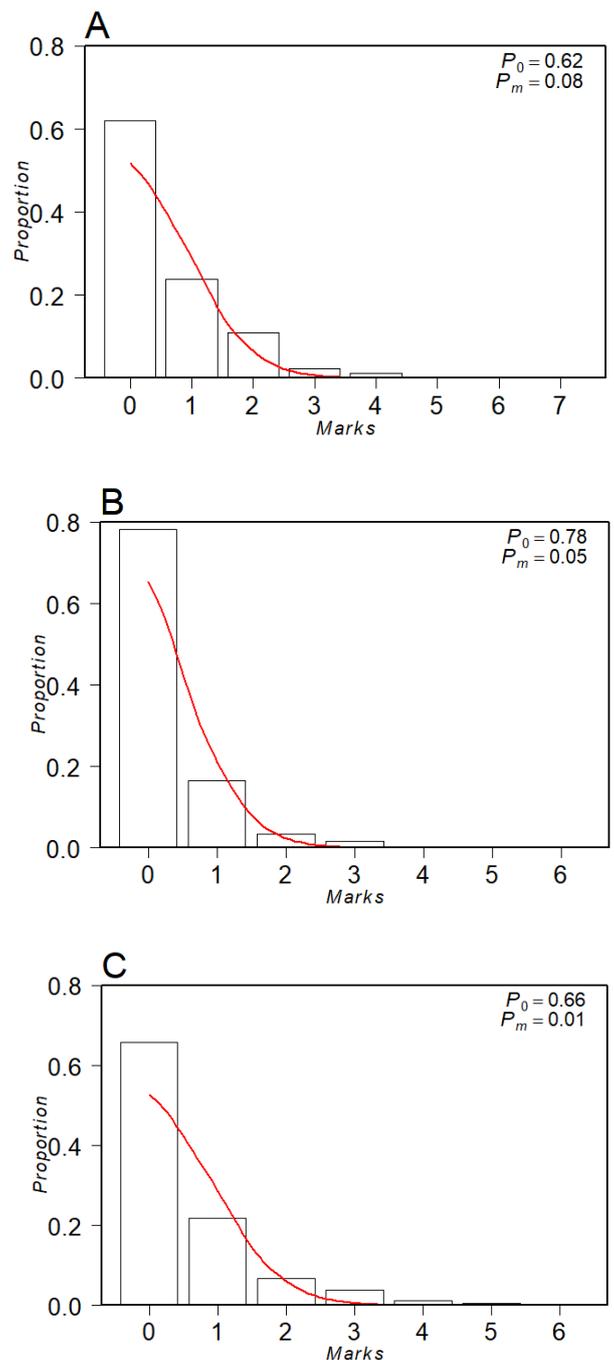
Figure 6. Marking bar charts, proportion of trees marked, and the number of marks given for habitat-tree selection, trainer included (A), habitat-tree selection (B) and trees selected to be removed (C). The numbers on the abscissa represent the number marks given to a tree. On the ordinate is the proportion of trees receiving these marks. The red curves indicate the reference of random tree marking derived from the binomial distribution.

3.4 Type of selection

This analysis focuses on the size preferences among the participants by comparing the proportion of trees selected (P_i^N) with the corresponding basal area of those trees (P_i^B). The relative basal area is shown on the abscissa and the B ratio on the ordinate. The dotted line running across the two plots indicates the reference line of B-ratio = 1; random tree selection or tree size does not influence tree selection.

The plots in Fig.7 depict selection scenarios: habitat-tree selection with the trainer included and trees selected for removal. In Fig. 7A, groups 1, 5, 6 and the trainer reveal a preference for marking larger trees. Groups 2 and 3 show a weak tendency to mark large trees as habitat trees (not particularly influenced by tree size). Group 4 is considered an outlier, since the preference for marking smaller trees is revealed, which goes against recommendations and theories on TreM occurrence (Kadavý et al., 2024). In Fig. 7B, Groups 1, 5 and 4 show a preference for marking small trees to be removed, in accordance with (potentially) benefitting the frame trees (Kruse et al., 2023). Groups 6 and 3 show low to no impact on tree size influencing marking behaviour in this category. Group 2 is considered the outlier in this category. Revealing a strong preference for marking large trees to be removed. A potential explanation for this behaviour can be the economic incentive, since the groups were ranked according to both economic and ecological performance in Kadavý et al. (2024).
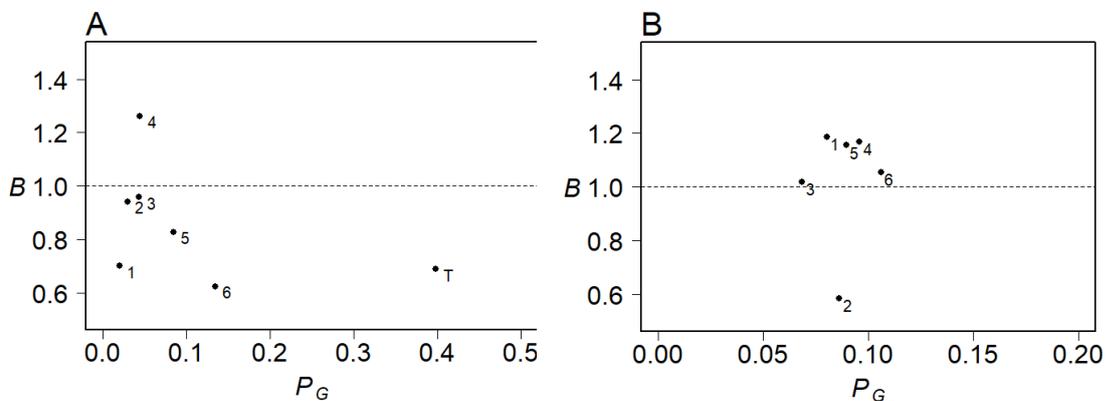
Figure 7. Scatter plot of the type of selection, B-ratios and the proportion of selected basal area for habitat-tree selection, trainer included (A) and trees selected to be removed (B). Numbers (down-right of each dot) represent the corresponding group; the trainer is represented by "T". Dotted line indicates the reference to random tree selection (B-ratio = 1).

3.5   Slenderness (*h/d*-ratio)

The *h/d*-ratio of a tree can indicate individual morphology, past resource allocation and forest management. These ratios, pooled for each participant, can reveal selection preferences and patterns in tree selection behaviour. To visualise the tree marking results from the different selection categories, two bean plots were produced (Fig. 8). The abscissa illustrates the participants, and the ordinate is arranged according to a logarithmic scale to visualise the results. The dotted line running across both plots illustrates the overall *h/d*-ratio mean of all participants and the line across each bean illustrates the individual group mean.

   The two bean plots represent the tree selection scenarios, habitat-tree selection and trees selected for removal. Table 6 reveals all the *h/d*-ratio mean and median results from the two scenarios.
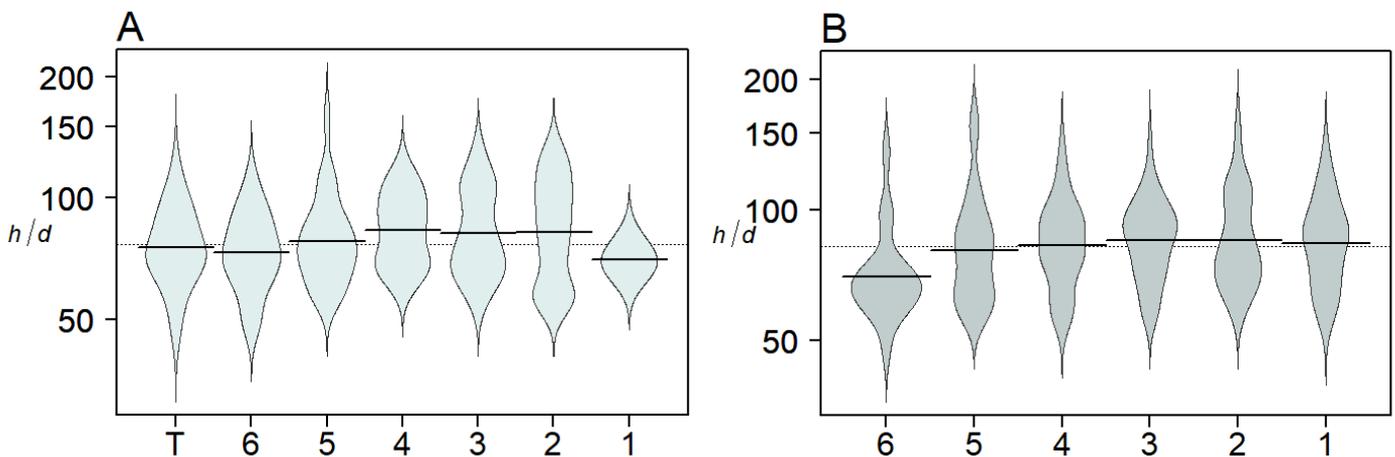
Figure 8. Bean plots of the h/d ratio, habitat-tree selection (A) and trees selected to be removed (B). The numbers represent the corresponding group; the trainer is represented by "T". The dotted line running across the plots is a reference to the overall mean selected in each category. The line running across each bean is a reference to the internal mean.

In Fig. 8A, a bimodal selection pattern can be observed for groups 4, 3 and 2 and a unimodal pattern for the other participants concerning habitat-tree selection. Groups 1, 6 and the trainer have chosen trees with mean results < 80 (stable, see Table 3), in accordance with consistent habitat trees (Burschel & Huss, 1997). Groups 2, 3, 4 and 5 have all selected trees with mean results above or very close to 80 (unstable). However, all these groups show a large variation in their selection, indicating a diverse size distribution in habitat-tree selection. Regarding trees selected to be removed (Fig. 8B), is group 6 considered an outlier, who display a mean *h/d*-ratio of 72.5. While all other groups have values ≥ 80.

Table 6. Mean and median results for each participant, including selection scenarios: Habitat-tree selection with the trainer included & trees selected for removal

h/d-Ratio	<u>Participant</u>	**1**	**2**	**3**	**4**	**5**	**6**	**Trainer**
Fig. 8A Mean		70.7	86.2	84.3	84.8	80.9	75.2	77.4
Fig. 8A Median		71.1	83.9	79.3	86.1	74.7	73.4	74.2
Fig. 8B Mean		86.3	87.9	87	85.2	84.4	72.5	
Fig. 8B Median		85.5	80	89	80.8	79	68.2	

3.6 Selection probabilities

To investigate factors influencing selection probability, a logistic regression model was employed. This approach allows for the estimation of the probability that a given tree is selected versus not selected based on a set of predictor variables. The response variable was binary, **1** if marked and **0** if not. The three different regression analyses included in this section depict only the selection scenario of habitat-tree selection with the trainer included (Fig. 9).

DBH dependent

Fig. 9A illustrates the selection probabilities for all participants as a function of DBH. The trainer (blue curve) shows the steepest increase, indicating that habitat-tree selection probability increases with DBH. The same pattern is true for group 6 (green), although to a lesser degree. All other groups show relatively flat curves, indicating low or no influence of DBH on habitat-tree selection.

Mingling dependent

Fig. 9B illustrates selection probabilities as a function of the mingling index for the participants. The most prominent trend is observed again in the curve belonging to the trainer, which shows a clear and consistent increase in selection probability with higher mingling values. This suggests that trees with more heterospecific neighbours (i.e., more mixed surroundings) have a higher likelihood of being selected. At the highest mingling level (1.0), the selection probability reaches nearly 0.4, compared to
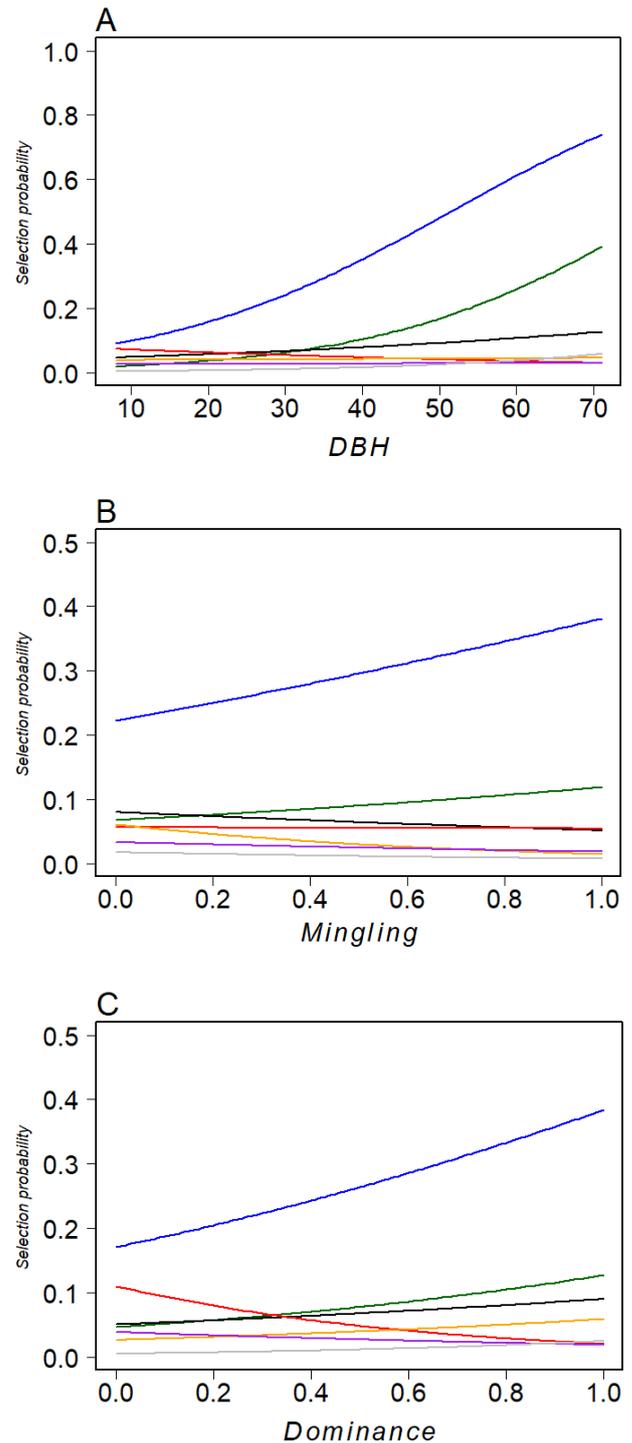
*Figure 9. Selection probability influenced by predictor variables: DBH (A), species mingling of nearest four neighbours (B) and tree dominance of the four nearest neighbours (C) for habitat-tree selection. Colours corresponding to the participants: Grey-group 1, purple-group 2, orange-group 3, red-group 4, black-group 5, green-group 6 & blue-**trainer**.*

approximately 0.2 at the lowest mingling levels (0.0). Group 6 also show a correlation with increased mingling levels, with a selection probability of 0.1 for mingling level 1.0. All other groups show no or a negative relationship with selection probability and mingling level.

Dominance dependent

Fig. 9C illustrates selection probabilities as a function of the dominance index (i.e., the proportion of k nearest neighbours that are smaller than tree i) for the participants. For the third time, the most noticeable trend observed was for the trainer. Showing a clear increase in selection probability with higher dominance values. At the highest dominance level (1.0), the selection probability reached approximately 0.4. Groups 5 and 6 are showing a slight correlation between increased dominance index and selection probability. Group 4 are the only participant showing a negative correlation between increasing dominance index and selection probability. All other groups show weak or no correlation between dominance index and selection probability.

3.7   *B*-ratio & selection probabilities

To further assess the selection behaviour of the participants, another logistic regression was performed where the probability of selecting a tree was modelled as a function of its DBH from Fig. 9. The model parameters β_0 and β_1. Intercept, β_0: tendency to select a tree depending on DBH, Slope, β_1: how strongly DBH
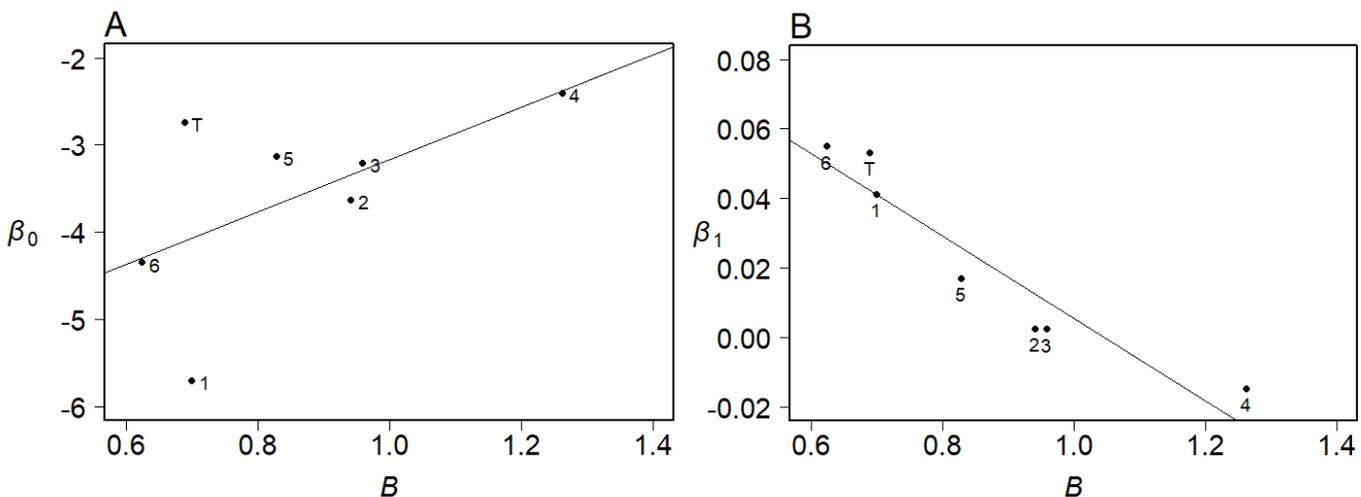
Figure 10. Linear relationship between B-values and the model parameters for habitat-tree selection with the trainer included. Model parameter β_0 and B-values (A) and slope parameter β_1 and B-values (B). The numbers (right of each dot) represent the corresponding group; the trainer is represented by "T".

influences selection probability. The fitted logistic models were then examined in relation to the participants' selection tendencies, quantified by the B-ratio (Eq. 5).

The first selection scenario explored is habitat-tree selection with the trainer included. Fig. 10 shows that there is a positive correlation between B-ratio and β_0. As the B-ratio increases, so does the selection tendency regardless of size (A). Group 4 is showing a tendency to mark many trees with small diameter, 2 and 3 show no selection bias based on size. Groups 1, 5, 6 and the trainer project a higher tendency of marking larger trees. There is a negative correlation between B-ratio and β_1. The selection probability decreases with DBH. The trainer, as well as groups 6 and 1, show the highest indication that DBH influences their marking of habitat trees. Group 4 illustrate a marking behaviour where DBH has the lowest influence on habitat-tree selection.
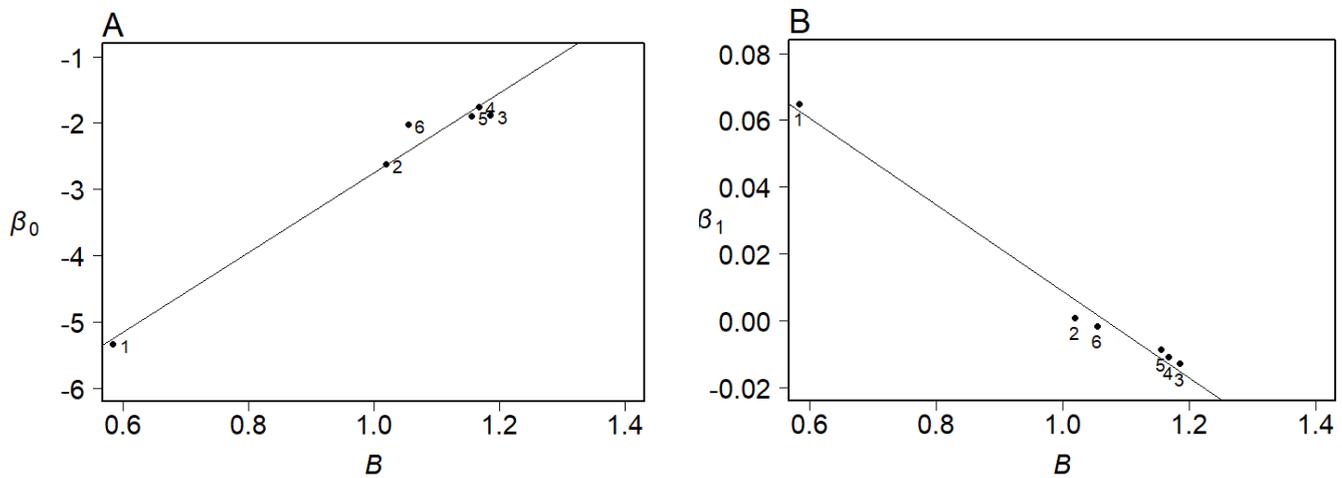
Figure 111. Linear relationship between B-ratio and the model parameters for habitat-tree. Model parameter β₀ and B-values (A) and slope parameter β₁ and B-values (B). The numbers (right of each dot) represent the corresponding group; the trainer is represented by "T".

The second selection scenario explored is habitat-tree selection without the trainer included. Fig. 11 shows the same correlations between β_0 and β_1 as in the previous selection scenario. In β_0, groups 3, 4 and 5 show a tendency to mark many trees with small diameter, 2 and 6 have no selection bias based on size and group 1 shows a higher tendency to mark larger trees. Group 1 shows the highest indication that DBH influences their marking of habitat trees. Groups 3, 4 and 5 show that DBH has the lowest influence on marking habitat-trees.

3.8   Location diversity index (Clark & Evans)

The aggregation index $R´$ was used to analyse the spatial distribution of selected habitat trees, with the trainer included. The location diversity index was calculated as 1.04 for all trees included in the marteloscope, indicating a random spatial distribution. Likewise, all habitat trees marked by the trainer exhibit random spatial distribution, with a calculated $R´$ value of 0.01 (Table 7). Group 1 expressed the lowest location diversity index result, suggesting a clustered selection pattern. Group 5 expressed the highest location diversity index result among all groups. While the result is > 1, it is not great enough to indicate regular spatial distribution, however a strong indication of random spatial distribution. Groups 2, 3, 4 and 6 all display results approximately equal to 0.8, indicating random spatial distribution with low tendencies of clustering of the marked habitat trees.

Table 7. Location diversity index results, selection scenario: Habitat-tree selection with the trainer included.

Participant	1	2	3	4	5	6	Trainer
$R´$	0.496	0.857	0.827	0.873	1.037	0.798	1.010

3.9   Habitat-tree species mingling

Habitat-tree mingling examines the four nearest neighbours ($k = 4$) of a tree i marked, to investigate if tree i is of the same species as its neighbours. A M_i value of 1.00 declares that no tree of the four nearest neighbouring trees is of the same species. A M_i value of 0.00 states that all four neighbouring trees are of the same species as tree i. M_i values of 0.00 – 0.25 indicate low mingling, values 0.75 – 1.00 indicate high mingling and 0.50 indicate intermediate mingling.

Table 8 presents the mean empirical mingling distribution results for all habitat trees marked by the participants. Groups 1 and 3 represent the lowest mingling results of the participants, with the highest proportion of marked trees in the low mingling category. The trainer and group 6 present the highest mingling results, with approximately 30 % of their marked trees in the high mingling category.

Table 8. Tree mingling, selection scenario: Habitat-tree selection category.

M_i Participant	1	2	3	4	5	6	Trainer
0.00	0.28	0.29	0.50	0.24	0.32	0.21	0.25
0.25	0.49	0.39	0.32	0.44	0.35	0.35	0.27
0.50	0.24	0.20	0.08	0.14	0.18	0.15	0.15
0.75	0.00	0.12	0.10	0.12	0.06	0.05	0.12
1.00	0.00	0.00	0.00	0.06	0.1	0.25	0.22

4. Discussion

4.1 Selection agreement

Agreement and conformity are closely related but conceptually distinct phenomena. Agreement refers to the extent to which participants arrive at identical or highly similar selections, whereas conformity reflects the degree to which individual selection behaviour aligns with collective tendencies. Together, these concepts provide a structured framework for interpreting tree-marking behaviour in marteloscope exercises. Consistent with previous research, the present study revealed generally low levels of agreement across all selection scenarios, as indicated by Fleiss' kappa and the concordance index (Bravo-Oviedo et al., 2020; Pommerening et al., 2015; Pommerening et al., 2018; Stoyan et al., 2018b; Vítková et al., 2016).

Low agreement in marteloscope exercises has repeatedly been observed and should therefore not be interpreted as an anomaly. Rather, it appears to be an inherent characteristic of human tree selection behaviour, particularly in complex management contexts such as CCF. Whether low agreement constitutes a problem remains an open question, as different selection pathways may ultimately lead to comparable silvicultural or ecological outcomes (Bravo-Oviedo et al., 2020). From this perspective, low agreement may reflect the plurality of valid decision-making strategies rather than a failure to apply management principles correctly.

In the present study, agreement metrics were particularly low for habitat-tree selection, which is likely attributable to the fact that the participating groups were assigned different target numbers of habitat trees in the original experiment. Under such conditions, high agreement cannot reasonably be expected, as the task itself structurally limits convergence in selection decisions. This effect is also reflected in the conformity results, where groups selecting similar numbers of habitat trees exhibited closer conformity values, suggesting that task constraints exert a strong influence on observed agreement patterns.

In contrast, selections for tree removal showed slightly higher conformity and agreement values. This may be explained by the more uniform number of trees selected across groups in this scenario, as well as by shared silvicultural heuristics commonly applied when identifying trees for removal. With the exception of Group 6, which displayed markedly lower conformity, the clustering of conformity values among the remaining groups suggests a relatively homogeneous decision-making pattern. This homogeneity is likely related to the shared educational background of the participants, who had undergone similar forestry training and instruction.

Although overall agreement was low, the results nevertheless demonstrate that marteloscope exercises are capable of revealing meaningful patterns in selection

behaviour. Rather than striving for maximal agreement, future applications may benefit from focusing on understanding the conditions under which agreement emerges, how it is influenced by task design and training and how divergent decisions can still converge towards similar management objectives. From a practical perspective, persistently low agreement may pose challenges for the broader implementation of CCF, as consistency and transparency in decision-making are often viewed as prerequisites for acceptance within the forestry sector and by society at large (European Commission, 2021; Kruse et al., 2023). Addressing this issue through improved training frameworks, decision-support tools and benchmarking, therefore, remains an important area for future research.

4.2   Selection behaviour & probability

The analysis of selection behaviour revealed pronounced differences among participants in both how many trees were selected and which tree attributes influenced these decisions. Rating and marking bar charts proved particularly useful for disentangling active and passive components of tree-selection behaviour, as previously suggested by Pommerening et al. (2018). Active rating behaviour, reflecting the overall intensity of selection by each participant, varied considerably between groups, whereas passive rating behaviour highlighted trees that were consistently perceived as either suitable or unsuitable for a given selection scenario.

Evidence of passive rating behaviour was observed in all selection categories, most notably through the high proportion of unselected trees (P_0). This pattern suggests the presence of an implicit consensus regarding trees that were considered of low or no relevance within the context of the exercise. Such "negative agreement" has been described as a characteristic feature of marteloscope experiments, where many trees are excluded for reasons that appear self-evident to participants (Pommerening et al., 2018; Pommerening & Grabarnik, 2019). In addition, trees receiving a high number of marks, represented by bars exceeding the binomial reference line, indicate instances where selection was perceived as obvious across participants, further reinforcing the presence of shared heuristics despite low overall agreement.

Active rating behaviour, as illustrated by the rating bar charts, differed more strongly between selection scenarios. Habitat-tree selection reflected the predetermined task structure, with participants selecting markedly different proportions of trees according to their assigned targets. In contrast, the selection of trees for removal exhibited a more uniform distribution among most groups, suggesting that removal decisions were guided by more widely shared silvicultural principles. The lower activity observed in Group 6 can likely be

attributed to volume constraints, which limited the number of trees that could be selected without exceeding the target volume.

The B-ratio analysis provided further insight into size-related selection preferences. For habitat-tree selection, the trainer and several groups exhibited a preference for selecting larger trees, consistent with ecological theory linking tree size to the occurrence and persistence of tree-related microhabitats (Kraus et al., 2016; Kozák et al., 2023). In contrast, Group 4 displayed a clear preference for selecting smaller trees as habitat trees, deviating from both the trainer's behaviour and prevailing conservation recommendations. While such behaviour is atypical, it has been documented in previous studies and may reflect alternative interpretations of habitat value or uncertainty in assessing TreM development (Cosyns et al., 2019).

In the removal scenario, most groups showed either weak size dependence or a tendency to remove smaller trees, a pattern that aligns with thinning practices aimed at promoting future crop trees. Group 2 constituted a notable exception, demonstrating a strong preference for removing larger trees. This behaviour can be interpreted in light of economic considerations, as Group 2 achieved the highest economic performance in the original study by Kadavý et al. (2024). The alignment between economic ranking and selection behaviour suggests that financial incentives can exert a strong influence on tree-selection decisions, even in an exercise explicitly designed to balance ecological and economic objectives.

Slenderness (h/d ratio) further illuminated differences in selection behaviour. For habitat-tree selection, the trainer and some groups predominantly selected trees with h/d ratios below 80, indicating stable individuals well suited for long-term retention. Other groups selected trees with higher and more variable h/d ratios, suggesting a broader and less consistent interpretation of suitable habitat trees. The bimodal distributions observed in several groups may reflect uncertainty or competing selection strategies, although the lack of comparable studies limits the extent to which such patterns can be interpreted conclusively.

Logistic regression analyses reinforced these observations by quantifying the influence of specific predictors on selection probability. The trainer consistently exhibited strong positive relationships between selection probability and DBH, species mingling and dominance, reflecting an ecologically informed and internally consistent decision-making strategy. Group 6 showed similar but weaker tendencies, whereas most other groups displayed flat or inconsistent selection probability curves, indicating limited sensitivity to these structural and spatial attributes. These findings support earlier work suggesting that experience and training shape the extent to which participants rely on measurable tree attributes in their decisions (Pommerening & Grabarnik, 2019; Joa et al., 2020).

Taken together, the results demonstrate that selection behaviour in marteloscope exercises is shaped by a complex interplay of task constraints,

individual heuristics, ecological knowledge and economic considerations. Even within a relatively homogeneous participant group, distinct behavioural profiles emerged, ranging from ecologically aligned strategies closely resembling expert behaviour to economically driven or exploratory approaches. This diversity underscores the importance of viewing human tree-selection behaviour not as a single, uniform process but as a spectrum of decision-making strategies that may nevertheless converge towards similar management outcomes.

4.3 Location diversity index & habitat-tree mingling

Spatial patterns and species mixing are central components of biodiversity-oriented forest management and are particularly relevant in the context of CCF. In this study, the mingling index and the location diversity index provided complementary insights into how participants incorporated spatial and compositional considerations into their habitat-tree selection decisions.

Among the participant groups, mingling patterns varied considerably. Group 6 exhibited the closest alignment with the trainer, selecting habitat trees with comparatively high mingling values and a spatial distribution approaching randomness. This suggests an implicit recognition of the ecological benefits associated with species mixture and spatial dispersion. In contrast, several groups selected habitat trees with lower mingling values, indicating a tendency to retain trees surrounded by conspecific neighbours. Such patterns may reflect a stronger focus on individual tree characteristics, such as size or apparent habitat features, rather than on neighbourhood context.

The location diversity index further elucidated these differences. The trainer's selections resulted in a near-random spatial distribution of habitat trees, which is generally considered favourable for ensuring broad-scale habitat availability and reducing spatial clustering of ecological functions. Random or dispersed patterns minimise the risk that localised disturbances will disproportionately affect biodiversity hotspots. In contrast, most participant groups exhibited clustered or aggregated spatial patterns, suggesting a preference for selecting habitat trees in close proximity to one another. While clustering may enhance local habitat richness, it may also reduce landscape-level heterogeneity and increase vulnerability to disturbance.

These spatial tendencies may partly be explained by cognitive and perceptual factors. Participants may have been drawn to visually prominent trees or areas with conspicuous habitat features, leading to spatial aggregation. Additionally, limited experience in integrating spatial information into decision-making may have contributed to the observed clustering. Similar tendencies have been reported in previous marteloscope studies, where participants prioritised visually salient

attributes over spatial configuration (Cosyns et al., 2019; Pommerening et al., 2018).

Importantly, the observed differences in spatial patterns did not necessarily imply inferior management outcomes. As highlighted by Bravo-Oviedo et al. (2020), multiple spatial arrangements can be compatible with CCF objectives, depending on site conditions and management goals. However, the results indicate that explicit consideration of neighbourhood composition and spatial distribution is more consistently incorporated by experienced practitioners than by less experienced participants. This finding underscores the potential value of integrating spatial indices and visual feedback into marteloscope training to support the development of more spatially informed decision-making strategies.

Overall, the mingling and location diversity analyses demonstrate that habitat-tree selection is influenced not only by individual tree attributes but also by how participants perceive and prioritise spatial relationships within the stand. Enhancing awareness of these spatial dimensions may therefore represent an important avenue for improving biodiversity outcomes in CCF practice.

4.4 Economic and ecological trade-offs and removal strategies

Balancing economic objectives with ecological considerations represents one of the central challenges in forest management, irrespective of the applied silvicultural system. In CCF, this trade-off becomes particularly salient at the level of individual tree-selection decisions, where the choice to retain or remove a tree simultaneously affects stand structure, economic returns and biodiversity outcomes. The results of this study illustrate how participants navigated this trade-off in practice and how economic reasoning influenced removal strategies.

Across most participant groups, removal decisions exhibited greater uniformity than habitat-tree selections, suggesting the presence of shared silvicultural heuristics. Many groups preferentially selected smaller or suppressed trees for removal, a strategy consistent with thinning practices aimed at promoting the growth of future crop trees while maintaining stand stability (Kruse et al., 2023). This behaviour reflects an implicit prioritisation of long-term stand development and aligns with conventional forestry training.

However, notable deviations from this pattern were observed. Group 2 demonstrated a strong preference for removing larger trees, resulting in a markedly different size distribution among removed trees. This strategy mirrors economically optimised harvesting behaviour and is consistent with findings by Kadavý et al. (2024), where this group achieved the highest economic performance. The alignment between economic ranking and removal behaviour

underscores the influence of profit-oriented reasoning, even within an exercise designed to balance ecological and economic objectives.

The removal of larger trees has important ecological implications, particularly when such trees possess or have the potential to develop TreMs. Large and dominant trees are disproportionately important for biodiversity, serving as habitat hubs and structural anchors within forest ecosystems (Kraus et al., 2016; Kozák et al., 2023). Consequently, removal strategies prioritising immediate economic gain may conflict with long-term biodiversity goals, especially if habitat-tree identification is inconsistent or incomplete.

The conformity analysis further revealed that agreement was higher in the removal scenario than in habitat-tree selection, likely due to the more standardised nature of removal decisions. Nevertheless, the presence of economically driven outliers highlights the potential for divergent interpretations of management priorities, even among participants with similar educational backgrounds. This finding reinforces earlier observations that human decision-making in forestry is shaped not only by technical knowledge but also by value systems, risk perception and individual priorities (Joa et al., 2020; Pommerening et al., 2018).

Overall, the results demonstrate that removal strategies serve as a critical lens through which the economic ecological trade-off in CCF can be examined. While consensus may emerge around conventional thinning practices, the integration of biodiversity objectives requires deliberate attention and, in some cases, explicit guidance. Marteloscope exercises provide a valuable platform for exposing these trade-offs and for fostering reflection on how economic incentives influence management decisions, thereby supporting the development of more balanced and transparent CCF practices.

4.5 Implications for marteloscope use, CCF implementation and future research

The findings of this study highlight the value of marteloscope experiments as tools for investigating human decision-making in forest management, particularly within the context of CCF. Despite consistently low levels of agreement among participants, marteloscopes proved effective in revealing systematic patterns in selection behaviour, including the influence of tree size, spatial configuration, species composition and economic considerations. These results support the notion that marteloscopes are well-suited not only for training purposes but also as experimental platforms for behavioural and decision-science-oriented forestry research.

One key implication is that low agreement should not necessarily be interpreted as a failure of training or decision-making. Rather, it reflects the inherent complexity of CCF, where multiple management pathways may be

equally valid and context dependent. The presence of distinct decision-making profiles among participants, ranging from ecologically aligned strategies to economically driven approaches, underscores the need for training frameworks that explicitly address trade-offs, uncertainty and the absence of singular "correct" solutions. Marteloscope exercises offer a controlled yet realistic environment in which such complexities can be explored and discussed.

From an implementation perspective, the results suggest that the broader adoption of CCF may benefit from enhanced transparency and consistency in decision-making processes. While experienced practitioners demonstrated more stable and ecologically informed selection behaviour, less experienced participants exhibited greater variability and weaker sensitivity to structural and spatial indicators. Integrating quantitative feedback mechanisms, such as selection probability curves, conformity indices and spatial metrics, into marteloscope training could help participants better understand the consequences of their decisions and foster convergence towards ecologically robust outcomes without enforcing rigid prescriptions.

Several methodological limitations should be acknowledged. The study was conducted within a single marteloscope and involved participants with relatively similar educational backgrounds, which constrains the generalizability of the findings. In addition, group-level analyses necessarily obscure individual decision-making processes and may mask within-group heterogeneity. Nevertheless, these limitations also provided a controlled setting in which subtle behavioural differences could be identified, thereby enhancing the internal validity of the analysis.

Future research should build on these findings by expanding marteloscope studies across diverse forest types, geographic regions and participant groups, including professional foresters, conservation practitioners and private forest owners. Longitudinal studies assessing how selection behaviour evolves with repeated training would be particularly valuable for evaluating learning effects and the persistence of decision-making heuristics. Moreover, emerging digital marteloscope platforms (Balestra et al., 2025) offer promising opportunities to overcome logistical constraints associated with traditional field-based exercises, enabling larger sample sizes, standardised experimental conditions and international collaboration.

Finally, interdisciplinary approaches that integrate insights from behavioural science, economics and political science, such as proportional decision rules and crowd-based selection methods (Pommerening et al., 2020), may further enhance the capacity of marteloscope research to support CCF implementation. By embracing the diversity of human decision-making rather than seeking to eliminate it, future developments can contribute to more resilient, inclusive and socially acceptable forest management strategies.

5. Conclusion

This thesis examined human tree-selection behaviour in a marteloscope context to improve the understanding of decision-making in CCF. By integrating agreement metrics, conformity analysis, selection probabilities, spatial indicators, and assessments of ecological trade-offs, the study provides a multifaceted view of how individuals and groups approach tree retention and removal in complex forest environments.

The results confirm that agreement among participants is consistently low, in line with previous marteloscope studies. Rather than indicating random or flawed decision-making, low agreement appears to be an inherent feature of CCF, reflecting multiple valid management pathways. Conformity analyses revealed structured collective tendencies underlying this variability, demonstrating that meaningful decision patterns exist even when exact agreement is limited.

Distinct decision-making profiles emerged among participant groups despite similar educational backgrounds. The trainer's baseline-selections reflected consistent preferences for large, structurally dominant trees in mixed and spatially dispersed configurations, whereas several student groups showed greater variability and weaker sensitivity to structural and spatial attributes. These differences highlight the role of experience and values in shaping tree-selection behaviour.

Overall, the findings underscore the value of marteloscope exercises as tools for both research and training, enabling quantitative analysis of human behaviour and explicit exploration of ecological trade-offs. Embracing behavioural diversity rather than striving for uniformity may support more adaptive, transparent, and ecologically robust CCF practices, particularly when combined with interdisciplinary approaches and emerging digital tools.

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Popular science summary

Human decision-making in Continuous Cover Forestry

Forests are more than collections of trees; they are complex ecosystems shaped by both natural processes and human decisions. Over the past centuries, changes in land use and increasing industrial demands have led to a global decline in old-growth forests. These forests are particularly valuable because they host high levels of biodiversity, much of which depends on deadwood and tree-related microhabitats such as cavities, cracks and decay structures. Preserving and restoring these features has therefore become a central goal of modern forest management.

One approach that has gained renewed attention is Continuous Cover Forestry (CCF). Unlike traditional clear-cutting systems, CCF aims to maintain a continuous forest canopy by selectively removing or retaining individual trees. While this approach holds promise for balancing timber production with biodiversity conservation, it also places great responsibility on forest managers. Every decision to remove or retain a tree influences forest structure, economic outcomes and ecological values. Understanding how such decisions are made is therefore crucial for the successful implementation of CCF.

Studying tree selection with marteloscopes

To study human decision-making in forestry, researchers often use marteloscopes. A marteloscope is a carefully mapped forest plot in which all trees are measured, numbered and evaluated. Participants, such as students, foresters, or trainers are asked to "mark" trees for specific purposes, for example, as habitat trees to be retained or as trees to be removed. Because all trees are known in advance, researchers can later analyse how different people make decisions under the same conditions.

This thesis used data from a marteloscope exercise involving forestry students and a silviculture trainer. The aim was not to determine which selections were "right" or "wrong", but to explore how people make choices, how consistent those choices are and how they reflect ecological and economic priorities. Several analytical tools were used, including measures of agreement and conformity, selection probabilities, tree size indicators and spatial indices describing species mixture and tree distribution.

Do people agree when choosing trees?

One of the most striking findings was that agreement among participants was generally low. Even when participants shared similar educational backgrounds, they often selected different trees. At first glance, this might seem problematic.

However, earlier studies have shown that low agreement is common in marteloscope exercises and may reflect the complexity of forest management rather than poor decision-making.

Importantly, this study showed that low agreement does not mean that decisions are random. When looking more closely, clear patterns emerged. Some trees were seldom selected, suggesting an implicit consensus that they were of little interest. Other trees attracted many marks, indicating that participants broadly agreed on their importance. In other words, while participants did not always choose the same trees, they often followed similar underlying reasoning.

To better capture this behaviour, the study introduced the concept of conformity, which measures how closely individual decisions align with the overall tendencies of the group. This approach revealed meaningful structure in the data that traditional agreement metrics alone could not detect.

Different ways of thinking about forests

Despite their similar training, participants displayed distinct decision-making profiles. The silviculture trainer consistently selected large, stable trees in mixed-species neighbourhoods and avoided clustering habitat trees in one area. This strategy reflects current ecological knowledge: large trees are more likely to host valuable microhabitats and spatially dispersed habitat trees help maintain biodiversity across the forest.

Some student groups showed similar tendencies, while others focused more on economic considerations. One group, in particular, tended to remove larger trees, a strategy that maximised short-term economic value but potentially reduced long-term ecological benefits. Other groups appeared more exploratory, selecting trees with a wide range of sizes and characteristics, possibly reflecting uncertainty or competing priorities.

These differences highlight an important point: forest management decisions are shaped not only by technical knowledge, but also by values, experience and perceptions of risk. Even within a relatively homogeneous group, multiple valid management strategies can emerge.

Balancing ecology and economy

A central challenge in CCF is balancing economic returns with ecological responsibility. This trade-off was clearly visible in the removal decisions analysed in the study. While many participants followed conventional thinning principles; removing smaller or suppressed trees, others prioritised economically valuable trees.

Large, old trees are particularly important for biodiversity, as they are more likely to develop microhabitats over time. Removing such trees may increase short-term profits but reduce habitat availability in the long run.

What does this mean for forestry?

The results of this thesis suggest that marteloscopes are powerful tools for understanding how people think about forests. Rather than aiming for perfect agreement, marteloscope exercises can be used to reveal hidden assumptions, explore trade-offs and encourage reflection among participants. They offer a safe environment in which different perspectives can be compared and discussed.

For CCF to be widely accepted and successfully implemented, transparency in decision-making is essential. Training programs that incorporate feedback on selection behaviour, such as visualisations of tree size, spatial patterns, or group conformity, may help future foresters develop more consistent and ecologically informed strategies.

Looking ahead, digital marteloscopes and interdisciplinary approaches combining forestry with behavioural science hold great promise. By acknowledging that forest management is as much about people as it is about trees, we can move towards more resilient, adaptive and sustainable forests for the future.

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           mixtures

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           look at 3-year-old seedling growth patterns above- and belowground and their
           mycorrhizal symbionts according to their distance to a forest edge.

2025:04   Författare: Jelle van Zanten
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           temperate woody species in southern Sweden.

2025:05   Författare: Adrien Lamodière
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