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Tamm Review: Individual-based forest management or Seeing the trees for the forest

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ABSTRACT

In the last century, local or individual-based forest management was introduced by various forest scientists including Schädelin, Abetz and Pollanschütz as an alternative to traditional global thinning methods. They suggested breaking large forest stands down into smaller neighbourhood-based units. The centre of each of these neighbourhood-based units is a frame tree (also referred to as final crop tree, elite tree or target tree) with clearly defined properties that depend on the management objectives. In each management intervention, trees in the neighbourhood of frame trees that in the next 5–10 years are likely to influence the frame trees negatively are removed selectively. In contrast to global methods, management is only carried out where there are frame trees. Local or individual-based forest management methods were first introduced in a commercial forestry context, but rather constitute generic methods that can be efficiently applied in management for conservation, carbon sequestration and recreation. They are also often applied in the context of continuous cover forestry (CCF).

In this study, we analysed the behaviour of test persons selecting frame trees in 26 training sites, so-called marteloscopes, from all over Great Britain. Although the test persons were new to individual-based management, statistical performance indicators suggested that frame trees were selected in accordance with the theory of local or individual-based forest management. Unexpectedly the test persons even achieved a comparatively high degree of agreement. This result contrasts the low agreement and partly unsatisfying performance indicators incurred in the selection of frame-tree competitors, the second step of local forest management. The outcomes of this study highlight that training in individual-based forest management needs to put more emphasis on the identification of frame-tree competitors.

1. Introduction

The introduction of *local* or *individual-based* forest management was a fundamental change in paradigm, because this concept includes the strategy of breaking a large forest stand down into smaller neighbourhood-based units that Schädelin (1934) referred to as *thinning cells*. A small number of clearly defined individual trees form the centres of these management units and all efforts are exclusively directed towards these trees rather than towards the forest stand as a whole, as this is typically done in traditional, *global* forest management (Pommerening and Grabarnik, 2019). In this paper, these special trees are referred to as frame trees. For a forest operator marking trees or for a forest harvester driver, the small management units or thinning cells are more natural to perceive and easier to work through one by one.

Frame-tree management is frequently associated with continuous cover forestry (CCF) and is often marginalised as a technicality assisting forest managers to put CCF into practice (Wilhelm and Rieger, 2018; Bartsch et al., 2020). Judging by the absence in the literature of attempts to generalise the concept of individual-based forest management beyond economic scenarios even in countries such as France, Switzerland, Austria and Germany where these methods were first devised, forest scientists and practitioners appear not to be fully aware of the enormous difference the introduction of these concepts has made to forestry and conservation and of the great potential individual-based forest management has for delivering ecosystem goods and services.

The objectives of this article therefore were (1) to review the general

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methods and techniques of individual-based forest management without intimate reference to specific forest management objectives. Such specific references are often made in silvicultural textbooks and as a result the generic elements of the methods are lost. The second objective was (2) to analyse the behaviour of test persons who were asked to select frame trees in 26 experiments carried out throughout Great Britain. The behaviour of test persons selecting frame trees has not been studied before and this analysis explicitly considers the human component of local forest management methods, when introducing them to novices.

1.1. *Definition and terms of individual-based forest management*

Individual-based forest management is a bottom-up approach where in a *first step* a number of trees with certain characteristics matching the forest-management objectives are selected and visibly marked in the field. In this paper, following British convention, these trees are referred to as *frame trees* (also termed final-crop trees, target trees, plus trees, elite trees) for the appealing metaphor of a framework of special trees that form the backbone or resilient scaffold of a forest stand or a tree population (Pommerening and Grabarnik, 2019). Frame trees are supposed to stay on in the forest stand long-term and most importantly to benefit from any future forest operation. To achieve this, in a *second step*, based on the nearest-neighbour principle, trees in close proximity of frame trees are selected that are likely to influence the frame trees negatively in the next 5–10 years (Fig. 1). For instance, in temperate climates, the most important criterion is to ensure that the crown growth of frame trees is not obstructed by neighbours. In arid and boreal climates, where competition for light is less important, other environmental criteria must be used. Forest managers identify competitive neighbours as an ecological interpretation of the individual frame tree's "eye view". Whilst lacking more direct measures, competitiveness is usually defined by a combination of size (crown and total height) and intertree distance (Klädtke, 1993; Pommerening and Grabarnik, 2019).

In each local thinning, only the neighbourhood of frame trees is considered, hence the term "local thinning method" (Pommerening and Grabarnik, 2019). This is a selective process of low-impact forest management in the sense that neighbours are considered for removal only, if absolutely necessary so that in the same intervention with some frame trees no neighbour, with others one or two and again with others perhaps three neighbours are selected for removal. This decision is a compromise between promoting the frame trees' growth and promoting their functional properties, e.g. timber quality or habitat value. Everything else in the forest stand, particularly where there is no frame tree, is strictly left to natural processes without human interference. All non-frame trees can be referred to as *matrix trees* and an important part of their role is to serve frame trees through "mild, healthy competition" and provide by-products such as habitats, local climate, energy wood or pulp (Pommerening and Grabarnik, 2019). As mentioned earlier, frame trees and their immediate neighbours form a mosaic of small local management units (Schädelin, 1934) and it is important to consider neighbouring units when selecting new frame trees so that the distances between them are not too short and the removal of competitors is coordinated between units. By contrast, *global thinnings* are traditional methods and aim at affecting the whole forest stand in a uniform fashion.

In a way, frame-tree selection as part of individual-based forest management also serves as a didactic aid that helps field staff to separate "important" from "unimportant" trees regardless of the definition of importance. In our experience, it frequently happens that even forestry professionals unfamiliar with individual-based forest management are at a loss when asked to select trees for thinnings for the first time. They simply "cannot see the trees for the wood" and the frame-tree method literally is an eye-opener fostering their observation skills and perception (Pommerening and Grabarnik, 2019).

The frame-tree method can even be applied in intensively mechanised forest management. It suffices to mark frame trees permanently and in a clearly visible way. It is perceivable that after initial training harvester drivers can be trusted to select frame-tree competitors whilst driving through a forest stand and carrying out the thinning (Eberhard and Hasenauer, 2021). Marking frame trees is an effort that is required only once in the life time of a forest stand. The fact that all thinnings are oriented towards frame trees and occur in their neighbourhood leads to greater efficiency of management operations through a rationalisation of efforts. At the same time, harvesting, extraction or bark-stripping damage (caused by animals such as deers and grey squirrels) only matters, if frame trees are affected (Klädtke, 1993).

1.2. *History of individual-based forest management*

Early forest-management methods had their origin in agriculture and in analogy to agricultural fields it seemed "natural" to consider whole forest stands and their global characteristics when assessing timber sustainability rather than individual trees. Towards the end of the 19th century systems based on forest stands such as the *normal forest* were devised to ensure timber sustainability (Gadow and Bredenkamp 1992; Hasel and Schwartz, 2006; Bettinger et al., 2017). For some time alternative approaches based on individual trees such as the single tree selection system were even legally banned in various European countries, since it was believed that timber sustainability could not be guaranteed when they were applied because of a lack of refined methodology and widespread timber thefts (Schütz, 2001b). The stand approach also influenced research and supported a focus on unit-growth responses to different management strategies including yield tables as forecasting and planning tools.

The fundamental idea of individual-based forest management has roots that apparently go as far back as 1763 when Duhamel du Monceau mentioned the use of frame trees for oak management in France (Klädtke, 1993; Schütz, 2003). In the 19th century and at the beginning

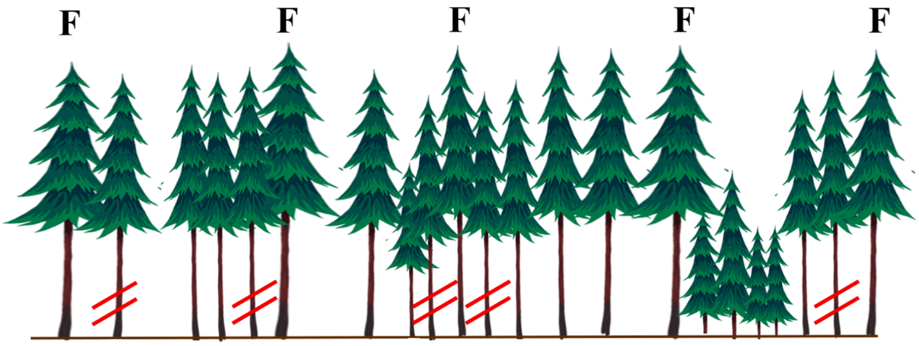

Fig. 1. Sketch of an imaginary single-species conifer forest. The frame trees are indicated by the letter 'F' and the stems of neighbours selected as perceived frame-tree competitors are crossed by double red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the 20th century, the concept was gradually introduced to commercial forestry applications in Austria, Germany and Switzerland, initially with little success and limited uptake. Then Schädelin (1926, 1934) and his successor Leibundgut (1966) systematically developed and promoted the concept in Switzerland, which they referred to as “Auslesedurchforstung” (selective thinning). The rationale of this method was to concentrate commercially valuable timber on just a few trees, i.e. the frame trees as opposed to maximising overall volume production of a forest stand, which was the traditional objective of forestry at the time. This implied that a lower overall yield was accepted provided that the frame trees and their management in the long term produced an economic surplus (Knoke, 1998). Schädelin’s original idea was to work with non-permanent frame trees, i.e. in each intervention, new frame trees would be selected, which could, of course, largely overlap with the frame trees selected in the previous intervention, but did not have to. Schädelin also proposed to initially appoint a large number of frame tree *candidates* (also referred to as *potential* crop trees) in early stand-development phases, which were later reduced to a smaller, definite number. The definite frame trees would then be promoted in later stand development phases through heavy release thinnings, i.e. by providing ample space around the crowns of each frame tree. Along with a number of precursors and colleagues, Abetz (1975, 1976) in Germany and Pollanschütz (1971, 1981, 1983) in Austria modified this concept by advocating a permanent selection of frame trees, which they referred to as Z-Bäume (“future” or “target” trees from German “**Z**ukunft” and “**Z**iel”). Permanence of frame trees is often ensured by visibly marking frame trees with ribbons or spray paint in the field and this has proved to be good practice. Abetz did not suggest heavy release thinnings in later stand development phases but recommended the continuation of frame-tree based thinnings. He also suggested selecting right from the start only such a number of frame trees that corresponded to the definite number of frame trees. Theoretically, the maximum definite number of frame trees is the number that can be supported by a given mature forest stand shortly before harvesting would commence. To mark the differences to Schädelin’s original idea, the Abetz/Pollanschütz approach was referred to as “Z-Baum-Durchforstung”, i.e. frame-tree thinning, however, this separation of terms is artificial, as from a theoretical point of view both approaches are essentially two variants of the same general individual-based concept.

Abetz’ and Pollanschütz’ approach of selecting only a definite number of permanent frame trees triggered a long debate that took place among practitioners and researchers about the risks associated with frame trees eventually dying, getting damaged or differentiating in any unfavourable way (e.g. becoming less dominant, getting exposed to bark stripping by deer or grey squirrel, deteriorating in timber quality) (Abetz, 1990; Dittmar, 1991; Klädtke, 1990; Schober, 1990; Spellmann and Diest, 1990). The debate reached its zenith around 1990. Part of this debate included Schädelin’s original idea of, as briefly mentioned before, initially appointing a larger number of frame tree candidates from which later, when eventually it has become clearer, if the trees were suitable, a smaller number of definite and permanent frame trees is recruited. However, research and field experience suggest that the risk of losing frame trees is low, if (1) they are not selected too early (Mosandl et al., 1991), (2) they are recruited from the most dominant trees of the forest stand, (3) their number is comparatively low, i.e. not more than approximately 150 trees per hectare, and (4) they are consistently favoured in regularly recurring interventions (Klädtke, 1997). Initially working with candidate frame trees has turned out to be an unnecessary complication (particularly with beginners) and usually leads to confusion and inconsistent management (Bartsch et al., 2020), where the fundamental idea of focussing on individual trees is gradually abandoned in favour of global stand management. Along similar lines, it has also been found to be more efficient to appoint permanent frame trees that are visibly marked in the field.

The trend towards individual-based forest management was supported by the advance in computer technology. Towards the late 1970s the increasing availability of individual-tree data and computing resources gave rise to new analysis and modelling methods that made individual-tree approaches even more feasible and particularly helped with checking up on timber and other forms of sustainability.

Numerous variants of the local-thinning and frame-tree concept are now applied in many European countries and occasionally also in North America and more recently in China (Pommerening and Sanchéz-Meador, 2018).

1.3. How and when frame trees are selected

Frame trees are essentially “trees of interest” or “trees of importance” that can be flexibly defined in various ways, e.g. in terms of economic value, habitat value, stand resilience, spiritual or aesthetic value. This implies that individual-based forest management can be applied in commercial forestry as well as in conservation and recreation management, since it is a general concept. Even in plantation management, individual-based methods can be implemented and make sense. In the absence of better information a good “rule of thumb” and default is to select approximately 100 frame trees per hectare. In broadleaved forests, where trees usually have larger crowns than conifers, 60–80 trees per hectare are appropriate whilst the number can range between 100 and 150 in conifer forests. Alternatively, the corresponding distances between frame trees of 10–15 m can be used as a reference in practical implementation (Wilhelm and Rieger, 2018). For conservation and for the transformation of plantations to CCF or when the selection process is delayed, 50 frame trees per hectare suffice (Schütz, 2001a). Much larger frame-tree numbers were recommended in the past (Schädelin, 1934; Abetz, 1975; Pollanschütz, 1981), but these original numbers created problems and have largely been abandoned. Too many frame trees usually lead to homogeneous stand structures and leave too few options for identifying trees to be thinned and consequently crown releases of frame trees are too weak. On the contrary, selecting too few frame trees may not use the full potential of a forest stand and leaves large parts of the forest virtually unmanaged.

Frame trees are selected at a comparatively early stage of stand development, e.g. when a top height of 12–15 m is reached. In conifer forests, the selection of frame trees usually starts at lower top-height values than in broadleaved forests (Klädtke, 1993). If the necessary growth data are available, a more refined criterion for the appropriate timing of selecting frame trees is the species-specific growth pattern on a given site: Once the culmination of height growth has occurred, the selection of frame trees can begin, otherwise it has to be postponed (Pretzsch, 2009). Frame trees are selected according to clearly defined criteria and these depend on the forest management objectives. For example in commercial scenarios, typical criteria are *vigour*, *timber quality* and *dispersion* (in this order) whilst in a conservation or in a recreation setting some of these are replaced or complemented by other criteria such as *habitat value*, *aesthetic value* and *species*. Such criteria can be flexibly amended according to changing management objectives, changing climate and shifting societal expectations. However, vigour is likely to be the most important and generic criterion across a wide range of management objectives, as the frame trees are otherwise difficult to maintain. Frame trees are therefore always likely to be the most dominant and prolifically growing trees of a forest stand or at least dominant within the respective species population in mixed-species stands. Dispersion and distances between frame trees are often referred to as the least important criterion, however, when appointing frame trees it is crucial that they never compete with each other. A good spread of frame trees across the whole stand area also avoids creating patches that are never thinned, although this is not necessarily a bad thing. Often unthinned parts of a forest stand are not a problem or in a conservation context are even desired, but on upland sites and with species that are susceptible to windthrow or with infectious diseases/bark beetle infestations that can spread in dense neighbourhoods they can increase the negative effects of disturbances (Pommerening and Grabarnik, 2019). A selection of frame trees according to vigour as the most important criterion often helps to establish a regular dispersal of frame trees at the same time, since competition processes often naturally enforce larger distances between dominant trees. Heterogeneous environmental conditions (e.g. soil depth and moisture), for example in upland forest ecosystems, can make it sometimes necessary to take natural trends into account by allowing clustered arrangement of 2–3 frame trees in groups. In such situations, it is necessary to provide large distances between the groups so that the frame trees can tap into resources from outside the groups (Busse, 1935; Mülder, 1990). In mixed-species forest stands, the frame trees can be recruited from the different species populations to reflect a desired future species composition or to meet conservation targets (Fig. 2).

Along similar lines, in a conservation scenario, native trees can act as frame trees whilst their competitors are non-native species or even invasive neophytes forming the matrix. Since the question of how many frame trees should be selected depends on species-specific crown sizes and these again partly depend on environmental conditions, it is theoretically possible to calculate a suitable maximum number of frame trees for a given target diameter. The target diameter defines the harvestable tree size, i.e. as soon as a frame tree's diameter at breast height has reached the target diameter, it can be removed from the site for whatever purpose. In conservation scenarios, target diameters can be replaced by expected maximum diameters for a given species and site. Common advice suggests staying well below the potentially possible frame-tree numbers, particularly, if it is intended to achieve a diverse horizontal and vertical woodland structure (Weihs, 1999). Since frame trees tend to reach their target diameters at different times and harvesting is often delayed, the removal of frame trees is staggered in time. Before their ultimate removal frame trees are meant to contribute offspring to the next forest generation and some of them can act as seed or habitat trees that are left in the forest until they die of natural causes.

1.4. *How frame trees are managed*

In the past, it was recommended to carry out several stem-number reduction thinnings before commencing frame-tree management (e.g. Abetz, 1975). However, as such thinnings (sometimes referred to as pre-commercial thinnings or respacings) are very expensive, they have largely been abandoned as part of *biological rationalisation*, where such operations are left to self-thinnings, i.e. to processes involving natural morality, and to natural size differentiation. Exceptions are made for species with flat root systems or in forest stands where infections took hold (Wilhelm and Rieger, 2018).

Frame trees are supported in local thinnings either by removing all other trees within a certain radius around each frame tree, e.g. in young stands, where neighbouring trees have so far differentiated little, or by selecting a certain number of most competitive neighbour trees (in middle-aged and older forest stands). In middle-aged forest stands, the selection of competitor trees around each frame tree automatically implies the crown thinning method. Later, when the frame trees are by far the most dominant trees of the forest stand and well looked after, frame-tree based thinnings can turn into low thinnings. It is also possible to stop thinnings altogether at that stage.

In low thinnings, otherwise known as thinnings from below, trees are removed mainly from the lower canopy and from among the smaller diameter trees (Helms, 1998). The main objective of this type of thinning is to promote the growth of larger trees by removing smaller ones. This effect, however, is only achieved in heavy low thinnings, i.e. low thinnings with a high thinning intensity (Pretzsch, 2009). In crown thinnings, also referred to as thinnings from above, trees are removed that are part of the main stand canopy in order to favour the best among the most dominant trees by removing their direct competitors (Helms, 1998). Crown thinnings are instrumental in diversifying forest stand structure and, due to the larger sizes of evicted trees, they also often lead to greater revenues in commercial forestry scenarios compared to low thinnings. Crown thinnings are also the main intervention method in CCF (Pommerening and Murphy, 2004).

The thinning type can also differ from frame tree to frame tree depending on its size and dominance. To remain within the boundaries of local forest management methods, thinning intensity is defined by the number of competitors or by the sum of basal area of competitors to be removed in the vicinity of each frame tree. Sometimes the sum of basal area is divided by the basal area of the frame tree (Schütz, 2000; Fig. 3).

Although there is a considerable variance, the two examples from Ardross and Cannock Chase clearly show that the relative cumulative basal area of frame tree competitors decreases with increasing frame-tree size, i.e. larger more dominant frame trees need less removal of competitors (or smaller trees are removed) than less dominant frame trees (Fig. 3). As frame trees become larger and more dominant, the trend curve approaches the horizontal line through 1 where the basal areas of competitor(s) and frame tree break even.

As Fig. 3 has demonstrated, thinning intensity can obviously differ from frame tree to frame tree depending on the local release requirements of the tree in question, however, default numbers can be defined as follows: On average a removal of 0–2 frame-tree neighbours qualifies for a weak thinning, 2–3 neighbours for a moderate thinning and 3+ neighbours for a heavy thinning. Local thinnings typically follow the growth dynamics of forest stands, particularly the tree crown-width development. Therefore thinning intensity in local thinnings is heavy early in stand development and weak towards mature, old-growth stages when tree growth is much reduced (Bartsch et al., 2020). This temporal trend of thinning intensity can in principle also be derived from Fig. 3.

Contributing to efficiency, the success of thinnings can be more easily checked in subsequent years, as only the frame trees need to be assessed. This rationalisation advantage of local thinnings clearly

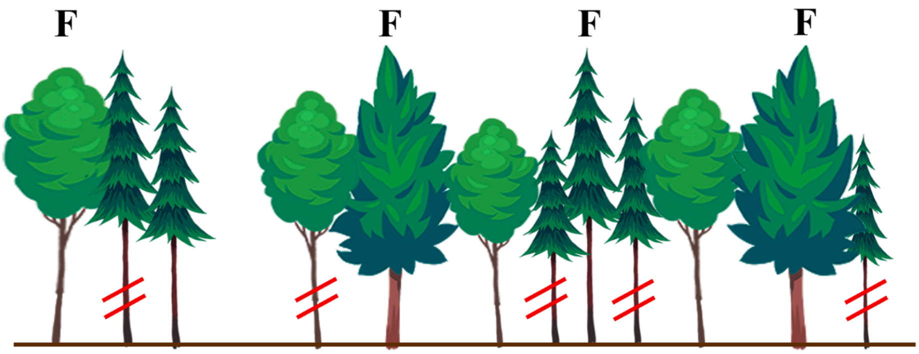

Fig. 2. Sketch of an imaginary mixed-species forest where frame trees were recruited from different species populations to support tree species diversity. The frame trees are indicated by the letter 'F' and the stems of neighbours selected as perceived frame-tree competitors are crossed by double red lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

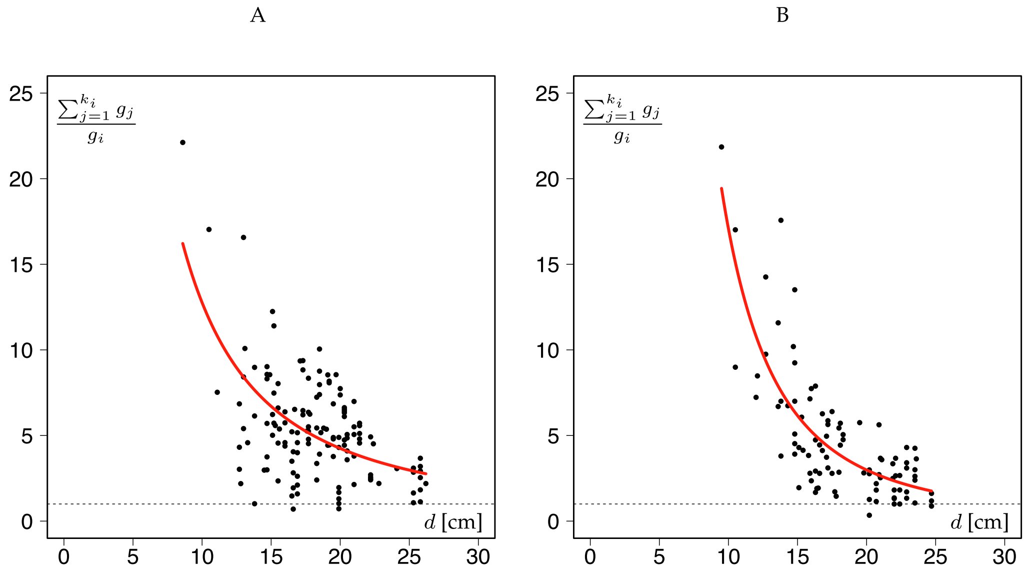

Fig. 3. The relationship between the stem diameter at breast height, *d*, and the ratio of sum of competitor basal area and frame-tree basal area for the marteloscope experiments Ardross 2013 and Cannock Chase 2012. g_i – frame-tree basal area, g_j – competitor basal area, k_i – number of competitors of frame tree *i*. The red trend line has been modelled using a simple power function. The dashed line marks the ratio value of 1.0, where cumulative competitor basal area and frame-tree basal area break even. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

supports the concept of permanent frame trees, since only then management success or failure can be reliably identified and thus treatments become more consistent (Klädtke, 1993; Pommerening and Grabarnik, 2019).

Abetz and Klädtke (2002) recommended checking up on the performance of frame trees by monitoring the ratio of total height and stem diameter (h/d ratio) as a performance indicator: Increasing h/d ratios of frame trees imply that neighbouring tree crowns are closing in and as a consequence, the frame tree allocates more biomass to height than to diameter growth. The larger the h/d ratio the more the stem diameters of frame-tree neighbours including potential competitors approach the size of the frame tree's stem diameter and reduce its diameter growth rate. A typical quantity illustrating the fundamental role of the h/d ratio in monitoring thinning requirements is the *A* thinning index that was suggested by Johann (1982):

$$dist_j^{\text{crit}} = \frac{h_i}{A} \times \frac{d_j}{d_i}, \tag{1}$$

The index defines a critical distance, $dist_j^{\text{crit}}$, between frame tree *i* and its nearest neighbours depending on the thinning-intensity parameter *A*. Any neighbouring tree *j* being located closer to tree *i* than the critical distance $dist_j^{\text{crit}}$ needs to be removed according to this measure. Frame trees with a larger h/d ratio are relatively more heavily released than those with a smaller h/d ratio. Values of *A* are theoretically continuous, however, Johann (1982) defined discrete values from 4 to 8 with decreasing thinning intensity, i.e. 4 – very heavy and 8 – very weak thinning. It is also possible to re-arrange Eq. (1) to solve it for *A* whilst replacing $dist_j^{\text{crit}}$ by the observed distance between neighbour tree *j* and frame tree *i*. $\max(A_i)$ is then a frame-tree specific thinning intensity parameter (Hasenauer et al., 1996). The *A* thinning index also demonstrates the nearest-neighbour principle in local thinnings and is often used in computer simulations of individual-based forest management. For analysing crown release it is recommended to calculate the *A* thinning index before and after the thinning or marking of competitors.

Assuming a commercial forest management scenario, for frame trees with $h/d > 80$ Abetz and Klädtke (2002) reckoned that it would take too long until trees reach their target diameters and individual-tree resilience to wind and snow would be quite low. For frame trees with $h/d < 40$ on the other hand timber quality would be very low because of increased taper as a consequence of very open conditions. Therefore $h/d = 80$ and $h/d = 40$ mark the boundaries of the *realisation space* of frame trees in the system devised by Abetz and Klädtke (2002).

For example, the h/d development of Sitka-spruce (*Picea sitchensis* (Bong.) Carr.) tree no. 1947 in Artist's Wood (Gwydyr Forest, North Wales, UK) is well within the frame tree realisation space and close to the ideal line defined by $h/d = 60$ (Fig. 4). This tree just happened to be a dominant tree in Artist's Wood without being particularly favoured in thinnings, which emphasises that frame trees are supposed to be dominant trees. Instead of plotting the h/d development of individual frame trees it is also possible to monitor the mean h/d development of all frame trees of a given forest stand instead. Naturally, in other climates, different numbers and relationships may apply. The monitoring of the h/d development also allows determining the *thinning cycle*, i.e. the time

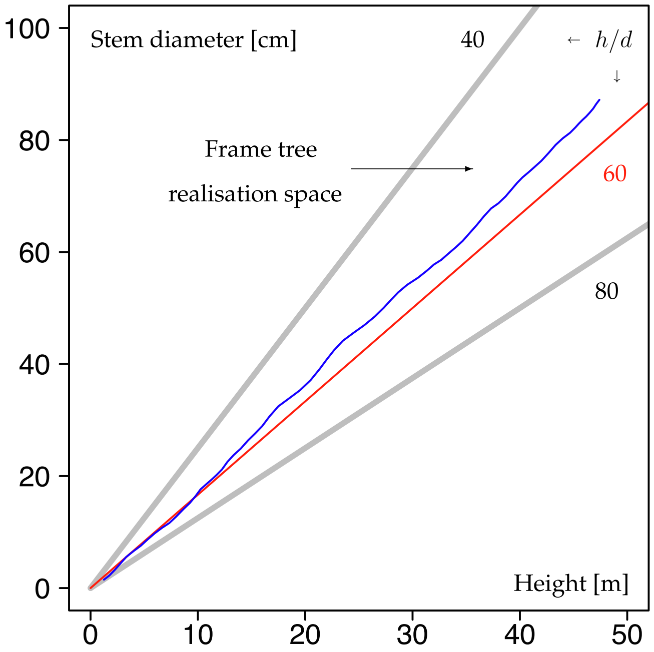

Fig. 4. Frame tree realisation space (within the grey boundary lines) defined by $h/d = 40$ and $h/d = 80$. Ideal h/d is 60 and the blue line gives the observed h/d development of dominant Sitka-spruce tree no. 1947 in Artist's Wood (Gwydyr Forest, North Wales, UK). Modified from Abetz and Klädtke (2002) and Pommerening and Grabarnik (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

between two subsequent local thinnings (Pommerening and Grabarnik, 2019).

Based on growth trials and observational plots, Abetz and Klädtke (2002) also developed stem-diameter growth curves (so-called frame-tree norms) dependent on age or stand height for various species and sites to be used for comparison with field observations. The authors designed these frame-tree norms for comparatively slow (N norm) and for fast (S norm) stem-diameter growth. However, if data from long-term frame-tree management are not available, it is also possible to use the growth records of nearby dominant trees instead. Their growth rates would form an upper boundary of observational data and suitable growth curves for frame trees can then be defined through quantile regression (Cade and Noon, 2003; Pommerening and Grabarnik, 2019).

1.5. Individual-based forest management for restructuring forests

In the past, comparisons between traditional global and local forest management methods were always based on global summary characteristics. As a result, it was often found that certain variants of local thinning methods showed similarities with some global thinning methods, but discussions never went beyond such comparisons of stand characteristics (Bartsch et al., 2020). These studies missed out on the fundamental difference of local forest management methods that centre on individual trees and therefore offer the opportunity to build spatial forest structure by assembling thinning cells or local management units around each frame tree like tesserae in a mosaic. More than crown thinnings alone, individual-based thinnings are instrumental in increasing spatial tree size and species diversity, because the localised approach prevents a homogenisation of forest structure. Several researchers and practitioners have recognised this potential and used methods of individual-based forest management to increase size and species diversity and for restructuring forest stands. The methods also create a framework of resilient trees (Bartsch et al., 2020). The most prominent field of application of individual-based forest management is the transformation of plantations to continuous cover forestry (Schütz, 2001a).

Reininger (2001) developed and tested a forest management method that he termed *structural thinning*. This is an important example illustrating how individual-based methods can be used to diversify forests. The core of this method involves selecting frame trees in two different canopy strata allowing the maintenance of two-storeyed high forests on a continuous basis. He put his structural-thinning method to a long-term practical test in pure and mixed Norway spruce (*Picea abies* (L.) Karst.) woodlands at the Schlägl estate in Austria. The method involves the simultaneous selection of permanent frame trees from upper (F_1) and lower canopies (F_2) at a fairly early stage of stand development (see Fig. 5).

As part of this method and using modern standards, 100–150 F_1 trees are selected from the most dominant trees in the stand. All subsequent interventions strictly aim at releasing the crowns of F_1 trees from the perceived competition of matrix trees in the same canopy layer. During these operations, F_2 trees are only released to such a degree that they can survive in a shaded "stand-by position"' but do not emerge into the F_1 stratum. However, in this concept, the main stand canopy is never fully closed at any time and the number of frame trees is moderate. Depending on initial stand conditions, 80–100 F_2 trees are recruited either from natural regeneration or suppressed trees of the same age as the main canopy trees or from both. F_2 trees are eventually released and allowed to progress into the main canopy when the target diameter felling of the F_1 trees commences. The new F_2 trees are then recruited from natural regeneration. The selection and maintenance of F_2 trees diversify horizontal and particularly vertical forest structure. The idea of this management method is that of a continuous two-storeyed forest, where target-diameter trees are not finally removed within a short period of time but are harvested individually as part of continued thinning operations (Weihs, 1999; Spiecker et al., 2004, Pommerening and Grabarnik, 2019).

Li et al. (2014) proposed *structure-based forest management* as a method to modify spatial characteristics of forest stands. Here the structure of the forest stand was modified by selecting trees for removal whose eviction would increase spatial species mingling, size differentiation and the diversity of tree locations. In addition to the stem-diameter distribution of residual trees, the authors also considered empirical distributions of nearest-neighbour structural indices.

2. Materials and methods

2.1. Data

The Technical Development Department of Forest Research at Ae (Scotland, UK) regularly holds forest management training seminars and as part of these events, marteloscope experiments are carried out. Marteloscopes are forest research and training sites where all trees are mapped, measured and numbered. For this study, data from 50 marteloscope experiments from all over Great Britain were analysed (Fig. 6). 26 of these experiments included the selection of frame trees and their competitors. During the experiment, a number of test persons (in the statistical literature referred to as raters) independently walk through these sites and note the frame trees along with the trees to be evicted from the forest on a sheet of paper or in a software application on a field computer (Pommerening and Grabarnik, 2019). The test persons typically are novices to individual-based forest management methods who have been given some initial training prior to the experiments. The rating experiments are usually part of commercial forestry scenarios.

Most of the sites include forest stands of Sitka spruce, hybrid larch (*Larix* × *marschlinsii* Coaz), Japanese larch (*Larix kaempferi* (Lamb.) Carr.) and Scots pine (*Pinus sylvestris* L.). In some of these stands, other species have later colonised the site, however, the aforementioned

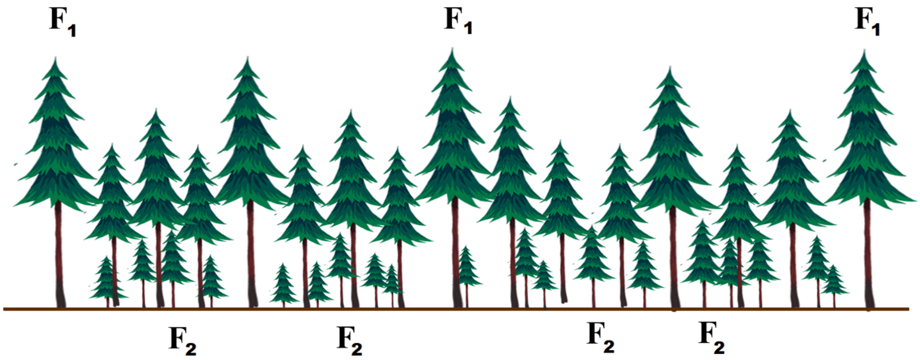

Fig. 5. Schematic illustration of the frame-tree method for promoting diverse forest structure described by Reininger (2001) aiming at a continuous two-storeyed conifer forest. F_1 – frame trees recruited from the upper canopy, F_2 –frame trees representing lower canopies.

Fig. 6. Locations of the UK marteloscope sites managed by the Ae Training Centre and Forest Research.

species represent the main species in terms of density. Peckett Stone at the Welsh-English border is a beech (*Fagus sylvatica* L.) forest and Dean (in the Forest of Dean) is a Norway spruce forest, i.e. they are exceptions from the aforementioned species composition (Pommerening et al., 2018; Pommerening et al., 2020).

All marteloscopes were located in even-aged forests that were originally planted as monocultures with only one species. Other species occasionally occur, but they are minorities and were not included in the thinning instructions. With the notable exception of Ae, each marteloscope had a size of 0.1 ha. The size of the Ae marteloscope was 0.133 ha. For each tree, the following variables were measured: diameter at breast height (d) (measured in centimetres at 1.3 m height), total tree height [m] and Cartesian coordinates in metres (Table 1).

Nearly all sites represent early forest development stages, i.e. the stage when frame trees are typically selected and individual-based thinnings begin. Only Ae and Peckett Stone are middle-aged stands. Stem size diversity as described by the coefficient of variation and skewness is comparatively low, which is typical of plantations at the brink of being transformed to CCF (Pommerening and Murphy, 2004).

The frame-tree selection part of the data included 26 groups of test persons rating the trees as part of training sessions. Each group was comprised of a number of test persons varying from a minimum of 6 (Cannock Chase, Crychan) to a maximum of 20 (Cannock Chase, see Table 1). About 95% of the 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., 2018; Pommerening et al., 2020). These test persons rated between 83 (Peckett Stone) and 323 (Tummel) trees.

In addition, the experiments conducted on each site included tree selections for thinnings, i.e. experiments where trees were selected for eventual removal. Two different thinning types were used by more or less the same test persons on the same marteloscope sites, however, in separate experiments. The first experiment involved a global method, i.e. heavy low thinning, whilst the second type of experiment included the principles of crown thinnings. In the spirit of local thinnings, frame-tree and crown thinning experiments were combined, i.e. as per the instructions given the trees evicted in the crown thinnings were supposed to be potential competitors of the frame trees, as reviewed in Section 1. Frame trees and competitors were selected in the same experiment. The test persons were provided with broad thinning instructions, which slightly varied from site to site depending on regional conditions. The previously published results from low-thinning and crown-thinning experiments (Pommerening et al., 2018) were used for comparison with the new results from the frame-tree selection.

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 stem diameters 1.3 m above soil level, k_d – skewness of the empirical stem diameter distribution, r – number of forest managers marking trees separately for the low and crown thinning experiments and n – number of trees eligible for selection. Several numbers of r indicate that several experiments have taken place in different years as specified.

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

2.2. Statistical measures of tree-selection behaviour

Eberhard and Hasenauer (2021) have argued that only those variations in marking matter that have an effect on the growth and development of the residual forest stand. From an operational and industry point of view this makes sense and certainly is a reasonable suggestion. However, in this paper we took a more basic view point by quantifying and analysing the tree marking variability in general to develop a better understanding of human-tree interactions.

In order to quantify the behaviour of test persons selecting trees in a forest stand, we included a number of measures in our study. There is an *active* and a *passive* selection process: The active process is the rater activity carried out from the point of view of the raters. A simple indicator of this activity is the number of trees selected by a single test person. The *passive* process involves the question of how the trees attract the attention of the raters. A simple indicator of this passive process is the number of test persons selecting a given tree. These indicators can be visualized as bar charts.

For the active rater activity, the *rater bar chart* shows the proportions n_i / n of trees selected, where n_i is the number of trees selected by rater i. The passive selection frequency of the trees can be analysed by the *marking bar chart* showing the proportions of k / n of trees selected, where k is the number of trees selected by different raters with $k = 0, 1, \ldots, r$ (Pommerening et al., 2018; Pommerening and Grabarnik, 2019).

A parameter derived from the marking bar chart is the proportion of trees that are not selected by any rater, P_0. This proportion constitutes a "negative agreement" on "unselectable" trees. It typically includes trees that even to the eyes of a layman suggest the risk of worsening stand conditions in terms of silviculture, ecosystem goods and services or biodiversity, if they were selected as frame trees. A complementary characteristic taken from the marking bar charts is the proportion of trees selected in the 20% highest classes of the marking bar chart, P_{m} (Pommerening et al., 2018)

From the rating bar chart the coefficient of variation r_v of the proportions n_i/n of trees selected by test person i can be calculated, i.e. the proportions of the rater bar chart. Small values of r_v indicate a high degree of agreement in terms of the number of trees to be selected.

Fleiss' kappa is a standard characteristic for measuring the degree of agreement (Fleiss, 1971; Fleiss et al., 2003), which is frequently used in applied statistics. 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. (2).

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

where 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 votes.

We also included the ratio of the proportion of number of trees (N) selected and the proportion of basal area (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).

$$B = \frac{\text{Proportion of the number of trees selected}}{\text{Proportion of the basal area of selected trees}} = \frac{P_N}{P_G} \tag{3}$$

In our case, this measure quantifies the human tree selection strategy of the aggregated tree list by comparing the numbers of trees selected with their cumulative size. If $B < 1$, a smaller proportion of trees has been selected compared to their proportion of cumulative basal area. In a management 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 $B > 1$. In a management 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., 2018).

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. All calculations were carried out using our own R scripts (version 3.6.3; R Development Core Team, 2020) and the irr (Gamer et al., 2012) package.

3. Results

3.1. Marking and rating bar charts

The marking and rating bar charts related to the selection of frame trees are very different from those computed from the tree selection for low and crown thinnings. A typical example is given for the marteloscope in the Tummel forest in Fig. 7. As a result of frame-tree selection there is a comparatively high proportion of trees left that are not selected by any test person as indicated by the first bar in Fig. 7 Aa and P_0. This value is quite low for the thinning from below (Fig. 7 Ba) and higher again as a result of the crown thinning (Fig. 7 Ca). This outcome is partly related to the different numbers of trees selected, which are $\overline{n} = 24.5$, 148.4 and 54.4 on average in panels A, B and C, respectively.

It is very typical and part of the definition of these thinning types that in low thinnings many more trees are selected than in crown thinnings. Even lower is the number of frame trees. Therefore it is more likely to incur smaller P_0 values with smaller values of $\overline{n}$. However, the differences in $\overline{n}$ do not fully account for the difference in P_0, otherwise there would simply be a uniform reduction of mark proportions in all classes of Fig. 7 Aa compared to the other selection methods. Negative agreement on trees that are not selectable also plays an important role, as Fleiss' kappa characteristic confirmed. The complementary P_{m} measure is 0 for frame tree selection, 0.26 for low thinnings and 0.02 for crown thinnings. This is consistent with previous research (Pommerening et al., 2018; Pommerening and Grabarnik, 2019) and shows that there is often high negative agreement (P_0) where there is low positive agreement (P_{m}) and vice versa. For low thinning (Fig. 7 Ba), as in previous research the typical U-shape of bars is again recognisable in contrast to the exponential shape that applies to frame- and crown-tree selections (Fig. 7 Aa and Ca).

The different general heights of the bars in the rating bar charts (Fig. 7 b) reflect the aforementioned differences in $\overline{n}$. The coefficient of variation of the proportions of the rating bar charts, r_{v}, clearly shows that the test persons were much in agreement as far as the number of frame trees are concerned. This number is in fact by far the lowest in each of the tree selection exercises and this is consistent with the frame-tree theory as reviewed in Section 1. r_{v} is highest for the selection of competitors of frame trees (Fig. 7 Cb). Finally, the Fleiss' kappa characteristic κ scored highest in low thinnings (fair agreement) followed by the frame tree selection (slight agreement) and lowest in the selection of the frame-tree competitors (slight agreement). As previously concluded (Pommerening et al., 2018), this implies that the test persons were much more comfortable with the traditional low-thinning tree selection than with the newly introduced crown-thinning method. The novel information here, however, is that the frame-tree selection, which in the British marteloscopes studied is part of the crown-thinning method, achieved markedly more agreement than the selection of frame-tree competitors.

3.2. Relationships describing tree selection behaviour

The trend of parameter P_0 that we discussed for Fig. 7 Aa is apparently a general trend (Fig. 8 Aa). For frame-tree selection the parameter is significantly higher than in the related crown thinnings ($p < 0.001$) and lowest for thinnings from below. The distribution of parameter P_{m} (Fig. 8 Ba) shows no visual difference between frame trees and crown

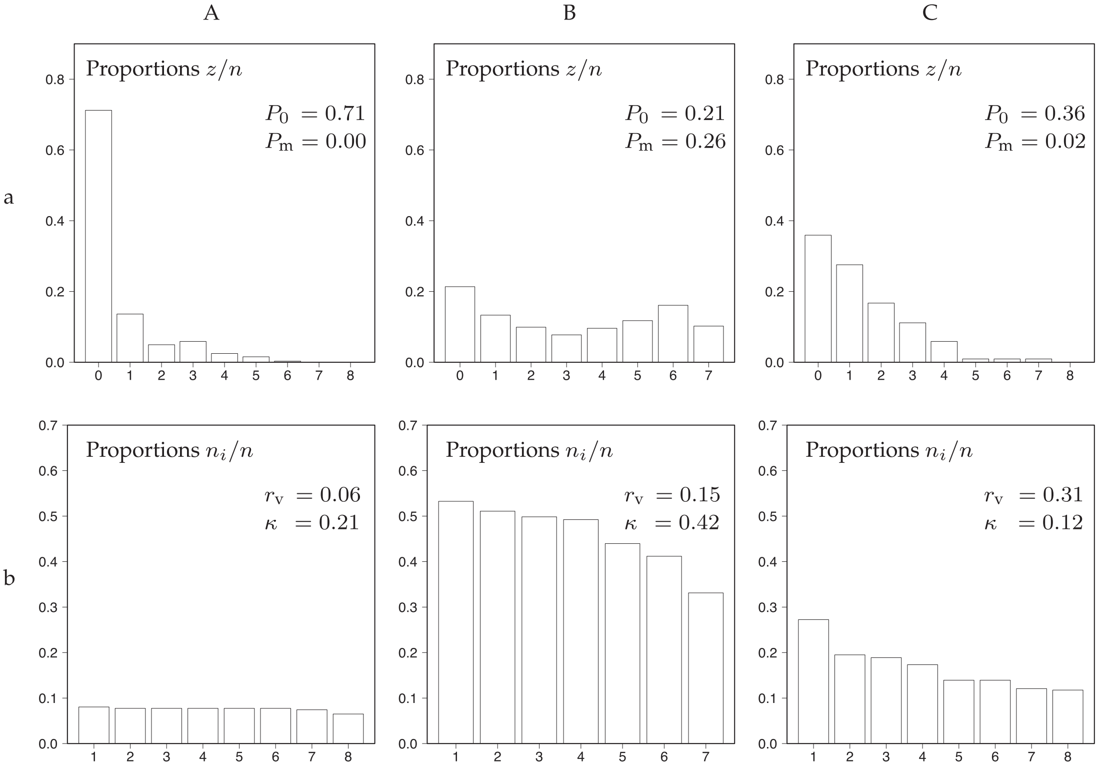

Fig. 7. Marking (row a) and rating (row b) bar charts for the marteloscope experiments in the Tummel forest in 2019. Frame-tree selection (panel A), trees selected for a thinning from below (panel B) and trees selected for a crown thinning (panel C). In row a, the marks per tree and in row b, the marks per test person are shown. κ – Fleiss' kappa, P_0 – proportion of trees marked "0" by all test persons, P_m – proportion of trees marked in the 20% highest classes of the marking bar chart, r_v – coefficient of variation of the proportions of the rating bar chart.

thinnings and this impression is confirmed by the paired *t* test ($p = 0.6$). P_m of both tree selection types are near 0 and dramatically lower than that relating to low thinnings, i.e. there is no elevated positive tree-selection agreement as is commonly the case in low thinnings in the UK.

The Fleiss kappa characteristic reveals that the test persons significantly ($p < 0.001$) more agreed on frame trees than on frame tree competitors (Fig. 8 Ca). Still agreement according to κ was highest when selecting trees for the traditional thinning from below. When applying the coefficient of variation of the proportions of the rating bar chart, r_v, for the frame trees we found nearly the same uniformity in terms of the numbers of trees selected by different test persons as for low thinning, whilst the frame-tree r_v significantly ($p < 0.001$) differed from the higher numbers related to crown thinnings. This suggests that despite the "confusion" caused by the introduction of the new crown-thinning method the test persons reached a remarkable agreement in the numbers of selected frame trees.

The following statistics include tree-size variables. The *B* ratio was calculated for each test person and then the average across all test persons in each experiment was considered. We could confirm the results made by Pommerening et al. (2018) indicating a clear separation between low and crown thinning (Fig. 8 Bb). Interestingly the frame trees scored even lower than the trees selected for the crown thinnings ($p < 0.001$), i.e. the selected frame trees were significantly more dominant than even the frame-tree competitors and this also supports the theory as described in Section 1. The stem-diameter coefficient of variation, v_d, revealed that tree-size variation was low for both frame trees and trees selected for crown thinnings, whilst it was largest for the trees marked for thinnings from below (Fig. 8 Cb). The difference between trees selected for frame trees and crown thinnings was significant ($p < 0.001$), i.e. the frame trees selected were very homogeneous also in terms of size. Finally, the ratio of total tree height and stem diameter, h/d, that often is used for monitoring frame-tree performance (see Section 1), showed clear differences between the three different types of tree selections (Fig. 8 Ac). Mean $\overline{h/d}$ ratios were lowest for the frame trees followed by the trees selected as frame-tree competitors. Apparently, trees selected as frame trees and frame-tree competitors were dominant trees with comparatively free crowns, otherwise their h/d ratio would be higher. This is also consistent with the theory. The frame trees had h/d ratios within the realisation space recommended by Abetz and Klädtke (2002), though close to the upper boundary, see Fig. 4. The largest and most variable mean $\overline{h/d}$ ratios were the result of the tree selection for the heavy low thinnings. Also here the difference between trees selected for frame trees and crown thinnings was significant ($p < 0.001$).

As a summary, we can classify the results of all fifty experiments according to the Fleiss-kappa interpretation table published in Stoyan et al. (2017). As in Pommerening et al. (2018), the updated figure (Fig. 8 Bc) clearly shows that in all cases agreement was low and did not exceed one case of moderate agreement. As concluded in previous publications, the traditional low-thinning method led to substantially more agreement among the test persons than the new and unfamiliar method of frame-tree based crown-thinning. However, in the selection of frame trees there was markedly more agreement than in the selection of frame-tree competitors. With the frame-tree selection there was no case in the poor-agreement class and there were 13 cases in the fair-agreement class.

4. Discussion

Local forest management methods based on comparatively small numbers of frame trees are a flexible and transparent way of managing woodlands. The methods are generic, i.e. with modifications and adaptations to management objectives and local conditions they can be applied to any woodland community. They are suitable both for plantation and CCF management. Past discussions and policies have often failed to see the full potential local and individual-based forest

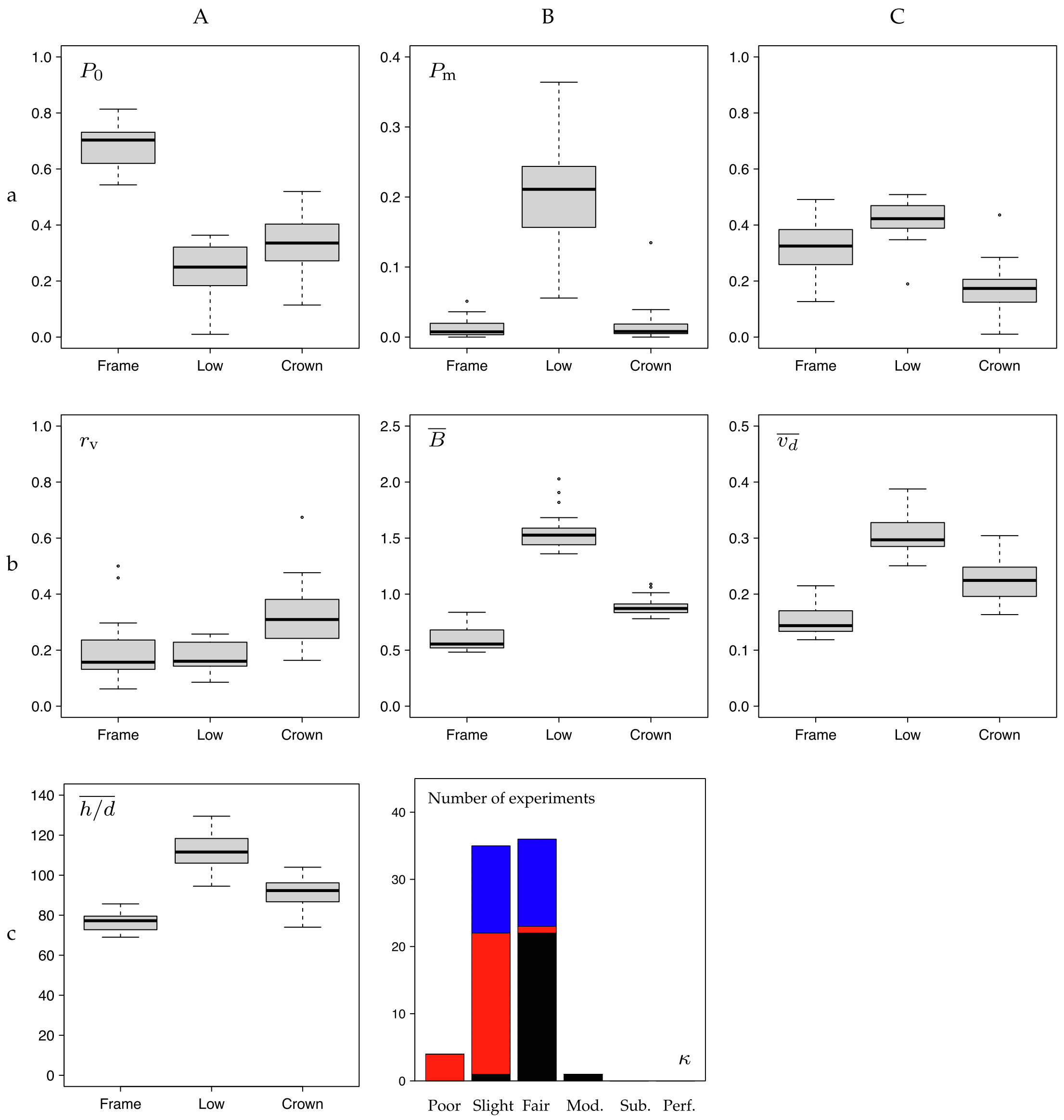

Fig. 8. Box plots depicting the empirical distribution of parameters derived from the marking and rating bar charts and from the variables of the selected trees. $\overline{B}$ – mean ratio of the proportion of number of trees selected by the test persons and the proportion of basal area of the selected trees, $\overline{h/d}$ – mean ratio of total height and stem diameter of selected trees, κ – Fleiss' kappa, P_0 – proportion of trees marked "0" by all test persons, P_{m} – proportion of trees marked in the 20% highest classes of the marking bar chart, r_{v} – coefficient of variation of the proportions of the rating bar chart, $\overline{v_d}$ – mean coefficient of variation of the stem diameters of the selected trees. Frame – Frame tree selection, Low – Trees selected in thinnings from below/low thinnings, Crown – Trees selected in crown thinnings (=frame-tree competitors). Red – selection of frame-tree competitors, blue – selection of frame trees, black – selection of trees to be removed in low thinnings. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

management has for objectives other than commercial forestry. In fact frame-tree methods are very helpful in conservation management, where habitat trees (sometimes referred to as snags and veteran trees) or native trees in a matrix of non-native or even invasive species constitute frame trees (Mölder et al., 2020; Asbeck et al., 2020). For encouraging tree-species diversity, frame trees are selected so that they reflect the envisaged target species composition and thus ensure it. In mixed-species forest stands, the frame-tree selection criterion 'vigour' is of particular importance. Incidentally, the frame-tree concept is also very suitable for the management of forest cemeteries that have recently become very popular across the world (Quinton et al., 2020). Here trees typically act as grave markers and therefore it is important to keep these trees in good health. Consequently, they can act as frame trees and individual-based forest management ensures the vigour of these living grave markers. When it comes to climate-change mitigation, individual-based forest management provides useful methods for carbon forestry (Pukkala, 2018): Individual trees are selected and all subsequent management aims at maximising their carbon sequestration. Once these trees have reached natural life expectancy or need to be removed for whatever reason, their timber can be processed to produce furniture or construction material to ensure that the carbon they have stored is not released any time soon. Alternatively, it is possible to put large tree stems harvested from frame trees into long-term storage (Zeng, 2008).

Frame-tree management has also been suggested for reducing drought stress in conifer stands (Kohler et al., 2010; Gebhardt et al., 2014). The authors found that *Picea abies* (L.) Karst. trees could better cope with drought effects, if they were granted more growing space, i.e. if they grew in a local neighbourhood with low tree density. This is the typical structural context of frame trees and individual-based forest management. Repeated moderate reductions of local tree density around frame trees can enhance the stand-level capacity for plant-available water.

The strength of frame-tree methods is in managing local neighbourhoods where the majority of tree interactions takes place and not so much in maximising or optimising overall stand characteristics. It has been a major misunderstanding and consequently an obstacle to a more universal uptake that the results of local forest management were mainly assessed in terms of how their stand yield characteristics compared with those of global forest management. The real value of local forest management lies in a more efficient design of spatial forest structure and individual-tree resilience through a manipulation of neighbourhoods. In addition, the frame-tree concept is an important didactic tool for novices in the forest management profession to overcome initial difficulties in telling more important from less important trees. At the same time, the method helps to efficiently communicate forest management approaches through quantitative descriptions and this contributes to higher transparency.

Although individual-based forest management is still comparatively new to Great Britain, the results of our analysis in tree-selection behaviour from 26 marteloscopes suggest that frame trees were generally selected in accordance with the theory and current state of the art. This concerns the selection of mainly dominant trees, the low deviation in frame-tree size among the test persons as well as the low frame-tree h/d ratio.

Individual-tree forest management as carried out in the 26 marteloscopes typically includes two main steps, 1) the selection of frame trees and 2) the selection of frame-tree competitors. How exactly these two steps are implemented is usually a matter of personal taste. Some test persons first selected all frame trees and only then their competitors, others always selected the frame-tree competitors directly after appointing a new frame tree. In previous research, the large differences in human tree-selection behaviour between low and crown thinning strategies have been pointed out (Vítková et al., 2016; Pommerening et al., 2018), which essentially were differences in the behaviour of people who applied global versus local forest management. In this study, we specifically addressed the first step, i.e. the selection of frame trees, while previous research exclusively focused on the second step. Our results have shown that in step 1 of the local thinning method a significantly larger agreement is reached in the selection of frame trees as opposed to the marking of frame-tree competitors in the second step. Visually this is most clearly indicated by the shape of the marking bar charts with their high P_0 values (Fig. 7), but also quantitatively by the significantly higher Fleiss' kappa characteristic compared to the selection of frame-tree competitors (Fig. 8).

Our research demonstrated that the uptake and success of crown thinning methods apparently cannot be judged by agreement results that are solely based on the selection of trees for removal. First, crown thinnings can be carried out both as global and local thinnings, i.e. in any analysis these two variants need to be treated separately, as they are not the same and lead to different tree selections. When crown thinnings are carried out as local thinnings, the selection of frame trees and the marking of frame-tree competitors need to be analysed separately. As in our analysis, it may turn out that the selection of frame trees leads to significantly more agreement than the selection of frame-tree competitors. This suggests that participants in training courses need more support for the latter process. It also means that in the situation of extensive management with few available staff it is a good compromise to have experienced forest managers select and visibly mark the frame trees. Taking out frame-tree competitors can then be delegated to machine operators such as harvester drivers provided they have received intensive training.

5. Conclusions

Individual-based forest management includes local thinnings that are based on frame trees. The objective of each thinning intervention is to grant the frame trees growing space in their immediate neighbourhood where the majority of tree interactions occur. Individual-based forest management has a long history and great potential for a wide range of management objectives including commercial forestry, conservation, management for carbon sequestration, forest cemeteries and recreation. In this study, we applied a number of statistical performance criteria giving clues about the behaviour of test persons selecting frame trees in 26 marteloscopes throughout Britain. Although a comparatively new method in the country, the indicators suggested that frame trees were selected in accordance with the theory of individual-based forest management and – for a forestry context – in surprisingly high agreement. This is contrasted by the low agreement and partly unsatisfying performance indicators incurred in the selection of frame-tree competitors, the second step of local forest management. Apparently, the test persons were clear about marking frame trees but not so much about marking their competitors and therefore require more training in taking step 2.

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.

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Data accessibility statement

The data and the analysis R source code used in this study are available at https://zenodo.org/record/5499906 or using DOI 10.5281/zenodo.5499906.

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