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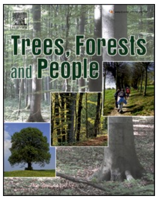

Towards a benchmark of national training requirements for continuous cover forestry (CCF) in Sweden

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ABSTRACT

Continuous cover forestry (CCF) is forest management based on ecological and biological principles. CCF particularly requires the abandonment of clearfelling practices in favour of more natural approaches of regeneration. Recently, CCF has been identified as a way to mitigate climate change, to bring about forest conservation and to meet the diverse requirements of recreation forests. EU strategies support the use of CCF and Sweden is committed to the transformation of 20% of its plantation forest land to CCF. This policy change meets the Swedish forest industry rather unprepared. CCF training is therefore urgently required and we applied marteloscope techniques to begin with establishing a benchmark of training requirements. A marteloscope is a forest research plot where all trees are measured and have clearly visible numbers on the stem surface. We carried out a first marteloscope experiment at the Svartberget experimental forest near Umeå in Northern Sweden involving 13 test persons that we asked to carry out CCF management by selecting trees that are supposed to stay behind and others that are to be taken out in order to achieve CCF objectives. We applied specialised statistics to analyse the trainees' choices and thus to measure their current state of silvicultural knowledge and experience. The results were interpreted in the context of data previously obtained from 26 comparable marteloscope experiments in Britain. The Svartberget results were in parts similar to and sometimes even closer to theoretical expectations than the British results, but also revealed that more intensive training was required in individual-based forest management, which is an important part of CCF. A new didactic technique, the *competitor-for-frame tree rule*, tightening the link between evicted and residual trees has contributed to the good tree-selection performance at Svartberget.

1. Introduction

Continuous cover forestry (CCF) is a type of forest management which is based on ecological and biological principles. Definitions of CCF usually include a number of tenets or principles that can greatly vary between countries and organisations involved (Pommerening and Murphy, 2004). The most prominent tenet of CCF is the requirement to abandon the practice of large-scale clearfelling in favour of more environmentally friendly harvesting and natural regeneration methods such as the selective harvesting of individual trees and the use of shelterwood regeneration systems. There are more than fifty semi-synonyms denoting similar forest management types including *alternatives to clearfelling, close-to-nature forestry, ecological* silviculture and *nature-orientated silviculture*. Objectives, definitions and standards can differ but all variants of CCF described by these labels share a rather high degree of similarity (Palik et al., 2021; Puettmann et al., 2015; Pommerening, 2023).

CCF is not a new phenomenon and the historic roots of this management type can be traced back to at least the second half of the 19th century (Pommerening and Murphy, 2004). Over the last century, CCF went in and out of favour at different rates and times in various European countries and in North America. In recent decades, CCF was re-discovered in different parts of the world as a toolbox for forest conservation and for mitigating climate change (Pommerening, 2023). At the same time there has also been an increasing dissatisfaction of European societies with industrialised forms of plantation or rotation

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forest management (RFM). Recently, the EU forest strategy for 2030 (European Commission, 2021) stated clearcutting should be “used only in duly justified cases” and the strategy promotes the ”creation or maintenance at stand and landscape level of genetically and functionally diverse, mixed-species forests, especially with more broadleaves and deciduous trees.” These political statements clearly support CCF and a recent policy paper published by the European Forest Institute provided explicit definitions, justifications and implementation guidelines for this strategy (Larsen et al., 2022).

Marked changes in forest policies tend to translate directly into changes of forest management practices and these often require the staff involved to suddenly apply very different methods they have not been much educated for nor have had any long-term experience with. Therefore any political decision to introduce a new forest management type that differs much from the majority forest practice in a given country or region requires a comprehensive training programme. The training courses offered should explicitly address different levels of forestry staff, e.g. forest managers/owners, forest planners and machine operators. The recent forestry debate in Sweden has markedly shaken up traditional views about forestry (Hertog et al., 2022) and as a response the Swedish Forest Authority have now made a commitment to facilitate the transformation of 20% of Sweden’s forests to CCF (Skogsstyrelsen, 2021). This policy change in Sweden meets both forest industry and forestry education rather unprepared. Experience from the introduction of CCF to countries with a plantation background similar to Sweden, particularly from Ireland and the UK, have clearly suggested that the introduction of CCF can only be successful if accompanied by goal-orientated training (Vítková et al., 2016; Cosyns et al., 2018; Pommerening et al., 2018). Plantation management is comparatively easy to apply, since it can be functionalised and thus broken down into small individual tasks that can often be delegated even to laypersons. CCF on the other hand involves holistic forest management that requires a simultaneous application of in-depth knowledge in forest ecology, tree physiology, soil science, forest operations and silviculture. To the average forest manager decision processes in CCF can therefore be overwhelming at first and to avoid or overcome mental blocks, special training is required (Soucy et al., 2016; Bravo-Oviedo et al., 2020).

Training requirements in the context of CCF naturally vary from country to country and from region to region. Without thorough preparation forestry training can be highly ineffective. For effective preparation, research is required into the aptitude of the forest industry to make the transition to CCF. Research information on this aptitude of the forestry sector will establish a crucial benchmark. A good way to establish a benchmark of training requirements is the use of marteloscopes. Marteloscopes are a comparatively new technique (Vítková et al., 2016; Cosyns et al., 2018; Pommerening et al., 2018) that has not been much explored in Sweden to date. A marteloscope is a research plot in the forest where all trees are measured and have clearly visible numbers on the stem surface. Test persons are then asked to carry out CCF management by selecting trees that are supposed to be taken out or to stay behind to achieve the CCF objective in question. The collection of data on the test persons’ decisions provides information on their tree-selection behaviour. By using appropriate statistics it is then possible to analyse the trainees’ choices and thus to measure their current state of silvicultural knowledge and experience. Marteloscopes can be used for any kind of silvicultural training and research on human tree-selection behaviour, but they were originally proposed in the context of CCF (Susse et al., 2011).

The first research marteloscope experiment was recently carried out at the research forest of the Swedish University of Agricultural Sciences at Svartberget near Umeå. This is one of very few marteloscope sites in Sweden and the only one which so far has been used for research purposes. The objective of this paper is (1) to analyse the results obtained from the Svartberget experiment. (2) Trends emerging from the results were identified and statistically interpreted in the context of 26 comparable experiments carried out earlier in Britain. (3) These trends were considered and discussed as part of a first step towards establishing a national training benchmark for Sweden.

The introduction of CCF to Britain started approximately 20 years ago. Since the British data cover a wide range of sites and individual tree-selection strategies in different parts of Britain, they are used in this study to create the equivalence of a statistical confidence region. Any Svartberget observation outside this confidence region is likely to indicate some special human behaviour that has not so far occurred in British experiments and therefore potentially merits a specialised training effort for Swedish forestry staff. Accordingly, our base hypothesis was that the tree selection behaviour of the Swedish participants in the Svartberget experiment was not significantly different from that of the British test persons.

2. Materials and methods

2.1. Marteloscope data

2.1.1. Site descriptions

The marteloscope site studied is located in the boreal region of Northern Sweden in the county of Västerbotten. The site is within the Svartberget experimental forest (64°, 24′ N, 19° 78′ E) near Vindeln/Umeå which is managed by the Swedish University of Agricultural Sciences (Fig. 1). The site is located at an elevation of approximately 120 m a.s.l. Mean annual temperature is 1.8 °C (−9.5 °C in January and +14.7 °C in July) and mean annual precipitation is 614 mm. The shrubs *Vaccinium myrtillus* L. and *Vaccinium vitis-idaea* L. can be found on the forest floor throughout the marteloscope site (Fig. 1).

Originally the stand has been planted approximately 76 years ago and was supplemented by natural regeneration. Since then there have been several thinnings. Currently, there are in total 308 trees with a stem diameter (measured in centimetres at 1.3 m above ground level) larger than 4 cm and three tree species, namely *Pinus sylvestris* L., *Picea abies* (L.) Karst. and *Betula pendula* Roth. present in the marteloscope plot (Table 1). The dominant tree species is *P. sylvestris* with a basal-area share of 81%, followed by *P. abies* with 14% and *B. pendula* with 5%. The stem diameters of the trees in the marteloscope form a bimodal empirical diameter distribution, where mainly *B. pendula* contributes to the mode in the range of very small stem diameters and it is mostly *P. sylvestris* diameters that form the second mode in the range of larger trees (not shown). The total basal area of the stand is 26.2 m^2/ha, which is rather low considering the age and development stage of the stand. The quadratic mean diameter, d_g, for *P. sylvestris* is 22.2 cm, while the smallest *P. sylvestris* tree has a stem diameter of 7.0 cm and the largest one of 33.4 cm. The d_g of *P. abies* is 15.4 cm, the smallest *P. abies* tree has a stem diameter of 4.3 cm, the largest one of 28.8 cm. Apart from one tree, *B. pendula* does not occur in the main canopy layer. There is scattered *B. pendula* regeneration in some of the more open areas of the stand. For each tree within an area of 50 m × 50 m (0.25 ha), the following variables were recorded: species, diameter at breast height (d) and total tree height.

Additionally, the data from 14 comparable marteloscope sites located all over Great Britain were included in this analysis (Pommerening et al., 2021). Most of the 14 British sites include forest stands of *Picea sitchensis* (Bong.) Carr., *Larix* × *marschlinsii* Coaz, *Larix kaempferi* (Lamb.) Carr. and *Pinus sylvestris*. In some of these stands, other species have later colonised the site, however, the aforementioned species represent the main species in terms of density. Peckett Stone at the Welsh-English border is a *Fagus sylvatica* L. forest and Dean (in the Forest of Dean) is a *Picea abies* forest, i.e. they are exceptions from the aforementioned species composition (Pommerening et al., 2021). For the British marteloscopes, some total-tree heights were only measured on a sample basis and then missing height values were estimated from nonlinear regression.

All British marteloscopes were located in simple-structured even-aged forests that were originally planted as monocultures with only one

Fig. 1. Test persons marking trees at the Svartberget marteloscope (64°, 24′ N, 19° 78′ E) near Umeå in Northern Sweden in November/December 2022.

Table 1

Description of the forest sites and marteloscopes included in this research. N – density, calculated as number of trees per hectare, G – basal area, calculated as the sum of cross-sectional tree stem areas at 1.3 m above soil level), d_g – quadratic stem diameter at 1.3 m above soil level, h_{100} – stand top height, calculated as the mean height of the largest 100 trees per hectare, v_d – coefficient of variation of all tree diameters 1.3 m above soil level before selection, k_d – skewness of the empirical stem diameter distribution, r – number of test persons selecting trees and n – number of trees eligible for selection. Several numbers of r indicate that several experiments have taken place in the same or in different years as specified. See also Pommerening et al. (2021).

Site	Main species	Year(s)	N [trees ha^{-1}]	G [m^2·ha^{-1}]	d_g [cm]	h_{100} [m]	v_d	k_d	r	n
Ae	*Picea sitchensis*	2011	1321	41.9	20.1	21.2	0.35	0.17	10	176
Ardross	*Larix* × *marschlinsii*	2012, 2013	2180	32.3	13.7	13.5	0.37	0.49	7, 8	218
Bin	*Picea sitchensis*	2010	1540	59.3	22.1	22.4	0.30	0.12	8	154
Black Isle	*Pinus sylvestris*	2013	2010	26.0	12.8	11.0	0.24	0.18	11	201
Cannock Chase	*Larix* × *marschlinsii*	2012, 2013	2040	35.8	14.9	14.8	0.29	0.07	6, 20	204
Cannock Chase	*Larix* × *marschlinsii*	2014	2040	36.7	15.1	17.0	0.31	0.15	16, 11, 9	204
Craigvinean	*Picea sitchensis*	2013	3000	53.0	15.0	15.0	0.22	−0.07	15	300
Craigvinean	*Picea sitchensis*	2015	3000	56.7	15.5	16.6	0.24	0.07	8, 7	300
Crychan	*Larix* × *marschlinsii*	2010	1930	41.2	16.5	16.2	0.28	−0.04	6	193
Crychan	*Larix* × *marschlinsii*	2013	1610	41.5	18.1	17.8	0.26	−0.17	8	161
Dalby	*Larix kaempferi*	2011	1900	46.2	17.6	18.8	0.28	0.31	9	190
Dean	*Picea abies*	2016, 2017	3050	36.2	12.3	13.2	0.34	0.37	18, 11, 9, 15	305
Dean	*Picea abies*	2018	2830	41.8	13.7	16.7	0.35	0.36	11	283
Glentress	*Picea sitchensis*	2013	1760	58.1	20.5	23.5	0.30	0.06	13	176
Haldon	*Picea sitchensis*	2014	1780	43.9	17.7	18.8	0.35	0.39	16	178
Loch Ard	*Picea sitchensis*	2015	2450	43.3	15.0	18.2	0.35	0.36	14	245
Peckett Stone	*Fagus sylvatica*	2011	830	34.7	23.1	24.8	0.29	0.33	11	83
Tummel	*Picea sitchensis*	2019	3230	42.4	12.9	13.3	0.28	−0.18	8	323
Svartberget	*Pinus sylvestris*	2022	1232	26.2	16.5	20.8	0.63	0.24	13	308

species (Table 1). Other species occasionally occur, but they are minorities and were not included in the thinning instructions. Such forest stands often mark the beginning of transformation to CCF and are therefore frequently included in marteloscope experiments, because they offer the opportunity to measure initial management steps taken by the test persons. With the notable exception of Ae, each of the British marteloscopes had a size of 0.1 hectares. The size of the Ae marteloscope was 0.133 hectares.

Stem size diversity as described by the coefficient of variation and skewness was comparatively low, which is typical of plantations at the brink of being transformed to CCF (Pommerening and Murphy, 2004). By far the highest coefficient of variation was observed at Svartberget. As already pointed out, overall stand basal area is rather low at Svartberget and only paralleled by the British marteloscope at Black Isle (Table 1).

2.1.2. *Marteloscope experiments*

The British data provided a statistical contrast for the results obtained from the Svartberget experiment and were used for establishing the equivalence of a confidence. They involved a total of 26 experiments and 285 test persons (Table 1). The British data were ideal for this purpose, since the marteloscopes were well spread across the country and represented very different situations in terms of site conditions, tree species mixture, tree density and tree selection patterns. In addition, the rotation-forest-management background and the lack of CCF skills in Britain are very similar to the current situation in Sweden. In both the Swedish and British experiments, 27 groups of test persons selected frame trees and their competitors.

Frame trees are trees of particular commercial, ecological, sentimental, spiritual or other value and all management is exclusively directed towards them until the end of their lifetime. This management particularly includes the selection and eventual removal of potential competitor trees amongst their nearest neighbours. Since competing neighbour trees usually occur in the vicinity of the frame trees they compete with, frame-tree orientated thinnings are carried out as *local* crown thinnings as opposed to *global* crown thinning where the trees selected for thinning can occur anywhere in a forest stand (see Pommerening et al., 2021, for details). The thinnings simulated by the test persons were intended to follow the principles of crown thinnings, i.e. only dominant frame-tree competitors were supposed to be selected for removal (Helms, 1998). Local crown thinnings are considered an important element of CCF and are instrumental in achieving uneven-aged forest structure and increasing resilience (Pommerening and Murphy, 2004; Pretzsch et al., 2017). Frame trees and competitors were selected in the same experiments and by the same persons. The test persons were provided with the theory of local crown thinnings as explained here and advised to select approximately 100 frame trees per hectare. No other limiting instructions were provided to empower the participants to use their own intuition and creativity in following the principles of local crown thinnings, since this typically is required from them in forest management practice.

Each experiment included a number of test persons varying from a minimum of 6 (Cannock Chase, Crychan) to a maximum of 20 (Cannock Chase, see Table 1). In the case of the British experiments, the test persons were trainees participating in regular forest management training seminars provided by the Technical Development Department of Forest Research at Ae (Scotland, UK). About 95% of the 285 British test persons were employed by the state forestry service (Forestry Commission, Natural Resources Wales) in different capacities ranging from machine operators to work supervisors and also included woodland officers and forest managers. The remaining 5% of the test persons mainly worked as forestry contractors (Pommerening et al., 2021). At Svartberget, approximately 40% of the test persons were experienced forest managers with many years of forest practice and 60% were inexperienced forestry staff with less than five years of forest practice. Since it is not easy to recruit test persons who are willing to sacrifice several ours of their own time, we depended on volunteers. The test persons made decisions on between 83 (Peckett Stone) and 323 (Tummel) trees (Table 1).

2.2. Statistical measures of tree-selection behaviour

For quantifying the behaviour of test persons selecting trees in a forest stand, we pursued several analysis techniques in our study that are well-known from previous research (Pommerening et al., 2018; Pommerening and Grabarnik, 2019). In general terms, we analysed cases where r test persons classify n trees. The binary classification involved two categories, i.e. “0″ (negative – not selected) and “1″ (positive - selected).

An informative indicator of tree selection behaviour is the proportion of trees that are not selected by any test person, P_0. Proportion P_0 constitutes a “negative agreement” on seemingly “unselectable” trees. It typically includes trees that to the eyes of all test persons suggest the risk of not improving or even of worsening stand conditions in terms of silviculture, ecosystem goods and services or biodiversity, if they were selected as frame trees or as competitor trees of frame trees (Pommerening et al., 2021).

We also considered the coefficient of variation r_m of the proportions $m \,/\, n$ of trees selected, where m is the number of trees that the test persons of a given experiment have chosen $k = 0, 1, \ldots, r$ times. Large values of r_m potentially indicate a high degree of agreement in terms of the number of times trees are selected by several test persons.

Fleiss’ kappa is a standard characteristic for measuring the degree of agreement (Fleiss, 1971; Fleiss et al., 2003) of a group of people, which is frequently used in applied statistics, e.g. in medicine. The concept of kappa is based on pairwise comparisons and has its roots in the one-way analysis of variance. Fleiss’ kappa can be expressed as in Eq. (1).

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

In Eq. (1), p_0 is the observed proportion of ratings in agreement and p_e is the expected proportion of ratings in agreement (see Pommerening et al., 2018 for details). The values of κ usually lie between 0 and 1 and agreement increases with increasing κ. Agreement here is defined as similarity in tree selection. For the interpretation of κ, Stoyan et al. (2018) proposed Table 2.

As an individual-person alternative to Fleiss’ kappa, we applied the relative conformity number, c_i'. This characteristic quantifies the tendency of test person or trainee i to conform with the general selection tendency of all test persons. The conformity of the selection result of test person i with those of the other participants in the experiment is characterised by the conformity number c_i. This is the mean of the numbers of test persons who also selected the trees chosen by test person i,

$$c_i = \frac{1}{n_i} \sum_{j=1}^{n} \mathbf{1}_{X_i}(j) \times s_j \text{ for } i = 1, 2, \cdots, r, \tag{2}$$

where n_i is the number of trees marked by test person i with “1″, X_i is the set of trees selected by test person i and s_j is the number of marks “1″ of tree j. $\mathbf{1}_{X_i}(j)$ has a value of 1, if test person i marks tree j with “1″, otherwise the value is 0. The characteristic c_i takes large values, if test person i selects the trees chosen by the majority of participants in the experiment. The quantity is more suitable for comparison when transformed to the relative conformity number c_i':

$$c_i' = \frac{c_i}{C_i} \text{ with } C_i = \frac{1}{n_i} \sum_{j=1}^{n_i} s_j \text{for } i = 1, 2, \ldots, r \tag{3}$$

Quantity C_i is the conformity number of an opportunist who selects n_i trees as the observed test person i, but s/he selects the n_i trees with the largest number s_j from the list of all trees. c_i' gives positive numbers smaller than 1 and a large value of c_i' indicates a high degree of conformity of test person i with the whole group of all other test persons (Pommerening and Grabarnik, 2019).

We also included B_i, the ratio of the proportion of number of trees, $P_i^{(N)}$, selected by test person i and the corresponding proportion of basal area, $P_i^{(G)}$, (derived from stem diameter using the area equation of the circle) of these trees (Kassier, 1993) in the analysis, see Pommerening et al. (2018) and Vítková et al. (2016).

$$B_i = \frac{P_i^{(N)}}{P_i^{(G)}} \tag{4}$$

Table 2
Interpretation of κ values (Eq. (1)) proposed by Stoyan et al. (2018).

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

In our case, B_i quantifies the human tree selection strategy by comparing the proportion of trees selected with the corresponding basal-area proportion. Practically speaking, the quantities $P_i^{(N)}$ and $P_i^{(G)}$ define intensities in terms of tree-number and basal-area proportions, respectively, of trees selected by the test persons. If $B_i < 1$, a smaller proportion of trees has been selected by test person i compared to their proportion of cumulative basal area. In a thinning context, this typically indicates a crown thinning and the trees selected show a tendency of being in the upper part of the empirical diameter distribution. A larger proportion of trees is selected compared to their proportion of basal area, if $B_i > 1$. In a thinning context, this is consistent with a thinning from below and trees were preferably selected in the lower part of the empirical diameter distribution (Pommerening et al., 2021).

Tree selection probabilities can be quantified and often depend on a number of predictor variables that influence the test persons' decisions. Tree size is an obvious choice for a predictor variable, since the tree selection probability should generally increase with increasing tree size in crown thinnings. In this analysis, we used tree stem diameter as predictor variable, as this is a size variable which is most frequently considered by test persons (Pommerening and Grabarnik, 2019). Stem diameter, d, is also closely related to thinning type and intensity, see Eq. (4). The binary nature of the tree-selection data suggests the use of simple logistic regression:

$$P_i^{(s)} = \frac{e^{\beta_0+\beta_1\times d}}{1+e^{\beta_0+\beta_1\times d}} \tag{5}$$

In Eq. (5), $P_i^{(s)}$ is the tree selection probability of test person i. Model parameter β_0 defines the location of the $P_i^{(s)}$ curve relative to the ordinate and is an expression of selection intensity whilst the slope parameter β_1 quantifies the strength of the influence of tree size on the test person's behaviour.

As a novelty in this study, we requested from the test persons to record for each tree selected for thinning the identification number or numbers of those frame trees that this eviction, in their opinion, was supposed to benefit. In the remainder of this text, we refer to this new feature as the *competitor-for-frame tree* rule. Using this information we were able to quantify the ratio of the basal-area sum, W_i, of trees j evicted to benefit frame tree i and the basal area, g, of frame tree i (Schütz, 2000):

$$W_i = \frac{1}{g_i}\sum_{j=1}^{k_i} g_j \tag{6}$$

In Eq. (6), k_i is the number of nearest neighbours j of frame tree i selected for eviction with the purpose of facilitating the development of frame tree i in the next 5–10 years. When trees are selected in accordance with silvicultural theory, W_i is typically large for small frame trees and decreases with increasing frame-tree size. For very large frame trees, W_i approaches 1 (Pommerening et al., 2021). We characterised observed W_i and thus the pattern implemented by test person i with a trend line based on the simple power function $\widehat{W}_i = b_0 \times d^{-b_1}$ with b_0 and b_1 as model parameters. For quantifying the variability of observed W_i in relation to this model trend curve and for quantifying the overall conformity of this characteristic with silvicultural theory, we calculated the efficiency measure

$$E = 1 - \frac{\sum_{i=1}^{n}(\widehat{y}_i - y_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}, \tag{7}$$

where $\widehat{y}_i$ is the ith prediction (modelled $\widehat{W}_i$ of the trend curve), y_i is the ith observation (observed W_i), n in this case is the number of frame trees for which a test person selected neighbouring trees for eviction and $\bar{y}$ is the mean observation. We also calculated relative bias (Eq. (8)) and relative RMSE (root mean square error; Eq. (9)) for $\widehat{W}_i$ using the same notation:

$$\text{r. Bias} = \frac{\sum_{i=1}^{n}(\widehat{y}_i - y_i)}{n\bar{y}}, \tag{8}$$

$$\text{r. RMSE} = \frac{\sqrt{\frac{\sum_{i=1}^{n}(y_i-\widehat{y}_i)^2}{n-1} + \left[\frac{1}{n}\sum_{i=1}^{n}(y_i - \widehat{y}_i)\right]^2}}{\bar{y}}, \tag{9}$$

Since the competitor-for-frame tree rule was not used in the British experiments, W_i was reconstructed from the British data using available tree location coordinates.

To broadly characterise aspects of forest structure, we also quantified the coefficient of variation of stem diameters v_d and the mean h / d ratio of the selected trees, i.e. the ratio of tree total height and stem diameter. All calculations were carried out using our own R scripts (R version 4.2.2; R Development Core Team, 2023) and the `irr` (Gamer et al., 2012) package.

3. Results

3.1. Agreement

The relative conformity numbers c_i' (Eq. (3)) of the Svartberget experiment are well within the point cloud of the British marteloscope experiments (Fig. 2). Neither for the selection of frame trees nor for the selection of their competitor trees the results justify the conclusion that the agreement achieved at Svartberget is statistically different from that achieved so far in Britain.

The general trend in the Swedish and in the British experiments as shown in Fig. 2 suggests that agreement decreases with increasing coefficient of variation v_d of selected tree stem diameters. The larger the agreement as expressed by c_i' the smaller is the variability of chosen stem diameters. In both data sets, this trend is stronger for frame trees (Fig. 2A) than for the neighbouring trees evicted to benefit the frame trees (Fig. 2B). This tendency suggests that there was more agreement on the selection of individual frame trees than there was on choosing competing neighbours.

Fleiss' κ characteristic (Eq. (1)) provides an agreement summary for whole experiments and the two data points of the Svartbarget experiment are situated in the lower part of the point cloud formed by the British experiments (Fig. 3A) suggesting that agreement was generally lower at Svartberget than it was in most of the British experiments. In both cases, $\kappa < 0.33$ which only qualifies for slight agreement, i.e. the second lowest agreement class in Table 2. There was some overlap between the data points of frame-tree and competitor-tree selection in Fig. 3A, however, the data point relating to the selection of the Svartberget competitor trees is well within the point cloud of the British frame-tree selection, i.e. the Svartberget data point is clearly outside the corresponding British data cloud. This result suggests a greater diversity of the proportions m / n of neighbouring trees selected and therefore a slightly larger agreement on the neighbouring trees of Swedish frame trees than in the British experiments.

Generally Fleiss' κ characteristic increases with the coefficient of variation r_m of the proportions m / n of trees selected. Large values of r_m are often caused by large values of P_0 and rapidly declining m / n proportions (Fig. 3B), which is typical of frame tree selections whilst the selection of frame-tree neighbours commonly produces more uniform m / n proportions (Pommerening et al., 2021). Considering P_0 and r_m, the point clouds relating to the selection of frame and competitor trees are more distinctly segregated (Fig. 3B) than when using κ instead of P_0 (Fig. 3A).

3.2. Tree selection preferences

Tree selection preferences can be studied by analysing the ratio B_i (Eq. (4)) and basal-area selection intensity $P_i^{(G)}$ involved in the

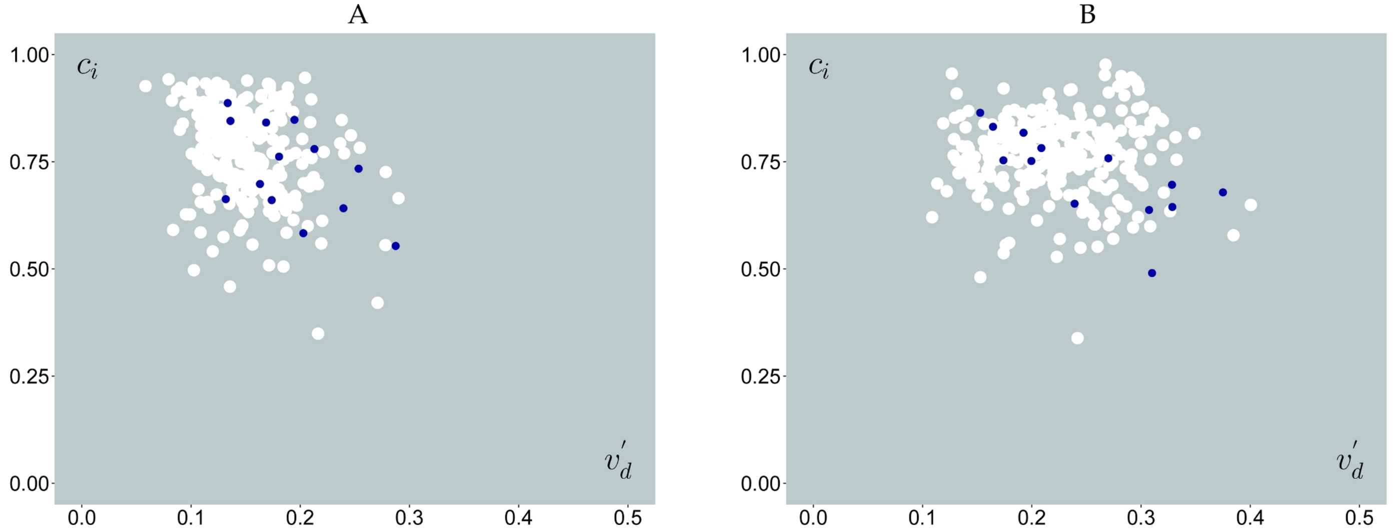

Fig. 2. Relative conformity numbers, c'_i (Eq. (3)), of the Svartberget (blue dots) and the British marteloscope experiments (white dots) depending on the coefficient of variation of selected stem diameters, v'_d. A: Frame-tree selection. B: Selection of potential frame-tree competitors amongst the nearest neighbours. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article.)

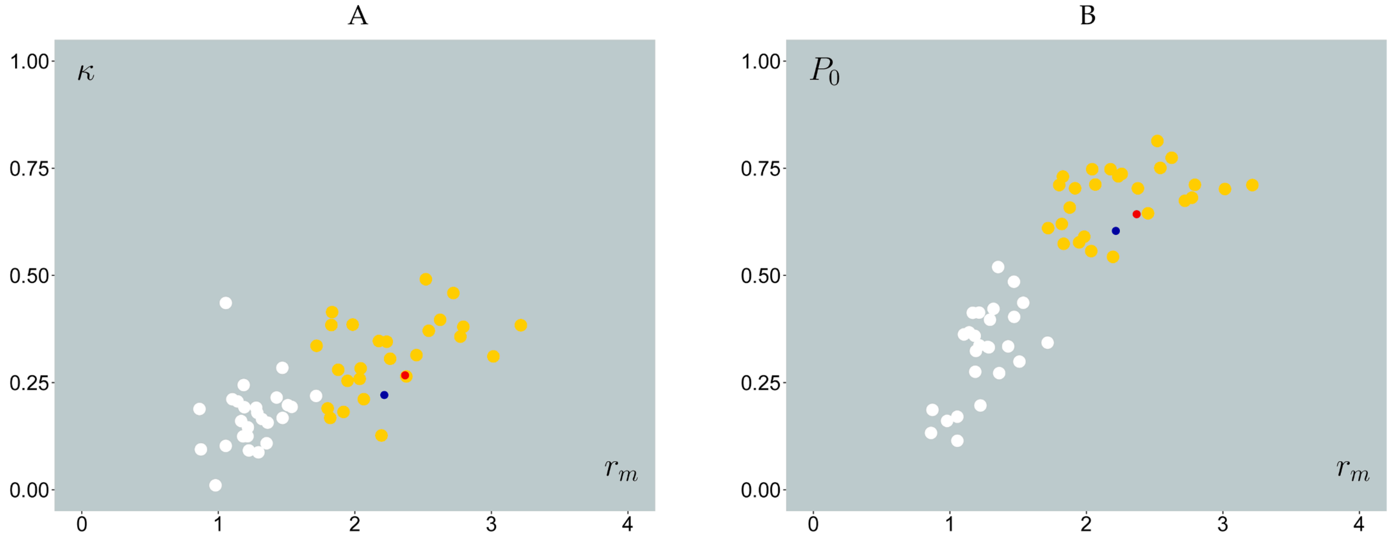

Fig. 3. Fleiss' κ characteristic (A, Eq. (1)) and the proportion of trees that were not selected by any test person, P_0 (B), in relation to the coefficient of variation of the proportions m / n of trees selected, where m is the number of trees that the test persons of a given experiment have chosen $k = 0, 1, \ldots, r$ times. The data points relating to the selection of frame trees are shown in gold (British experiments) and red (Svartberget experiment), whilst the data points relating to the selection of frame-tree competitors are shown in white (British experiments) and blue (Svartberget experiment). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

calculation of B_i (Fig. 4). Generally the British and the Swedish data clouds are more clustered and show less variability for the frame-tree (Fig. 4A) than for the frame-tree competitor (Fig. 4B) selection, which suggests a better agreement in the frame-tree selection. The Svartberget data points are in both cases located at the lower bounds of the British point cloud and in Fig. 4B some of the Swedish data points are even outside the confidence region.

This suggests that the tree selection at Svartberget was somewhat on the extreme side in terms of the ratio B_i which quantifies the tree-selection type. This is particularly remarkable in the case of the competitors of frame trees (Fig. 4B). In both cases of tree selection, the Svartberget results for B_i strongly point towards a consistent selection of the most dominant trees, as was requested from the test persons. In the British data, the B_i ratio achieved for selecting frame trees was generally lower than that for frame-tree competitors, i.e. the latter were markedly less dominant than the selected frame trees. In the Swedish data, the B_i ratio on average has the same magnitude for both types of tree selection. At Svartberget, selection intensity $P_i^{(G)}$ was on average slightly larger for frame trees than for their competitors which was not the case for the British data (Fig. 4).

The h/d ratio is an important resilience indicator of trees but also offers information on the frequency and intensity of past forest management interventions or disturbances (Pommerening and Grabarnik, 2019). There is also a natural trend of decreasing h/d ratios with increasing tree size (Fig. 5). The majority of the h/d ratio of trees selected at Svartberget are well within the confidence region created by the British data, although the Swedish h/d ratio values are generally rather large. This is particularly true for trees with a stem diameter

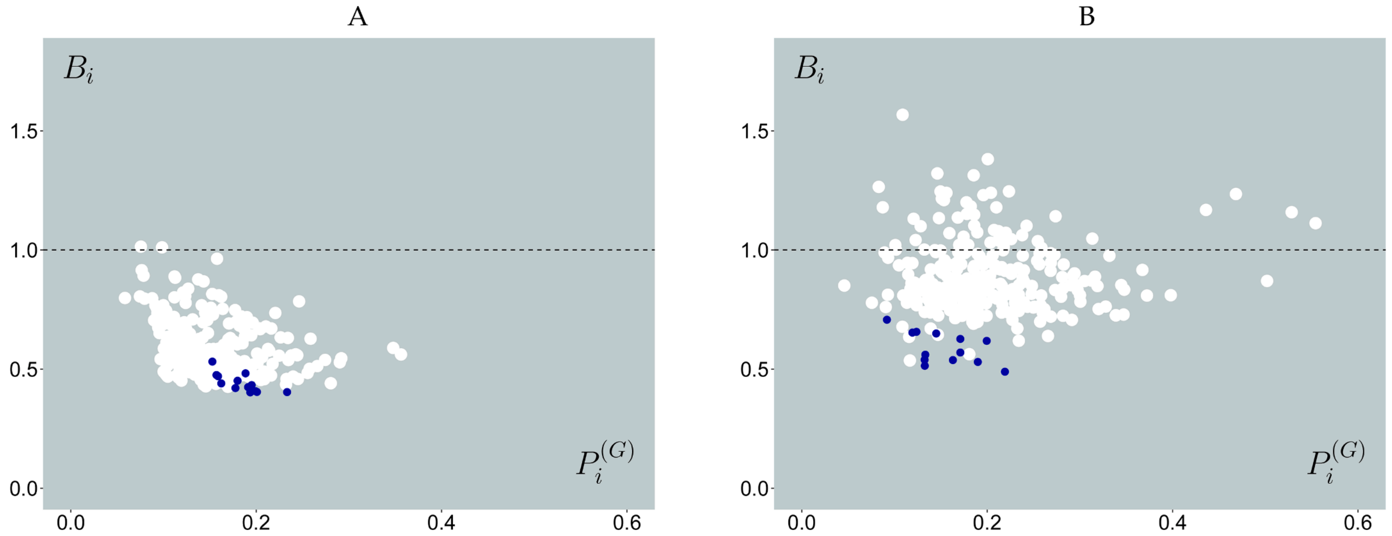

Fig. 4. B_i ratio (Eq. (4)) and basal-area selection intensity, $P_i^{(G)}$, of the Svartberget (blue dots) and the British marteloscope experiments (white dots). The dashed horizontal line through 1 marks the boundary between the selection of dominated and dominant trees. A: Frame-tree selection. B: Selection of potential frame-tree competitors amongst the nearest neighbours. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

larger than 15 cm.[1] Curiously, there is a group of smaller trees with $d <$ 15cm that were selected at Svartberget both as frame trees and frame-tree competitors and did not quite follow the common $h/d - d$ trend of the British data. Many of these small trees are therefore outside the confidence region. Most of these data points represent attempts to include *B. pendula* trees with small stem diameters and comparatively small h/d ratios in the tree selection. From a statistical point of view, this is a rather special result of the Svartberget experiment.

In the British data, there is a tendency for h/d ratios of selected frame trees (Fig. 5A) to be lower than those of their competitors (Fig. 5B), particularly in the case of trees with $d < 15$cm. This trend is only marginally reflected in the Swedish data, i.e. the h/d ratios of selected frame trees and competitors are largely the same.

We used logistic regression to quantify tree selection probabilities with stem diameter d as explanatory variable (Eq. (5)). For analysing the Swedish tree selection probabilities in the context of their British equivalents, we mapped the space of the two parameters β_0 and β_1 involved (Fig. 6). The Svartberget tree selection data points are inside the cloud of the British results. However, they are situated towards the lower bound of the corresponding British data point cloud, particularly the data points relating to the Swedish frame-tree competitor selection, both in terms of parameter β_0 and β_1 (Fig. 6B). This implies that both the selection intensity and the strength of influence exerted by stem diameter, d, were slightly lower than in most of the British experiments.

Generally for both countries involved, both parameters β_0 and β_1 showed a larger range of values, when frame trees were selected (Fig. 6A). This variation hints at subtle differences in the patterns of frame-tree selection which other measures such as the B_i ratio are not able to identify. For the selection of frame-tree competitors (Fig. 6B), some of the British β_1 parameters extended into the negative domain, which implies that the tree selection probability in these cases decreased with increasing stem diameter. In a thinning context, such behaviour typically leads to a thinning from below whilst positively signed parameters β_1 imply a crown thinning (Pommerening and Grabarnik, 2019). Neither in the British nor in the Swedish experiments can negative β_1 be found in the frame-tree selection, and these observations are consistent with those made for ratio B_i. For the Swedish experiment, even in the selection of frame-tree competitors no negative β_1 values occur which is a remarkable outcome.

3.3. Individual-based forest management

Finally, we analysed the ratio of the basal-area sum, W_i, (Eq. (6)) of evicted trees j and the basal area of the frame tree i (Fig. 7). Compared to the British curves describing the trend of W_i over stem diameter, d, the corresponding curve obtained from the tree selection data collected at Svartberget is rather flat and lies mostly outside the confidence region provided by the British curves for $d < 25$ cm (Fig. 7A). At first sight, this appears to somewhat contradict the near perfect results obtained for ratio B_i and the tree-selection probabilities, however, W_i is a more sophisticated characteristic that can be used to examine the trend of basal area ratios expected in individual-based forest management. Despite the introduction of the competitor-for-frame tree rule (see Section 2.2), the test persons participating in the Svartberget experiment only marginally followed this expected trend. Particularly for trees with stem diameters smaller than 25 cm, the competitor-basal area selected per frame tree was far too low (Fig. 7A).

We also quantified efficiency, relative bias and relative RMSE Eqs. (7)-(9) in relation to a simple power function with a view to quantify the variability of W_i and the compliance with the aforementioned trend (Fig. 7B). Overall efficiency was rather low with a median around 0.38. The efficiency value $E = 0.24$ obtained from the Svartberget experiment is below the lower quartile of the boxplot containing the British results. The relative bias produced by the Svartberget participants was 0.01 and therefore very close to the expected median of zero obtained from the British experiments. Since the median relative bias obtained from all experiments was roughly zero, variance of W_i must have had the greatest effect on relative RMSE. Mean relative RMSE of the British experiments was a little short of 0.50, but the corresponding value obtained from the Svartberget experiment was 0.90 and therefore even beyond the end of the upper whisker of the boxplot describing the British data. The results in Fig. 7B clearly emphasised that the Svartberget marteloscope results were not meeting the requirements with regard to individual-based forest management and that the test persons' decisions were very varied.

4. Discussion

Marteloscope experiments can be carried out for many different

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[1] To some degree this effect can be explained by the fact that trees of the same stem diameter growing on similar sites tend to be shorter in Britain than in Northern Sweden for the strong influence of wind throughout the UK. This influence decreases h/d ratios compared to sites that are less exposed.

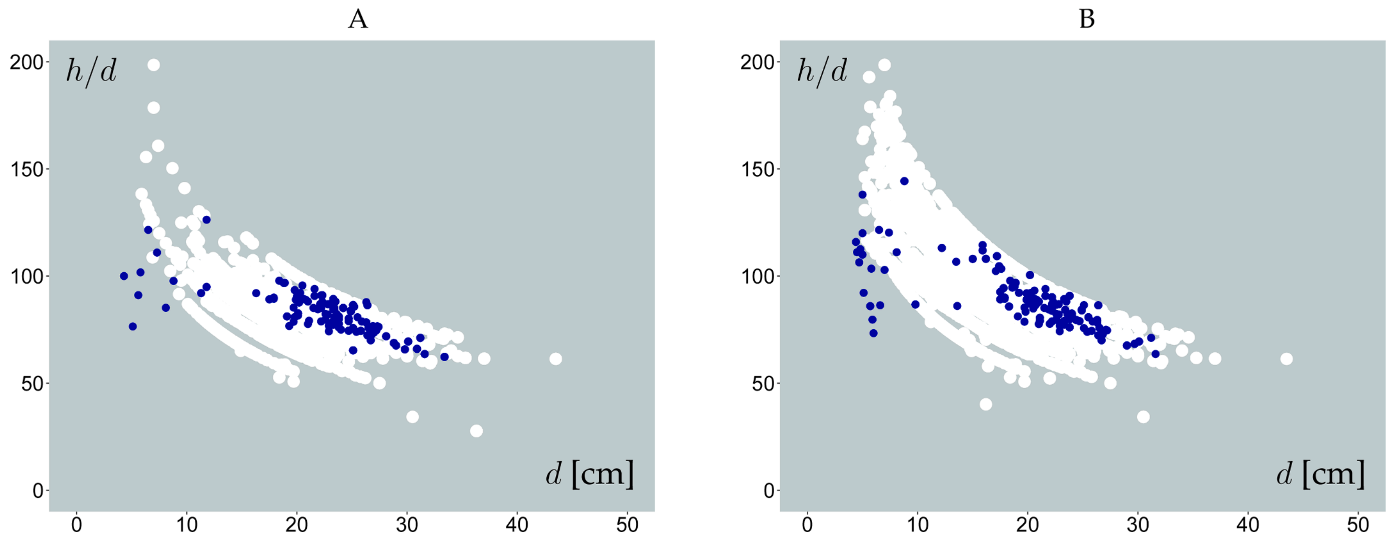

Fig. 5. h/d ratio and stem diameter, d, of trees selected in the Svartberget (blue dots) and the British marteloscope experiments (white dots). A: Frame-tree selection. B: Selection of potential frame-tree competitors amongst the nearest neighbours. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

purposes. Cosyns et al. (2018), for example, reported an application where test persons were asked to find a compromise between economic and ecological ecosystem goods and services when selecting trees for thinnings. The authors found that the selection of habitat trees, a form of frame trees selected for conservation purposes, was difficult for test persons in this context. Vítková et al. (2016) conducted marteloscope experiments with the aim to measure the success of encouraging test persons to switch from low to crown thinnings before and after training. Pommerening et al. (2020) proposed the use of marteloscopes in combination with multiwinner approval voting applied in political science for decision making in forest management and conservation. This can be a valuable tool in situations, where different stakeholders disagree on the best management solution. In this case, the marteloscope results can ensure that the opinion of each stakeholder is considered in the finalised intervention and the final decision is then a real group effort in a truly democratic sense.

Currently, CCF is being introduced to Sweden without prior training of forestry staff. To support this process, our long-term goal is to establish a benchmark for training, i.e. to use marteloscope experiments for understanding the state of the art of Swedish forestry staff in terms of applying CCF methods. Understanding how Swedish forestry staff currently respond to CCF instructions is of fundamental importance for defining a benchmark of CCF training. This benchmark is a pre-requisite for designing effective training at regional and national level.

In our first marteloscope application at Svartberget in Northern Sweden, we compared the results involving 13 test person with those from 26 experiments carried out in Great Britain. These 26 experiments involved 285 test persons and 14 different sites and were comparable in the sense that the management objectives of these experiments were the same as at Svartberget, i.e. frame-tree based forest management and crown thinnings. A comparison of the behaviour of Swedish and British test persons is useful, because in both countries most forest managers participating in marteloscope experiments have a strong RFM background with little or no experience and skills in CCF. In this paper, we

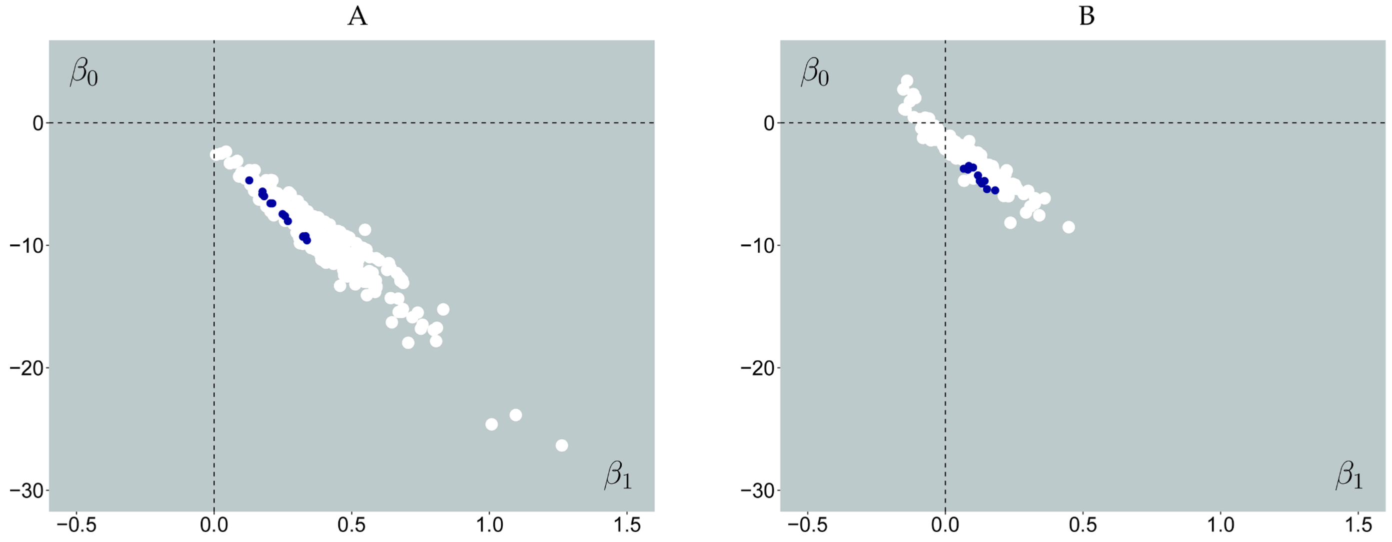

Fig. 6. Parameters β_0 and β_1 of the logistic regression used to quantify tree selection probabilities with stem diameter, d, as explanatory variable (Eq. (5)). The parameter values obtained from the Svartberget experiments are shown as blue data points whilst those observed in the British marteloscope experiments are given as white data points. The dashed lines are aids for orientation. A: Frame-tree selection. B: Selection of potential frame-tree competitors amongst the nearest neighbours. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

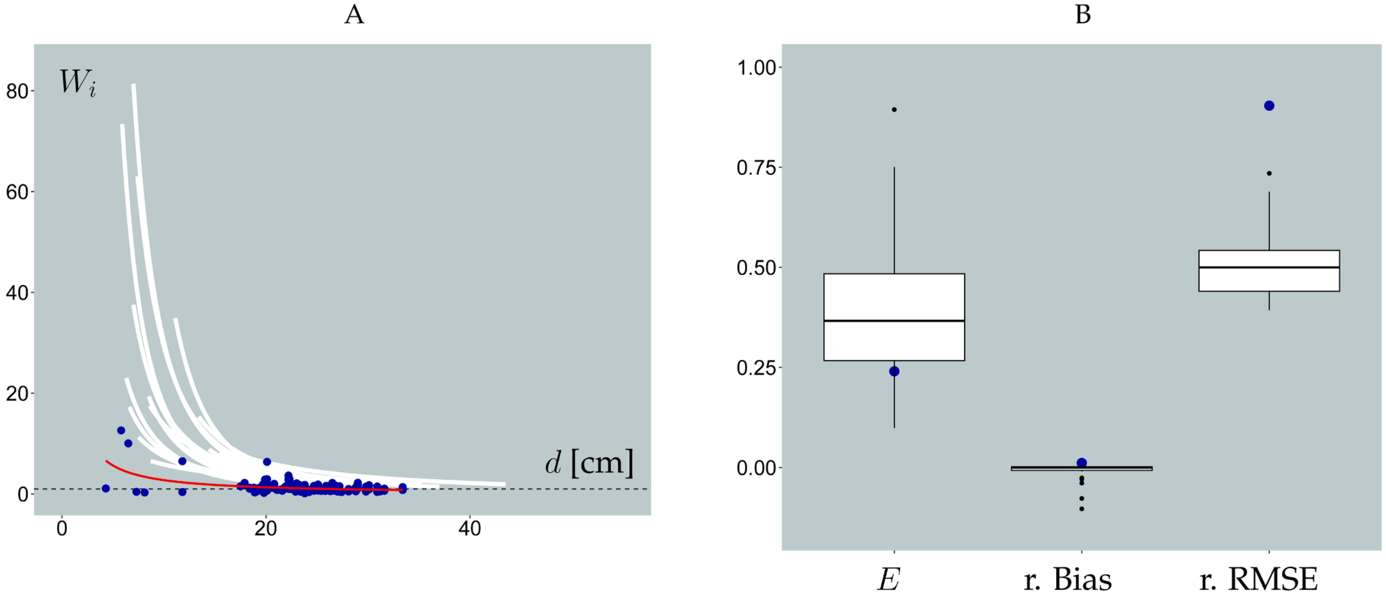

Fig. 7. A: Ratio of basal-area sums, W_i (Eq. (6)), of evicted trees j and the basal area of the frame tree i in relation to stem diameter d of the Svartberget (blue dots and red curve) and the British marteloscope experiments (white curves). For clarity the British data are represented by trend curves only, for which the power function $\widehat{W}_i = b_0 \times d^{-b_1}$ with model parameters b_0 and b_1 was used. The dashed horizontal line marks $W_i = 1$, where cumulative competitor-basal area and frame-tree basal area break even. B: Efficiency (E), relative Bias (r. Bias) and relative RMSE (r. RMSE) obtained from the British experiments (boxplots) and from the Svartberget experiment (blue dots). (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

have therefore piloted a new technique involving the use of data from the 26 available British marteloscope experiments for constructing equivalents of statistical confidence regions. This method was feasible, because the British experiments were well spread throughout the country and represented very different situations in terms of site conditions, tree species mixture and tree density (Table 1), but most importantly they included a high diversity of tree-selection patterns. This is the reason why we considered any of the Swedish Svartberget data that are outside this confidence region to be special and these cases deserve the attention of researchers, forest practitioners and policy makers in Sweden. Many of these special cases should be addressed in future CCF training.

The overall low agreement in individual-tree selection in terms of κ and P_0 was not statistically different from the patterns observed in Britain (Fig. 3A and B). Unusual, however, was the elevated agreement in selecting potential frame-tree competitors. According to earlier research, this task usually is the most difficult part of tree selection (Pommerening et al., 2021). Either the Swedish test persons at Svartberget were more skilled than the British test persons or the newly introduced competitor-for-frame tree rule (see Section 2.2) has helped consolidate the selection of frame-tree competitors. Better agreement in the selection of both frame trees and frame-tree competitors was also suggested by ratio B_i (Fig. 4). Here it is particularly likely that the competitor-for-frame tree rule has had a considerable didactic influence, since such low values implying the selection of few but very dominant trees in the first marteloscope experiments of this kind are rather unprecedented (cf. Vítková et al., 2016). When examining the test persons' record sheets, it came to light that numerous persons reflected on their choices and revised them whilst implementing the competitor-for-frame tree rule. Usually the switch from low to crown thinnings is hard to accomplish for experienced forest practitioners in countries with a strong RFM background. It is possible that the good results in terms of B_i were partly owed to the fact that 60% of the test persons were inexperienced forestry staff. Vítková et al. (2016) found that implementing crown-thinning principles is more difficult for test persons experienced in RFM than for inexperienced forestry staff (referred to as the *experience paradox*). The significantly low B_i ratios observed for the competitor selection at Svartberget (Fig. 4B) are consistent with the κ results for the same tree selection.

In terms of the h/d ratio, a group of *P. pendula* trees with a stem diameter $d < 15$ cm selected as frame or competitor trees appeared to be outside the confidence region created by the British data (Fig. 5). This anomaly is the result of attempts to actively include the small-diameter population of this species in future stand management. It was evident that there was hardly any difference between the h/d ratios of frame and competitor trees in the Svartberget experiment. According to silvicultural theory, frame trees are usually selected to have lower h/d ratios than their competitors, since the former are permanently exposed to wind and snow and need greater stem diameters to withstand these disturbance agents for a very long time (Pommerening et al., 2021).

The tree selection probabilities estimated for the Svartberget experiment were largely consistent with the results obtained for the B_i ratios. Remarkably, no negative values of slope parameter β_1 were observed even in the selection of frame-tree competitors (Fig. 6B) at Svartberget, which again emphasises the consistent selection of few but dominant trees by the 13 Swedish test persons even for competitor trees. This finding is not consistent with research results from Britain and Ireland, where markedly more agreement has been found for the selection of frame trees than for the selection of competitor trees (Vítková et al., 2016; Pommerening et al., 2021).

The ratio of the basal-area sum, W_i, of evicted trees and the basal area of the corresponding frame tree measures the success or failure of the newly introduced competitor-for-frame tree rule and helps assess people's skills in individual-based forest management. The power function modelled for the Svartberget tree selection was mostly outside the confidence region formed by the corresponding British functions (Fig. 7A). It is evident that the Swedish test persons did not select sufficient competitor basal area for individual frame trees with $d < 25$ cm. This finding was supported by the efficiency and relative RMSE measures (Fig. 7B) and clearly conflicts with the objective of frame-tree or individual-based forest management which is part of the CCF concept and accordingly was also part of the experiment at Svartberget. This conflict was not unexpected, since individual-tree silviculture is reportedly hard to adopt in countries where RFM dominates (Pommerening et al., 2021).

The deviations of the Swedish results from earlier results made in

Britain and Ireland may partly also be explained by the more complex forest stand structure at Svartberget which is reflected by the high stem-diameter coefficient of variation, v_d, in Table 1. Pommerening et al. (2018) found circumstantial evidence that tree selection is perceived as being easier in structurally more complex than in simple-structured forests.

5 Conclusions

On the assumption that the tree selection behaviour of the 13 test persons involved in the marteloscope experiment at Svartberget are somewhat representative of (Northern) Sweden, our results suggest that more intensive training is required in individual-based forest management, i.e. in forest management where all silvicultural activities focus on frame trees (Pommerening et al., 2021). The properties of frame trees, e.g. their h/d ratios, as opposed to those of their competitors, need to be pointed out in detail in such training and illustrated in field trips. This training needs to be supported by hands-on exercises in the forest, where trainees actively select frame trees under the guidance of experienced trainers. During these exercises, trainers need to explain the requirement to apply higher, individual-tree competitor selection intensities to smaller as opposed to larger frame trees. Future marteloscope experiments in Sweden will consolidate our initial training benchmark by incrementally adding new information on human tree selection behaviour and thus help consolidate the national training benchmark. There is circumstantial evidence that the introduction of the newly introduced competitor-for-frame tree rule has turned out to be an important didactic tool for CCF training and this indication should be explored more in the future. The continued use of this rule is clearly recommended, especially in a training context. Using data from other marteloscopes with a similar forest management background has proved to be a useful technique for identifying unusual results in one-off marteloscope experiments. This new technique should also be explored further in future experiments and facilitated by the introduction of specialised national and international repositories for marteloscope data. Such repositories should include the data of the trees involved as well as the recorded choices of the test persons.

Author contributions

A.P. and L.K. conceived the project idea and designed the methodology. C.E., J.W. and A.P. selected the marteloscope site. J.W. and L.K. collected the tree data in collaboration with Svartberget field staff. J.W. and L.K. invited the test persons and carried out the experiment. L.K. and A.P. analysed the experimental data and wrote the first manuscript draft. A.P. and B.T.E. co-authored a recent Formas (Swedish government research council for sustainable development) project proposal that included ideas and concepts used in this paper. C.E., J.W. and B.T.E. commented on various drafts of the text.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data and R scripts will be made available on request.

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