Seeing is building better understanding – the Integrate+ Marteloscopes

Technical Report · February 2018

14 authors, including:

Daniel Kraus
Bayerische Staatsforsten AöR (BaySF)
111 PUBLICATIONS **998** CITATIONS

SEE PROFILE

Andreas Schuck
European Forest Institute (EFI)
141 PUBLICATIONS **3,123** CITATIONS

SEE PROFILE

Frank Krumm
Swiss Federal Institute for Forest, Snow and Landscape Research WSL
103 PUBLICATIONS **1,184** CITATIONS

SEE PROFILE

Rita Bütler
Swiss Federal Institute for Forest, Snow and Landscape Research WSL
70 PUBLICATIONS **1,974** CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Project   Samsara2 model "evaludation" View project

Project   InTree project - Introduced tree species View project

Integrate+ Technical Paper

Seeing is building better understanding - the Integrate+ Marteloscopes

Daniel Kraus*[1,8], Andreas Schuck[2], Frank Krumm[3], Rita Bütler[4], Hannes Cosyns[3], Benoit Courbaud[5], Laurent Larrieu[6,7], Ulrich Mergner[8], Patrick Pyttel[1], Simo Varis[2], Georg Wilhelm[9], Manfred Witz[9], Eric Zenner[10] and Sergey Zudin[2]

Summary

Marteloscopes are multifunctional training tools that can create a better understanding of forest management and have been developed as didactic tools for virtual tree selections. With this paper the authors provide explanatory information on the more than 40 Marteloscopes that were established in the course of the project Integrate+. It presents the Marteloscope plot design, gives insight on their set up and the type of data that is recorded for each site. Methods are described on how to calculate e.g. habitat and economic values. The paper elaborates on the use of Marteloscopes as silvicultural training tools and their value in forest education. With the help of the tablet software "I+" virtual management interventions can be performed and the results immediately retrieved. We exemplary present a few options on how the Marteloscope dataset of more than 15,000 recorded trees may serve as stimulus for scientific investigations. Examples are stand development projections, future evolution of tree microhabitats and the calculating of structural complexity and competition indices. An annex separate to this paper contains the bulk of the Integrate + Marteloscopes in the form of information fact sheets.

Keywords:

Silviculture, Marteloscopes, Tree related Microhabitats (TreMs), habitat value, I+ software, training, structural complexity, competition index

Background

Silvicultural concepts and forest management practices have evolved towards ensuring not only wood production, but also at making forest stands more resilient against natural disturbances and climate change effects, conserving biological diversity and providing a multitude of ecosystem services.

These concepts are frequently referred to as integrative management systems when they strive to optimize conservation efforts, economic return and ecosystem services provision (Kraus and Krumm 2013). Increasing forest structural complexity is often advocated as a means to increase resilience and biodiversity (e.g. Puettman et al. 2009). Thus silvicultural practices take advantage of competition effects among trees to alter stand structure and composition by removing or retaining trees since competition is one of the main drivers determining the structure and

* Correspondence: daniel.kraus@waldbau.uni-freiburg.de
1 Chair of Silviculture, University of Freiburg, Tennenbacherstr. 4, 79085 Freiburg im Breisgau, Germany
Full list of author information is available at the end of the report

composition of tree communities (Oliver and Larson 1996). However, practical knowledge of the interacting effects of competition in tree communities from both an ecological and economic point of view is often still limited despite its importance. Growth of adult trees is mainly affected by competition for crown space whereas competition for light is particularly important for smaller trees. The most important silvicultural method to promote the growth and quality of residual trees is thinning by reducing competitors although growth response largely depends on site fertility and stand age (Assmann 1970). Often thinning intensity, however, is thought to be negatively related to structural complexity and species diversity. Especially the reduction of microhabitat structures on trees through silvicultural interventions may contribute considerably to the loss of biodiversity in managed forests. Furthermore the careful retention of such tree related microhabitats has the potential to contribute to increasing both the productivity, resistance and long-term resilience of forest ecosystems. In this context, a better understanding of tree and stand responsiveness to removal or retention becomes crucial to support silvicultural decisions. Best available knowledge from science and practice are thus the foundation for educated decision making. For ensuring continuity in silviculture, training is pivotal as scientific findings, policy orientation, societal demands and management requirements evolve over time. By adapting teaching and providing innovative, multi-disciplinary training opportunities forest managers will acquire up-to-date knowledge and expertise.

In forestry the main challenge is seen in conveying practice oriented forest management content. A novel approach in silviculture training to further develop forest management skills are so called Marteloscopes (Bruciamacchie et al. 2006, Schuck et al. 2015). These innovative training tools are applicable for a variety of educational aims and participants having different experience levels around topics including forest ecology and silviculture or forest management in general. Main focus for participants of training courses is to receive insight to stand structures and their dynamics while at the same time evaluating individual trees in terms of wood quality, economic and nature conservation value. To visualize and demonstrate effects of silvicultural decisions on tree growth and stand development, we used inventory data from Marteloscope plots of a wide range of different forest types across Europe.

To visualize and demonstrate effects of silvicultural decisions on tree growth and stand development, we used inventory data from Marteloscope plots of a wide range of different forest types across Europe. Within the Integrate+ project we focused on the following: (i) presenting practice examples in which integrative forest management concepts are being applied, and (ii) performing virtual tree selection exercises based on different silvicultural aims and forest management strategies. Furthermore, we evaluated (iii) silvicultural decisions in terms of ecological impacts and economic consequences.

Marteloscopes

The concept of Marteloscopes was originally developed in France. The term is derived from the French word for tree selection ('martelage') and the Greek term "skopein" (look), meaning literally "having a closer look" at a tree selection. The concept was at first mainly applied in private forests but its potential for field-based training and education for both forestry professionals and students was already recognised in the 1990s (Bruciamacchie et al. 2006). The use of the usually 1 hectare sized Marteloscope plots found application not only in France but soon after also in its neighbouring countries, becoming more and more known also far beyond. The demonstration project Integrate+ considerably contributed to this development in Europe (Kraus et al. 2016*a*, Schuck et al. 2016).

The aim of this paper is to compile in one document all explanatory information related to the Marteloscopes established in the course of the Integrate+ project. It describes the Marteloscope plot design, introduces recorded data and corresponding calculation methods (e.g. tree related microhabitat and economic values). It highlights the use as a training tool and introduces potential applications using the Marteloscope data. A main component of the paper is Annex I in which the bulk of the Integrate + Marteloscopes are presented. This is done in the form of individual Marteloscope Information Sheets. With this paper we intend to raise interest in the Marteloscope tool and the corresponding existing dataset which includes more than 15,000 recorded trees (see Kraus et al. 2017). Especially we hope to convey to the reader their use for education and training, as destinations for field visits and stimulus for scientific investigations. As new Marteloscopes are continuously being established the dataset will also steadily grow.

Marteloscopes plots

Methods and plot design

For this project, a total of 42 Marteloscope plots were established in a range of representative forest types across Europe (Figure 1). They cover a broad range of forest types including e.g. beech-oak, beech-fir (-spruce), oak-hornbeam, pine-spruce, altitudinal gradient (from 25 m − 1850 m) and site conditions (e.g. oligotrophic *Luzulo-Fagetum* or *Vaccinio-Pinetum* to mesotrophic *Galio-Fagetum* or *Milio-Fagetum*). Due to their demonstration character the selection of plots was based on either availability or particular demonstration criteria, e.g. representative silvicultural systems for a region, high abundance of habitat structures etc.. Further plot selection was limited by the frequency of future silvicultural interventions (i.e. no measures during the next 5 to 10 years) and their accessibility. Most plots are in public ownership (state and community forests) with a few also situated in private forest estates.
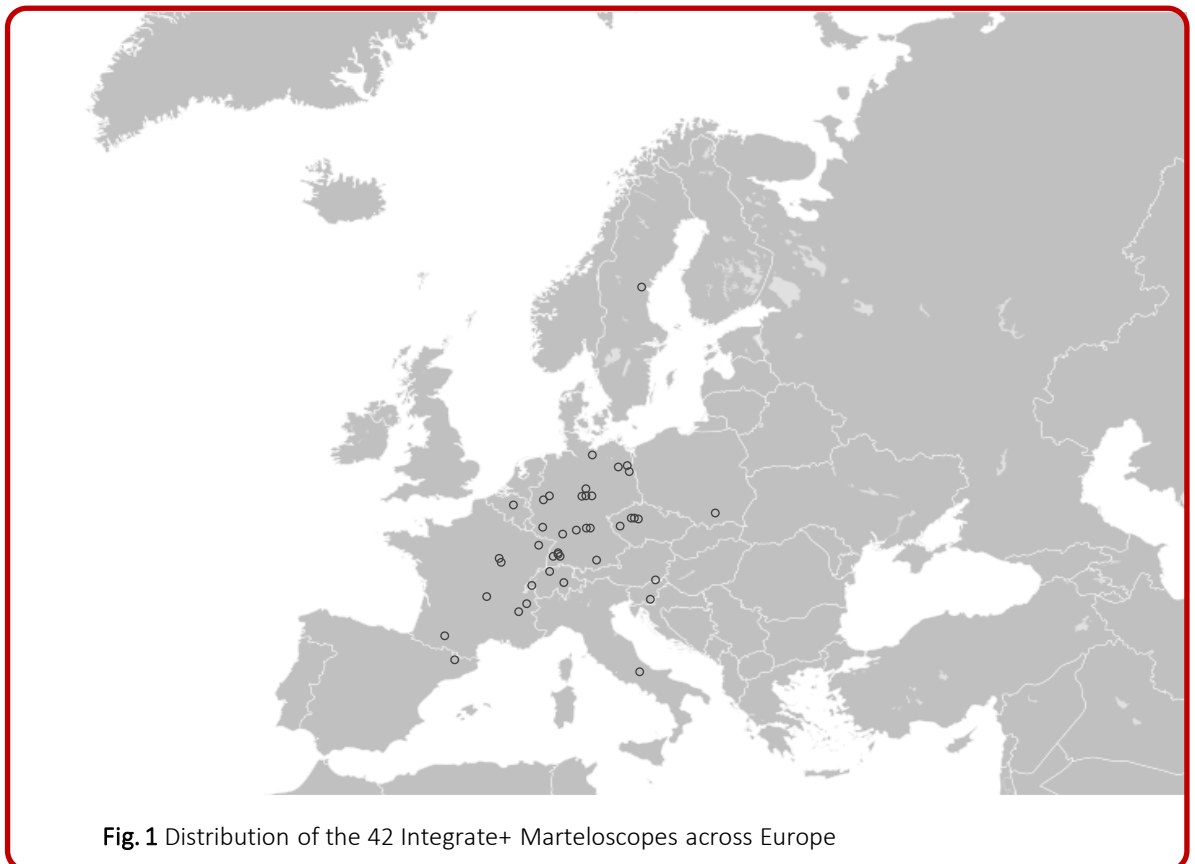

Fig. 1 Distribution of the 42 Integrate+ Marteloscopes across Europe

The standard size for the Marteloscope plots was 1 ha (100 m x 100 m) with a rectangular shape. Some of the plots, however, deviated from size and outline due to local conditions. The plots were divided into 4 quadrants to facilitate orientation and the use of data subsets. All corners and centre points (incl. the centre points of each quadrant) were permanently marked. All trees within the plot with dbh > 7.5 cm were numbered and marked.

We recorded the following data in each plot for trees above 7.5 cm breast height (dbh) (Table 1): (1) tree species, (2), tree location (stem base map) (3) tree status as dead/alive, (4) forest mensuration data (dbh, tree height and crown base height), (5) timber quality (estimated) and (6) tree related microhabitats (TreMs). Height measurements were conducted with a digital hypsometer (VERTEX IV, Haglöf, Sweden), dbh with a measuring tape. Tree locations were determined by using a compass (Suunto, Finland) and the distance function of the Vertex digital hypsometer as a standard.

Measurements took place from the tree to fixed centre points within the Marteloscope, in our case the centre points of the four Marteloscope quadrants. In some plots the measurements were carried out using specialized inventory software (Fieldmap, Czech Republic; GPS Trimble for some plots in France). TreMs recording was based on a specially developed catalogue for field data collection (Kraus et al., 2016*b*).

In addition to the spatial dendrometric data we collected information on management history (year of last intervention), forest type, plot location (state, region, country), elevation, means for annual precipitation and temperature, and the natural forest community. All trees were permanently marked with consecutive numbers. From the measured data each tree was assigned an economic and a habitat value. Derived parameters such as basal area and tree volumes were calculated based on standard calculation methods differentiated by tree species.

Table 1 Parameters recorded in the Marteloscope plots

Type	Unit
Tree species	Fagus sylvatica (Fasy), Abies alba (Abal) etc.
Tree location*	polar coordinates
Tree status	dead (0), alive (1)
Diameter at breast height	dbh [cm] (>7.5 cm)
Tree height	h [m]
Crown base height	h_{cb} [m]
Timber quality	Class (A, B, C, D/IT, F for fuelwood) and section length [m]
TreMs	abundance

Habitat value

Particular attention in the plots was given to TreMs (Kraus et al. 2016*b*) as these structures provide a multitude of ecological habitat functions for a large number of species that are closely associated to them (Larrieu et al. 2018). Retaining and restoring such structures in managed forests by selecting habitat trees can be well integrated into the work portfolio of forest managers. Their selection in turn can contribute to biodiversity conservation.

In order to describe the effect of forest management interventions on the quantity and quality of TreMs we calculated a habitat value for each tree.
The habitat value is intended to support visualizing the impact of harvesting on such tree related structures. A standardized assessment of the habitat value is based on a catalogue of tree microhabitats and serves as reference document for identifying and classifying TreMs (Kraus et al. 2016*b*).

Microhabitats

Tree related microhabitats can be considered as keystone structures for forest ecosystems (Tews et al. 2004, Möller 2005). They provide a wide range of specific conditions to specialized taxa, notably microclimatic conditions and substrates for sheltering, foraging or breeding. They are used by a large variety of animals including insects, arachnids, gastropods, birds, mammals, amphibians and reptiles, by vascular plants, bryophytes, fungi and lichens. Species assemblages can be very diverse, based on the composition of conditions. Some species can be exclusively linked to particular tree microhabitats. For example more than half of all European dendrotelm-dwelling insects are strictly dependent on this microhabitat (Dajoz 2007, Gossner et al. 2015). Base mould cavities supply habitat for the full life cycle of the click-beetle *Limoniscus violaceus* (Gouix 2011) and additionally serve as a simple and temporary shelter e.g. for rodents (Le Louarn and Quéré 2003). Even though certain tree related microhabitat types are relatively persistent (e.g. large mould cavities), they are still considered as ephemeral structures. They can change from one type to another over time supplying different conditions (missing bark evolving to a mould cavity), be periodically unavailable (dentrotelms without water in dry periods) or disappear when a tree either dies or a microhabitat bearing-tree is removed.
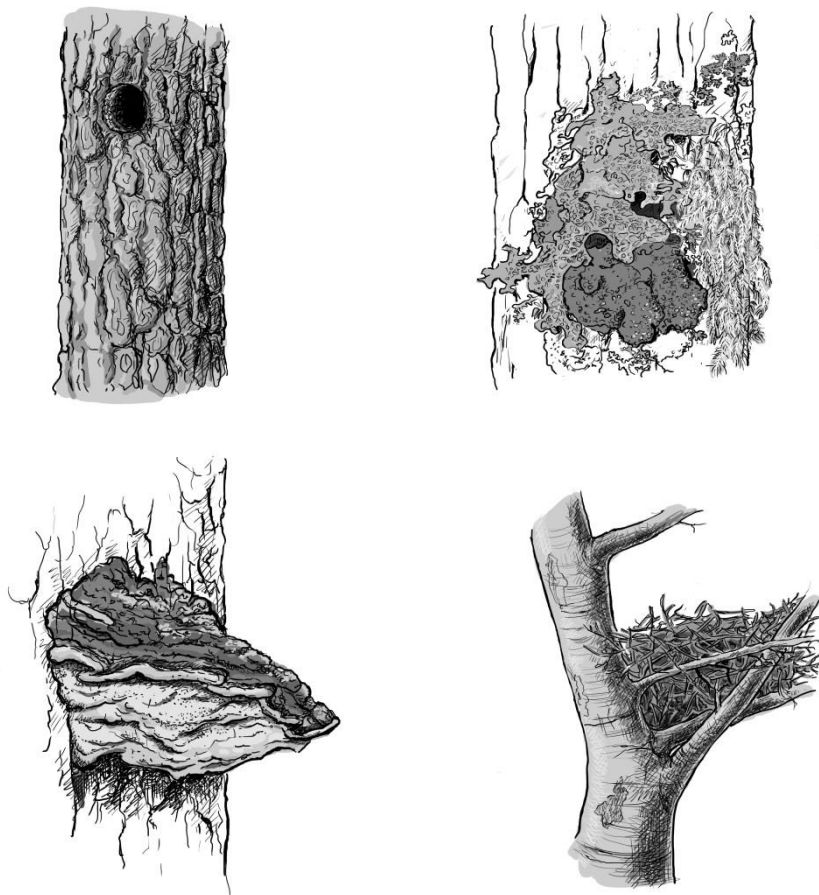

Fig. 2 Examples of different tree microhabitats

Table 2 The microhabitat types from Kraus et al. (2016*b*) used to derive the habitat value

Code	Type	Sub-type
CV11		$\varnothing$ = 4 cm
CV12		$\varnothing$ = 5-6 cm
CV13	Woodpecker cavities	$\varnothing$ > 10 cm
CV14		$\varnothing \geq$ 10 cm (feeding hole)
CV15		Woodpecker "flute" / cavity string
CV21		$\varnothing \geq$ 10 cm (ground contact)
CV22		$\varnothing \geq$ 30 cm (ground contact)
CV23	Trunk and mould cavities	$\varnothing \geq$ 10 cm
CV24		$\varnothing \geq$ 30 cm
CV25		$\varnothing \geq$ 30 cm / semi-open
CV26		$\varnothing \geq$ 30 cm / open top
CV31		$\varnothing \geq$ 5 cm
CV32	Branch holes	$\varnothing \geq$ 10 cm
CV33		Hollow branch, $\varnothing \geq$ 10 cm
CV41		$\varnothing \geq$ 3 cm / trunk base
CV42	Dendrotelmata	$\varnothing \geq$ 15 cm / trunk base
CV43		$\varnothing \geq$ 5 cm / crown
CV44		$\varnothing \geq$ 15 cm / crown
CV51	Insect galleries and bore holes	Gallery with single small bore holes
CV52		Large bore hole $\varnothing \geq$ 2 cm
IN11		Bark loss 25 - 600 cm^2, Decay stage < 3
IN12	Bark loss / Exposed sapwood	Bark loss > 600 cm^2, Decay stage < 3
IN13		Bark loss 25 - 600 cm^2, Decay stage = 3
IN14		Bark loss > 600 cm^2, Decay stage = 3
IN21		Broken trunk, $\varnothing \geq$ 20 cm at the broken end
IN22	Exposed heartwood / Stem and crown breakage	Broken tree crown / fork, Exposed wood $\geq$ 300 cm²
IN23		Broken limb, $\varnothing \geq$ 20 cm at the broken end
IN24		Splintered stem, $\varnothing \geq$ 20 cm at the broken end
IN31		Length $\geq$ 30 cm ; width > 1 cm ; depth > 10 cm
IN32	Cracks and scars	Length $\geq$ 100 cm ; width > 1 cm ; depth > 10 cm
IN33		Lightning scar
IN34		Fire scar, $\geq$ 600 cm²
BA11	Bark pockets	Bark shelter, width > 1 cm ; depth > 10 cm ; height > 10 cm
BA12		Bark pocket, , width > 1 cm ; depth > 10 cm ; height > 10 cm
BA21	Bark structure	Coarse bark
DE11		$\varnothing$ 10 - 20 cm, $\geq$ 50 cm, Sun exposed
DE12		$\varnothing$ > 20 cm, $\geq$ 50 cm, Sun exposed
DE13	Dead branches and limbs / crown deadwood	$\varnothing$ 10 - 20 cm, $\geq$ 50 cm, Not sun exposed
DE14		$\varnothing$ > 20 cm, $\geq$ 50 cm, Not sun exposed
DE15		Dead top $\varnothing \geq$ 10 cm
GR11	Root buttress cavities	$\varnothing \geq$ 5 cm
GR12		$\varnothing \geq$ 10 cm
GR13		Trunk cleavage, length $\geq$ 30 cm
GR21	Witch broom	Witches broom, $\varnothing$ > 50 cm
GR22	Epicormic shoots	Epicormic shoots
GR31	Cankers and burrs	Cancerous growth, $\varnothing$ > 20 cm
GR32		Decayed canker, $\varnothing$ > 20 cm
EP11		Annual polypores, $\varnothing \geq$ 5 cm
EP12	Fruiting bodies of fungi	Perennial polypores, $\varnothing \geq$ 10 cm
EP13		Pulpy agaric, $\varnothing \geq$ 5 cm
EP14		Large ascomycetes, $\varnothing \geq$ 5 cm
EP21	Myxomycetes	Myxomycetes, $\varnothing \geq$ 5 cm
EP31	Bryophytes	Epiphytic bryophytes, coverage > 25%
EP32	Foliose lichens	Epiphytic foliose and fruticose lichens, coverage > 25%
EP33	Lianas	Lianas, coverage > 25%
EP34	Ferns	Epiphytic ferns, > 5 fronds
EP35	Mistletoe	Mistletoe
NE11		Large vertebrate nest, $\varnothing$ > 80 cm
NE12	Nests	Small vertebrate nest, $\varnothing$ > 10 cm
NE21		Invertebrate nest
OT11	Sap and resin flow	Sap flow, > 50 cm
OT12		Resin flow and pockets, > 50 cm
OT21	Microsoil	Crown Microsoil
OT22		Bark Microsoil

The catalogue comprises 64 saproxylic (encompassing decaying wood) and epixylic (without decaying wood) microhabitat types such as cavities, large dead branches, cracks and loose bark, epiphytes, sap runs, or trunk rot characteristics (Table 2).

The habitat value is calculated for each tree based on the number of recorded TreMs. The calculation takes into account the relative rarity of a habitat in near-natural forests and the time span needed for it to develop.

The result is then expressed in so called 'habitat points'.

$$H_i = \sum_{j=1}^{n} N_j \times s_j \times (R_j + D_j) \quad \text{(eq.1)}$$

where H_i is the habitat value of tree i, N_j the number of microhabitat type j, R is a value for the rarity of a TreM, D is a value for the time a microhabitat takes to develop or is available, and s is a size score (physical size of a TreM) within a TreMs group (see Table 3 and 4).

Table 3 R and D values for TreMs in near natural-forests

Rarity gradient in near-natural forests (R-value)		Development time (D-value)	
very common	1	fast or linked to very common event	1
common	2	fairly fast or linked to fairly common event	2
fairly rare	3	from fairly slow to slow or linked to uncommon event	3
rare	4	slow or linked to rare event	4
very rare	5	very slow or linked to very rare event	5

Table 4 R and D-values for the TreM group CV1 (example). R-values are different for broadleaves (b) and conifers (c)

Code	Type	Sub-type	R-value b	R-value c	D-value	Size score
CV11		ø = 4 cm	3	5	2	1
CV12		ø = 5-6 cm	3	5	2	2
CV13	Woodpecker cavities	ø > 10 cm	4	5	2	3
CV14		ø ≥ 10 cm (feeding hole)	2	2	1	3
CV15		Woodpecker "flute" / cavity string	5	5	4	3

Economic value

A visual assessment of timber quality classes was performed in order to provide an estimate of the economic value (market price) for each tree. We used local criteria and knowledge of timber markets to decide which timber qualities a tree provides. We allowed up to five categories on each tree corresponding to a section of a distinct quality class.

Only general timber quality classes were used such as 'veneer' (A - quality), B and C- quality 'sawnwood' , 'industrial timber' (IT or D – quality timber) and 'fuelwood' (F or energy wood). The volume of each quality section was calculated based on a locally adapted and species-specific tapering factor (see Fig. 3).
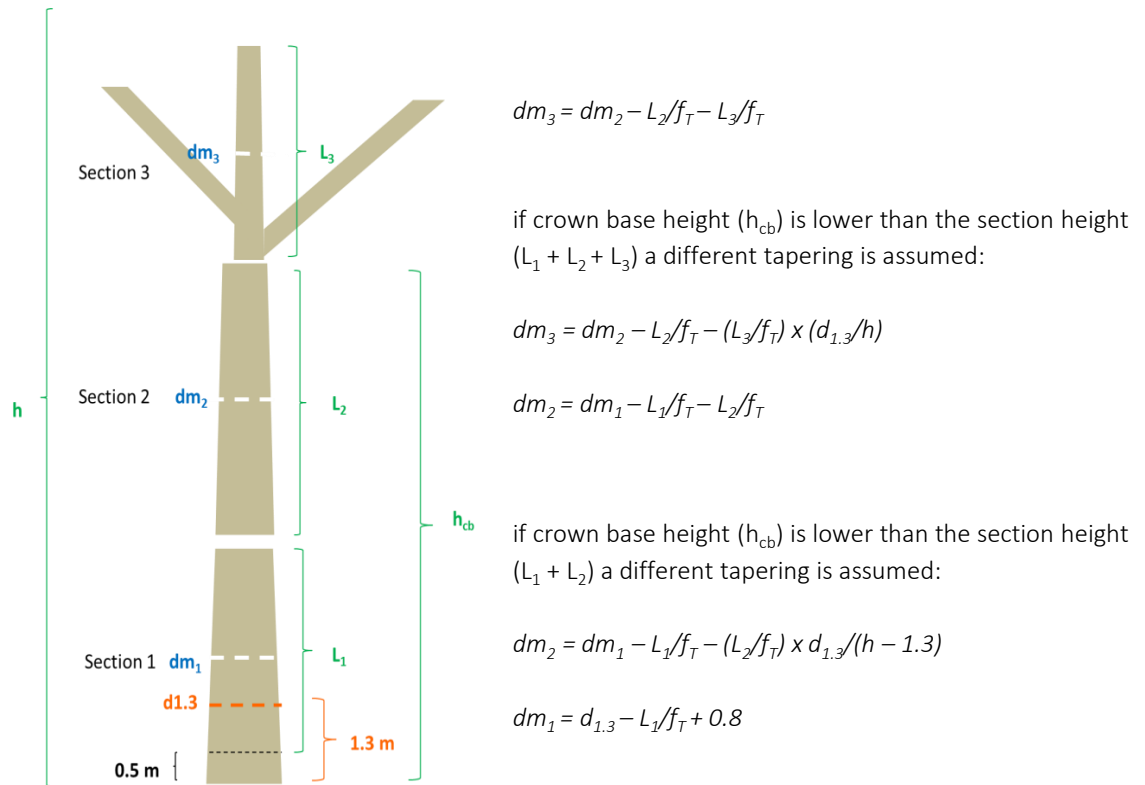
$$dm_3 = dm_2 - L_2/f_T - L_3/f_T$$

if crown base height (h_{cb}) is lower than the section height ($L_1 + L_2 + L_3$) a different tapering is assumed:

$$dm_3 = dm_2 - L_2/f_T - (L_3/f_T) \times (d_{1.3}/h)$$

$$dm_2 = dm_1 - L_1/f_T - L_2/f_T$$

if crown base height (h_{cb}) is lower than the section height ($L_1 + L_2$) a different tapering is assumed:

$$dm_2 = dm_1 - L_1/f_T - (L_2/f_T) \times d_{1.3}/(h - 1.3)$$

$$dm_1 = d_{1.3} - L_1/f_T + 0.8$$

Fig. 3 Volume calculation for a tree with 3 sections. More volume sections can be added following the same method. dm_1, dm_2, dm_3 are mid diameters for each section in [cm], L_1, L_2, L_3 are lengths in [m] for each section, f_T is a species specific tapering factor, $d_{1.3}$ is the diameter at breast height (dbh) in [cm], h is total height in [m], h_{cb} is the crown base height in [m]. A stump height of 0.5 m is subtracted from all harvested volumes.

Volumes are then calculated based on the mid diameters for each quality section accordingly:

$$V_1 = (dm_1/100)^2 \times \frac{\pi}{4} \times L_1 \qquad \text{(eq.2)}$$

where V_1 is the volume of Section 1 in [m³].

Timber market prices for each quality class were provided by local forest managers at the time of data collection (see Tab. 5). It is noted that timber market prices fluctuate so the monetary values attached to individual trees (in Euro or national currencies) are only rough indicators. They are however sufficient for Marteloscope training exercises.

Table 5 Example of a local timber price list used as a basis to determine economic values of each tree

Timber	Class	A	B	C	D/IT	Fuel
		€/m3	€/m3	€/m3	€/m3	€/m3
Oak	0	0	0	0	0	0
	1a	0	0	0	0	25
	1b	0	0	0	0	25
	2a	0	45	45	0	25
	2b	0	45	45	0	25
	3a	0	135	90	0	25
	3b	0	170	110	45	25
	4	500	250	130	45	25
	5	600	390	170	45	25
	6	800	390	170	45	25
Beech	0	0	0	0	0	25
	1a	0	0	0	0	25
	1b	0	0	0	0	25
	2a	0	0	0	0	25
	2b	0	0	0	0	25
	3a	0	62	62	0	25
	3b	0	71	63	45	25
	4	130	100	68	45	25
	5	200	120	73	45	25
	6	250	126	74	45	25
Hornbeam	0	0	0	0	0	25
	1a	0	0	0	0	25
	1b	0	0	0	0	25
	2a	0	70	64	0	25
	2b	0	70	64	0	25
	3a	0	92	68	0	25
	3b	0	92	68	45	25
	4	140	115	74	45	25
	5	180	125	82	45	25
	6	200	125	82	45	25
Maple	0	0	0	0	0	25
	1a	0	0	0	0	25
	1b	0	0	0	0	25
	2a	0	0	0	0	25
	2b	0	0	0	0	25
	3a	0	110	70	0	25
	3b	0	150	90	45	25
	4	600	200	110	45	25
	5	800	300	130	45	25
	6	1000	400	150	45	25
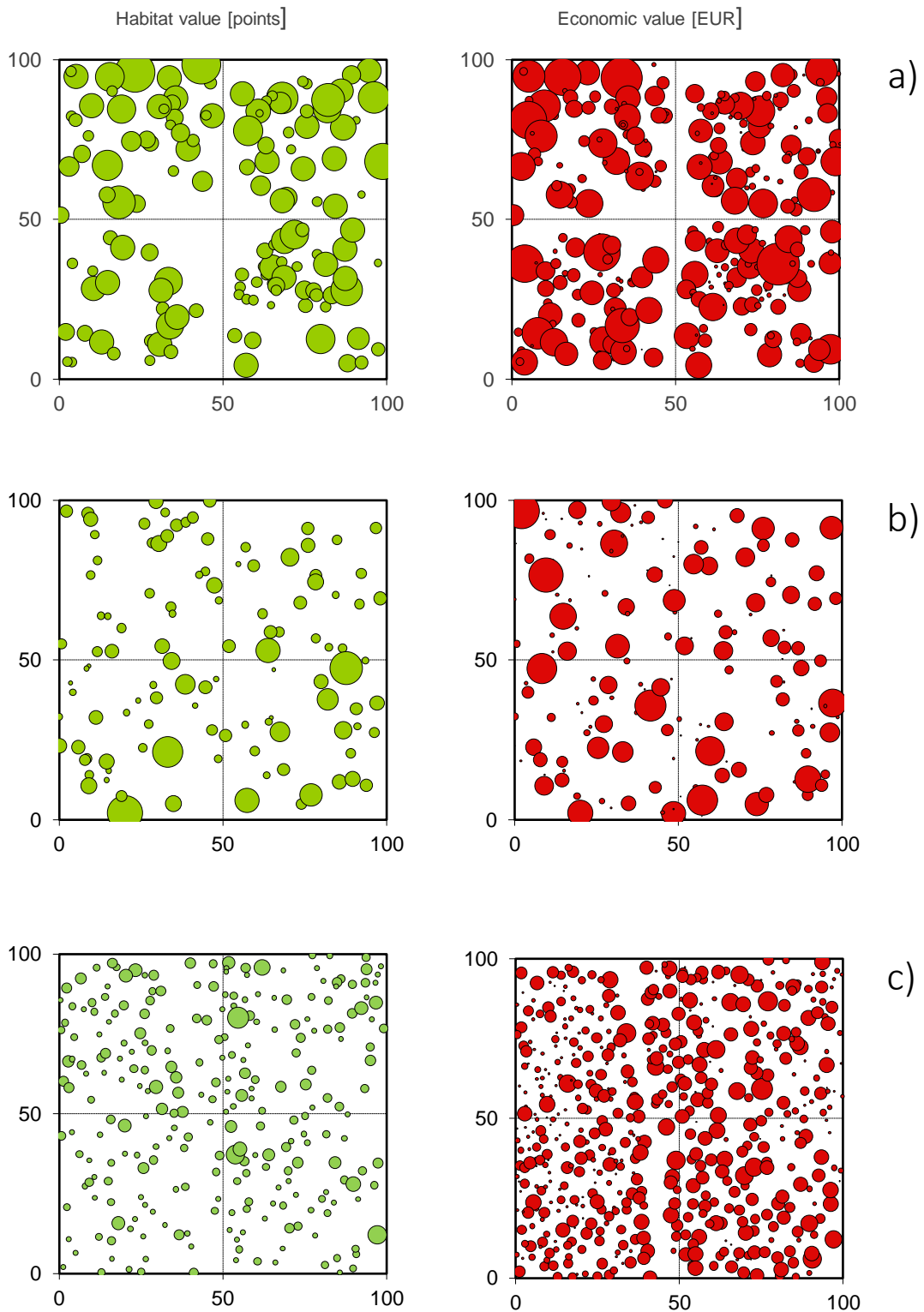
Fig. 4 Habitat and economic values for selected plots: a) Steinkreuz, Germany, b) Groenendaal, Belgium, c) Křivoklát, Czech Republic

Deadwood and natural regeneration

Additionally, we recorded spatial information on lying and standing deadwood as an important structural element in some of our plots (see Table 6). Since the accumulation of large dimensioned deadwood and the creation of gaps through dying and decaying trees results in a three-dimensional restructuring of a forest stand (Juutilainen et al. 2011), new niches are created enriching species assemblages. It also serves as an important substrate for many specialized species, acts as water storage and supplies nutrients through its slow decay through the soil to plants and trees (Jonsson et al. 2005).

Deadwood is delivered continuously under natural forest development or may occur in large quantities following disturbances such as windthrow, wildfires or bark beetle infestations. It can also be accumulated during silvicultural interventions. Intensive forest management over the past centuries, however, resulted in low levels of both standing and lying deadwood and thus a loss of numerous deadwood dependent species (Müller et al. 2005).

Many managed forests have less than 10 m³ ha^{-1} of deadwood on average whereas natural forests can have up to 200 m³ ha^{-1}, in some cases even 400 m³ ha^{-1} (Lassauce et al. 2011, Müller and Bütler 2010). Scientific evidence on the role of deadwood in forest ecosystems has led to a rethinking also for managed forests.

Thus larger amounts are increasingly being accepted and may even become part of a strategy to accumulate deadwood as a long-term nutrient reservoir or as structural element (see Table 6). Therefore mapping deadwood in Marteloscopes can add an additional information layer to the dataset since the effect of harvesting on deadwood dynamics can be demonstrated.

We recorded the following data in the plots for deadwood (Table 7): (1) tree species (if not identified we noted down broadleaved/coniferous), (2) deadwood type (standing: snag, stump; lying: log, tree crown), (3) object location as polar coordinates and orientation of lying deadwood (deadwood map), (4) decomposition stage (5 decay classes according to Hunter 1990), (5) deadwood mensuration data (diameter, height or length of object). Diameters were measured with a caliper (Haglöfs, Sweden). For logs and tree crowns we took the diameter at the larger end (d_1) and at the smaller end (d_2), for stumps (created through tree fellings) we took the diameter at the top (d_0). Snags, being a standing, dead tree and high stumps (resulting from management measures) were recorded with the tree measurements when larger than 1.3 m. Deadwood locations were determined, for the few plots where deadwood was recorded, by using a compass (Suunto, Finland) and the distance function of the Vertex digital hypsometer as a standard.

Table 6 Deadwood volumes per hectare for selected plots

					Decay class				
Plot	Snags	Stumps	Logs	Total	1	2	3	4	5
[ ]	[m³ ha^{-1}]	[m³ ha^{-1}]	[m³ ha^{-1}]	[m³ ha^{-1}]	[m³ ha^{-1}]	[m³ ha^{-1}]	[m³ ha^{-1}]	[m³ ha^{-1}]	[m³ ha^{-1}]
Steinkreuz	0,0	6,6	18,2	24,8	0,1	1,3	16,8	6,1	0,6
Löran	3,3	0,6	8,1	11,9	2,5	3,2	1,9	0,7	0,3
Rosskopf	1,5	9,1	19,7	30,3	2,8	8,3	11,6	5,4	0,4
Mooswald	0,0	3,8	8,4	12,3	0,0	6,6	2,7	1,9	1,1
Sihlwald	13,3	1,4	80,7	95,5	2,4	27,3	7,4	43,6	1,4
Heches	6,7	2,5	65,8	74,9	0,0	16,2	35,8	13,1	2,4
Waldhaus	0,5	29,8	127,7	158,1	35,8	25,3	54,4	41,6	0,0

Table 7 Deadwood parameters recorded in the Marteloscope plots

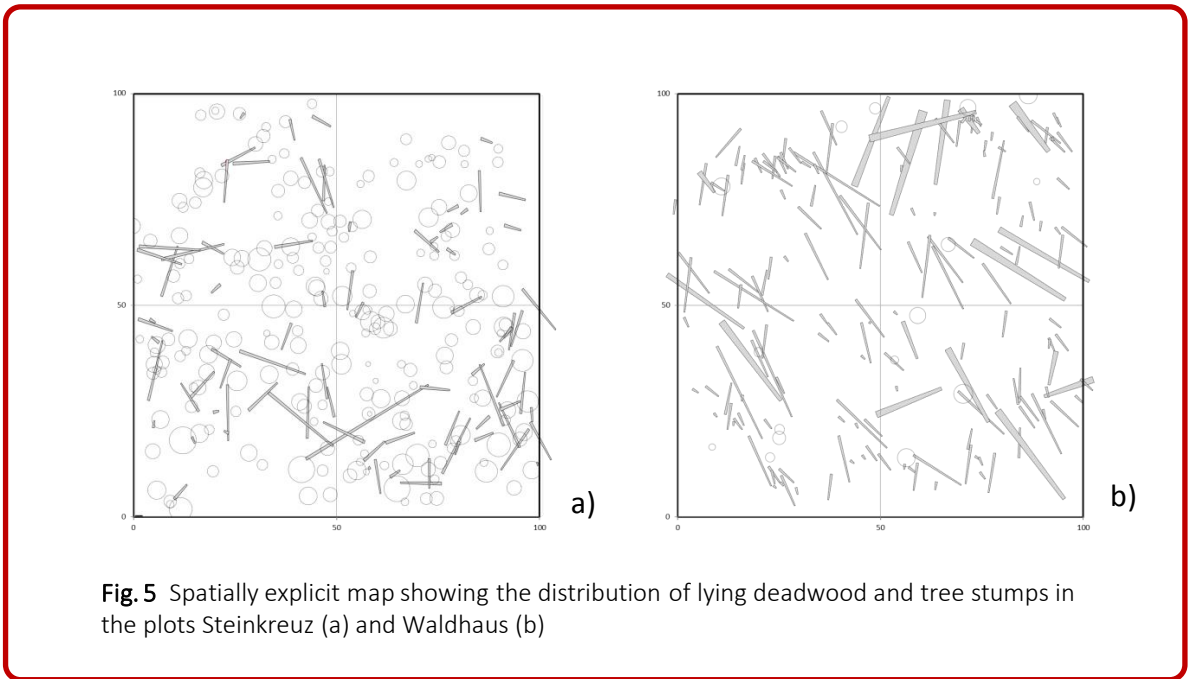| Type	Unit
Tree species	Fagus sylvatica (Fasy), Abies alba (Abal) etc.
Deadwood type	Snag, log, stumps, crown
Location	polar coordinates and orientation of logs in [°]
Decay stage	5 classes (according to Hunter 1990)
Diameter	$d_{1.3}$ [cm] for snags, d_0 [cm] for stumps, d_1 and d_2 for logs
Height	h [m] for stumps and snags
Length	L [m] for logs

Fig. 5 Spatially explicit map showing the distribution of lying deadwood and tree stumps in the plots Steinkreuz (a) and Waldhaus (b)

Potential stand development trajectories including regeneration and ingrowth dynamics are difficult to predict. The information from the regeneration layer is important to evaluate the effect of tree removals on future stand development, especially when using a growth simulator. Thus, for some plots we also estimated coverage of natural regeneration of the stand, and mapped seedlings (height ≥ 20 cm and < 200 cm) and saplings (height ≥ 200 cm and DBH < 5 cm) differentiated by their height (Fig. 6). Also, browsing damage during the previous year, and annual terminal shoot length of the previous three years of the largest individual per tree species were measured.
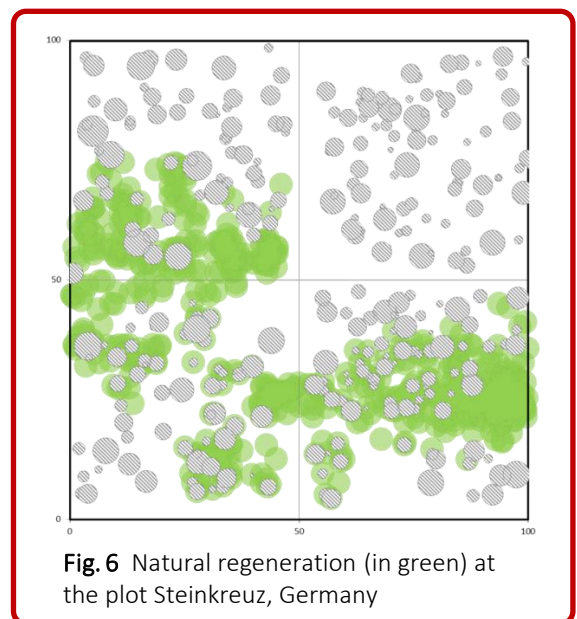
Fig. 6 Natural regeneration (in green) at the plot Steinkreuz, Germany

Martelscopes and training

Each Marteloscope possesses unique stand and individual tree characteristics and together with the data collected on this stand and its individual trees, it determines which subjects can be discussed and trained at a particular site. Typical teaching examples in a Marteloscope are e.g. to comprehend potential management conflicts induced by the need to address multiple ecosystem services such as protection, timber harvesting, recreation and biodiversity conservation or which stand regeneration method to best apply for reaching set silvicultural targets. The distinguishing feature of Integrate+ Marteloscopes is that for each individual tree detailed data on their economic value and habitat value were determined. Whereas the recording of economic tree values is common in Marteloscopes, the assessment of trees' microhabitats and habitat values is rather unique. This makes the Marteloscopes particularly suited to discuss and learn about biodiversity-related topics as well as about trade-offs between economic and ecological (habitat) objectives in forests. Hence, the majority of training sessions within the Integrate+ Marteloscopes focus on these topics.

In Marteloscopes, different teaching methods can be applied in accordance to predefined learning objectives. In general, self-directed learning formats are favoured that encourage, problem-oriented learning. Conventional lecture formats can be embedded into Marteloscope exercises and can show useful to provide additional explanation to a limited extent. However, participants are encouraged to seek their own solutions for a given task. They move independently in a Marteloscope, which fosters self-learning processes and stimulates the application of already acquired knowledge and motivates to educate oneself further. A discussion session at the end of the exercise frames the individual's made observations and collected experiences in a broader context and fuels self-reflection.

Marteloscope exercises are either carried out individually or in small groups. Both approaches have their benefits.

Main advantage of working in small groups is that they provoke already discussions during the tree selection process. Exercises last between one to two hours and are accompanied by a trainer. The "I+" tablet software is used to record the exercise decisions by training participants. Own selection of single trees in a stand makes parameters such as basal area, tree volume or height more tangible and provides a better understanding of forest practitioners' skills acquired through years of field practice. By adapting the degree of independence and difficulty levels of given tasks, Marteloscopes offer a high variation of training levels. All exercises are supported by an innovative tablet based software, "I+" which allows virtual silvicultural interventions. The training participant can virtually implement also management scenarios which are rather unrealistic or excessive to demonstrate their consequences. This raises lively discussions directly in the Marteloscope.
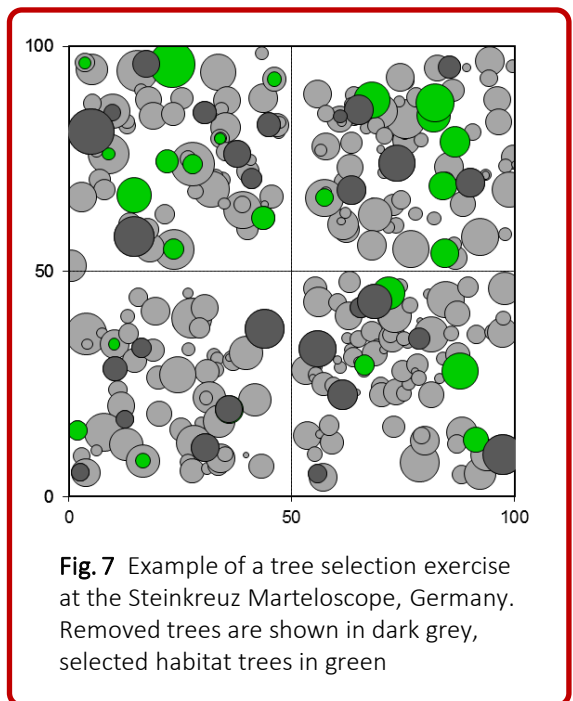

Fig. 7 Example of a tree selection exercise at the Steinkreuz Marteloscope, Germany. Removed trees are shown in dark grey, selected habitat trees in green

Further actual management guidelines including nature conservation objectives (deadwood accumulation, habitat tree selection) can be easily practiced and tested.

Important will be to analyse exercise results in social science research to investigate tree selection behaviours of individuals and different stakeholder groups. This will help to better understand what drives decision-making in forests. However, scientific research has to meet several requirements for hypothesis testing considering i.a. sampling design, objectivity and comparability, which are often not compatible with the educational objectives of the Marteloscope trainings. Therefore, in the scope of the Integrate+ project exercises protocols were developed to find synergies and combine particular educational objectives with specific research objectives.

Pommerening et al. (2015) have investigated human tree selection behaviour using Marteloscopes. First results indicate that there is rarely consensus between different test persons given the same task. Indications of this high interpersonal variation have been confirmed by Spinelli et al. (2016) and Vitkova et al. (2016). We applied the methods suggested by Pommerening et al. (2015) to some of our Marteloscope exercises to assess participants tree selection: we used thinning type as a suitable indicator and thinning intensity as a characteristic of impact since it affects the development and structure of a forest stand. Thinning type was measured as the NG ratio, defined as the relative number of trees removed divided by the relative basal area removed. Thinning intensity was defined by the proportion of basal area removed (measured on the abscissa in Fig. 8a in relative basal area, rG).

Also it can be useful information to see how sustainable an intervention suggested by a participant is. When using growth rates, tree volume or basal area removed in an exercise can be compared to the increment over the next 10 years (Fig. 8b).

All participants above the horizontal line representing the initial quadratic mean diameter performed a tree selection corresponding to a crown thinning, those below this line made decisions leading to a thinning from below. The vertical solid line marks the basal area increment over a 10 year period (dashed vertical lines give a region of allowance of ±10%). Accordingly, basal-area values of removed trees smaller than 6.4 m^2 lead to an increase of stand basal area, values larger than 6.4 m^2 result in a decrease.
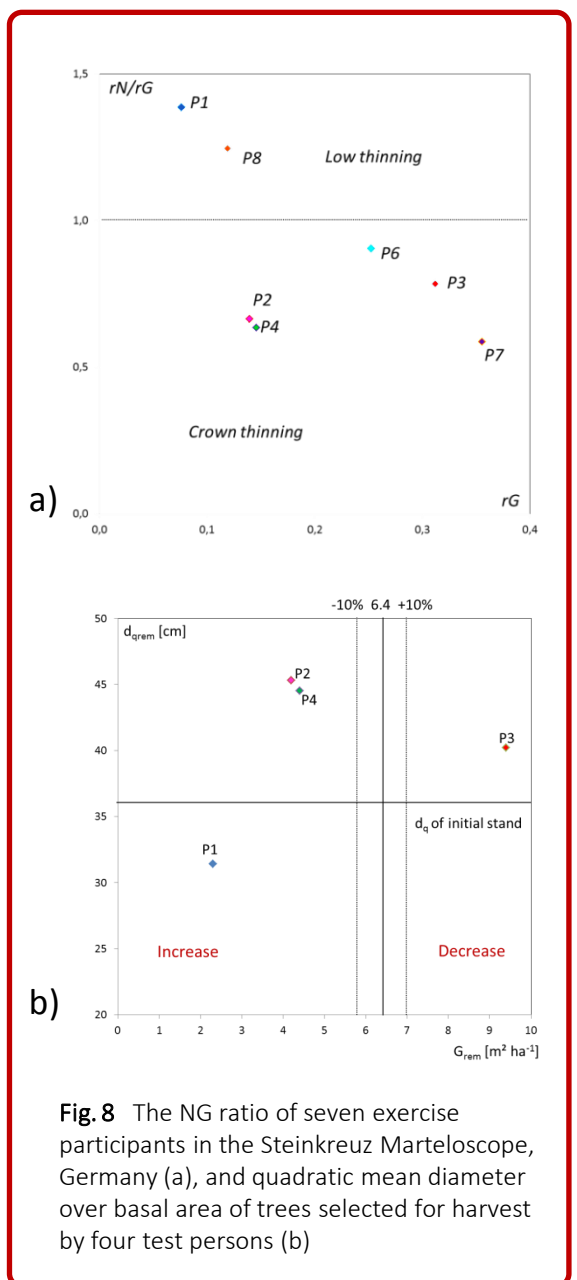

Fig. 8 The NG ratio of seven exercise participants in the Steinkreuz Marteloscope, Germany (a), and quadratic mean diameter over basal area of trees selected for harvest by four test persons (b)

Synthesis and applications

Our Marteloscope plots have proven further valuable as exploratory forests for other research applications since they provide datasets with spatially explicit information on trees, structure and TreMs (Kraus et al. 2017). Such types of datasets are currently rather rare. They can serve research targeted at better understanding for example tree related microhabitat formation, their dynamics and the effects of their spatial distribution on associated taxa (Larrieu 2014; Courbaud et al. 2017). In the following a set of exemplary applications are presented to illustrate how Marteloscope plot data and any derived or processed information (e.g. results from virtual interventions) can be further used and applied.

Stand development projections

Currently we can only provide snapshots of the immediate effects of harvesting in our Marteloscope plots. The use of growth simulators can process the information generated by Marteloscope interventions and project these into the future. We used the Samsara2 model (Courbaud et al. 2015) to run simulations after different harvesting scenarios in Marteloscope plots. Samsara2 is implemented in the Capsis simulation platform (de Coligny et al. 2003; Dufour-Kowalski et al. 2012) which enables both interactive or automatic simulations and the visualization of simulation results. Harvests can be simulated using specific algorithms (Lafond et al. 2012, 2014). In our case all simulated stands are Marteloscopes of 1 ha size with ground cell area of 25 m^2 (5 m × 5 m). Radiation interception, which is the process requiring most of the computing time, is usually updated only every 5 years, whereas demographic processes are calculated on an annual basis.

A stand simulated in Samsara2 is based on a list of trees and a list of saplings that have explicit 3D coordinates on a plot (Fig. 9). This plot is attributed a slope and an exposure value, and is divided into ground cells. Trees are characterized by species, trunk diameter at breast height (dbh), crown dimensions, and location.

Seedlings are simply characterized by their species, height, and location. Individual tree crown dimensions are calculated using allometric relationships relating total height, crown base height, crown base radius, and dbh (Vieilledent et al. 2010). The irradiance of each cell under canopy and the amount of radiation intercepted by each adult tree during a growing season are calculated together, in an integrated approach based on light ray interception by crowns in 3D (Courbaud et al. 2003). The annual basal area increment of a tree depends on the amount of radiation intercepted during a growing season. This relationship integrates both an ontogenetic effect (interception depends on tree size) and a competition effect (incident radiations depend on neighbors) on growth. In Samsara2, the mortality submodel simulates only background mortality. The death of a tree is the result of a Bernoulli trial, the probability of mortality depending on dbh and local competition. When saplings reach an arbitrary height defined by the user, they are recruited as adult trees in the model.
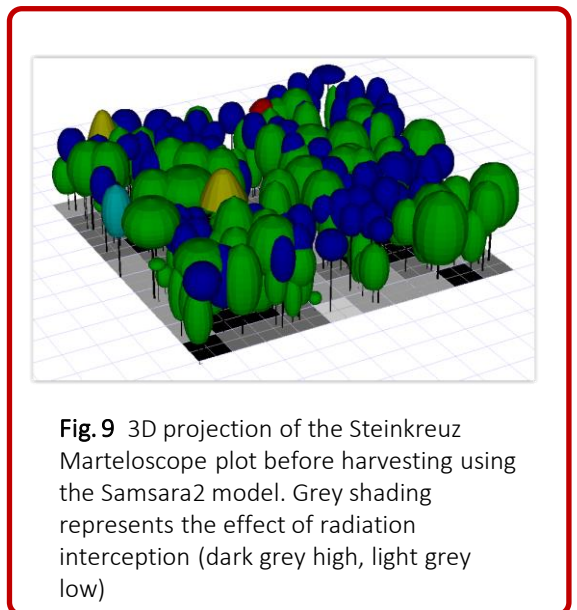

Fig. 9 3D projection of the Steinkreuz Marteloscope plot before harvesting using the Samsara2 model. Grey shading represents the effect of radiation interception (dark grey high, light grey low)

The spatially explicit, individual-based Samsara2 model was designed to determine the relationships between stand structure and dynamics in uneven-aged mixed temperate forests and to predict the impact of management strategies (i.e. variations in the

distribution of cuttings over time and space and among trees) at the population scale (i.e. a forest stand). This makes it possible to analyze the development of individual trees within a stand and the resulting collective dynamics, summarized by synthetic variables such as density, basal area, distribution of trees among size classes, indices summarizing the spatial distribution of trees, cumulated harvests and the like. Giving specific focus on the dynamics and management of uneven-aged stands which are composed of trees at different development stages requires the simultaneous simulation of demographic processes (growth, mortality, and recruitment), and interactions among trees of different sizes (e.g. competition). Light interception by tree crowns is the key driver in uneven-aged stand dynamics as they present a strong vertical heterogeneity favoring asymmetric competition both between trees canopy and seedlings (Schütz 1997).

Fig. 10 Simulation of different interventions with Samsara2 performed for the Marteloscope Steinkreuz (simulation period 20 years): a) harvest of approximately 85 m³/ha with a strong focus on the removal of defective trees (negative selection), b) harvest of approximately 45 m³/ha with a positive selection of elite and habitat trees.

In the model, light distribution among trees, irradiance on the ground, and seed dispersion are spatially explicit and their spatial heterogeneity drives the changes in forest structure. In Fig. 10 we show the results of a simulation of two relatively contrasting interventions during a Marteloscope exercise at Steinkreuz. The projection of stand development and the light model was run for 20 years.

Microhabitat development and future habitat potential

A pressing question stated by forest managers is often not directed at how to retain sufficient habitat structures but how to ensure a continuous supply of TreMs formation on trees also in future. Consequently implementing negative selection often depletes those trees which display promising future habitat potentials. A simple method to estimate the TreM formation rate would be to use the variation of their numbers on trees which are observed repeatedly. Unfortunately, such repeated measurements are still largely missing due to the relatively recent interest researchers have taken in this subject (Lindenmayer et al. 2011). Moreover, trees have rarely been permanently labeled in the field during previous studies, which does not allow re-measurements. Certain TreM types such as cracks are rare even in near-natural forests. Their detection and formation thus requires large tree samples. Extensive measurement efforts will become necessary to build large databases with repeated observations of TreMs.

We identified a list of structures (Table 8) on trees we believe have a relatively high probability to develop into TreMs during the lifetime of a tree. Based on these criteria the so called Future Habitat Potential can then be calculated for each individual tree. These structures can be revisited periodically e.g. in Marteloscopes where all TreMs have been recorded in the initial set up for measuring the rate and quality of TreM formation on a single tree. Repeating TreM inventories on the same trees will then allow to improve the accuracy of the Future Habitat Potential predictions.
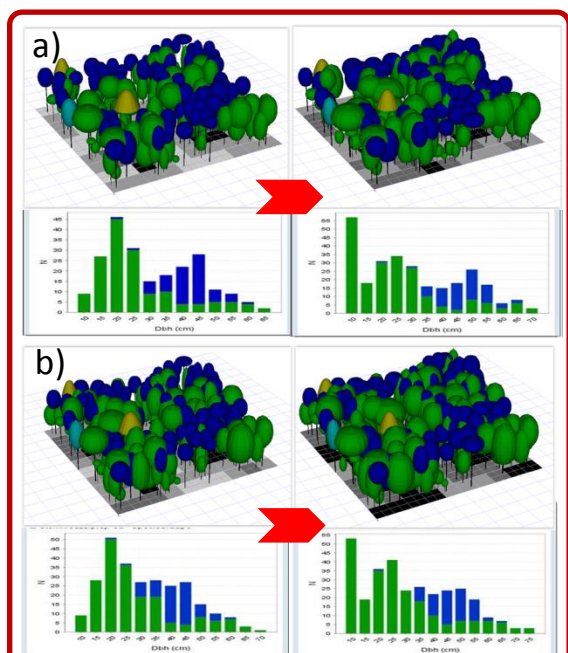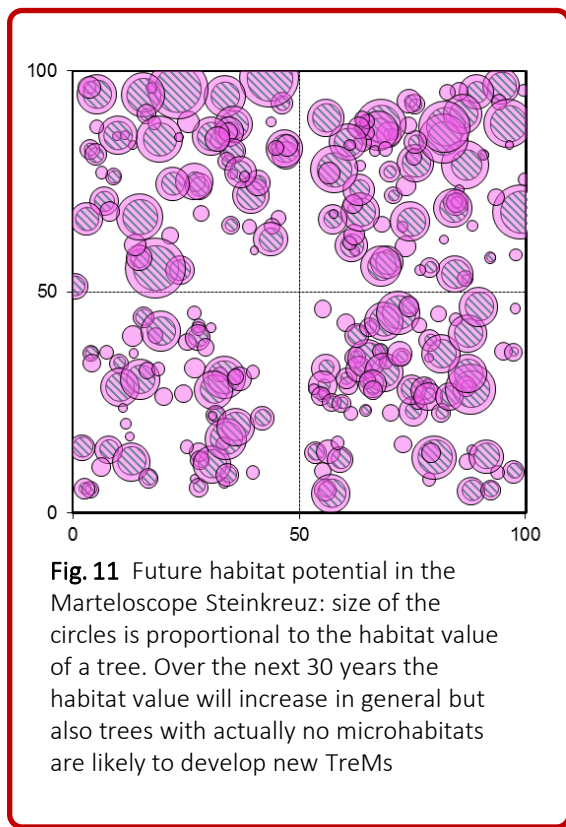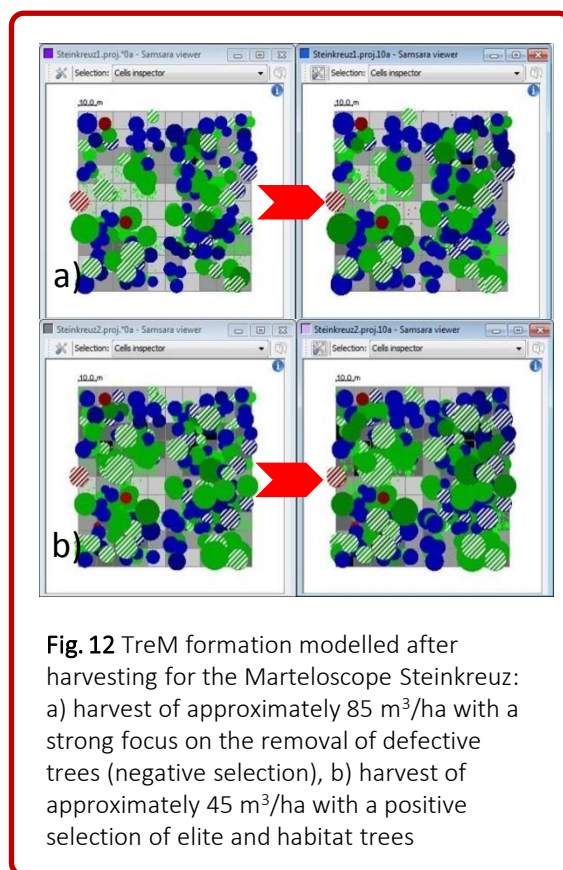
Fig. 11 Future habitat potential in the Marteloscope Steinkreuz: size of the circles is proportional to the habitat value of a tree. Over the next 30 years the habitat value will increase in general but also trees with actually no microhabitats are likely to develop new TreMs

Table 8 Structures with a high probability to develop into TreMs

Type	Score
Forks	0,6
Branch scars	0,3
Dead branches	0,4
Frost scar	0,3
Bulges	0,5
Spiral grain	0,2
Exposed sapwood	0,8
Necroses	0,6
Fissures	0,4

We also tested a new method proposed by Courbaud et al. (2017) where we estimated the probability of TreM formation during tree growth based on cross-sectional data from our Marteloscope plots (i.e. the presence of TreMs on trees of different diameters). The challenge is that usually there is no information on tree ages making it difficult to relate TreM formation to a time scale.

Therefore, age is replaced by dbh. Further survival analysis techniques are applied which can estimate the expected duration of time until an event such as death in biological organisms or failure in mechanical systems occurs (Hosmer et al. 2008; Meeker and Escobar 1998). With this input the probability of TreM formation can be estimated as a function of tree species, tree dbh and tree dbh increment. In Fig 12 we show the results of modelled TreM formation after two different interventions at Steinkreuz using the TreM submodel of Samsara2.

Fig. 12 TreM formation modelled after harvesting for the Marteloscope Steinkreuz: a) harvest of approximately 85 m³/ha with a strong focus on the removal of defective trees (negative selection), b) harvest of approximately 45 m³/ha with a positive selection of elite and habitat trees
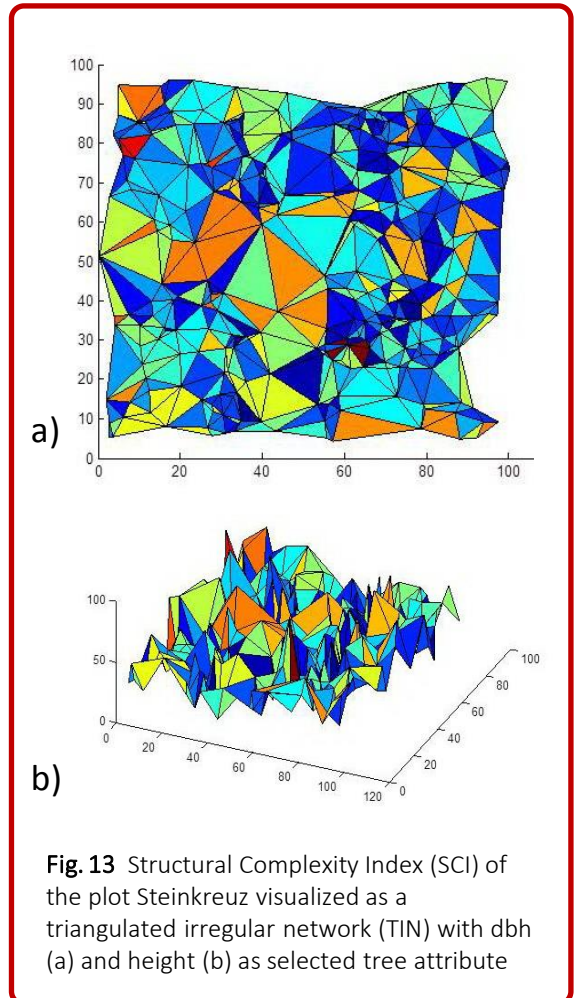
Structural complexity

An increasing complexity of stand structure often leads to a higher number of animal and plant species and to greater ecological stability (Larrieu et al. 2015). However, the multidimensional character of forest stands makes it hard to characterize structural complexity.

However, the multidimensional character of forest stands makes it hard to characterize structural complexity. The horizontal distribution pattern of trees, stand density, the differentiation of dimensions, and species intermingling constitute the most important aspects of stand structure that influence growth processes, habitats, species richness, and stability of forest ecosystems (Pretzsch 2009). Additionally the spatial arrangement of plants, both horizontally and vertically, the structure of tree canopies and the presence of canopy gaps, snags, and coarse woody debris are the principal characteristics that influence the diversity of animals (Kimmins 2005). The density of TreM-bearing trees is positively correlated with the saproxylic beetle species richness in several forest contexts (Bouget et al. 2013, 2014). While some of these attributes are hard to define and difficult to measure in the field, tree stem diameter and position are standard in measurement protocols of forest inventories. For quantification, the Structural Complexity Index (SCI) describes structural complexity by means of an area ratio of the surface that is generated by connecting the tree tops of neighbouring trees to form triangles to the surface that is covered by all triangles if projected on a flat plane (Zenner and Hibbs 2000). Hence, in our plots we focused on these variables and defined structural complexity as the spatial arrangement of tree dimensions, both horizontally and vertically according to Zenner and Hibbs (2000). The SCI integrates both vertical (size differentiation) and horizontal (spatial position) components of forest structure. It is based on the position of trees whose xy-coordinates are complemented with a tree attribute, such as dbh or height, as a z-coordinate. By a spatial tessellation approach (Delaunay 1934) each tree is connected to its neighbours such that triangles are defined. Those triangles then form a continuous faceted surface, i.e. a triangulated irregular network (TIN) (Figure 13a). If tree height is selected as the z-coordinate, this TIN can be visualized as connecting the tops of neighbouring trees (Fig. 13b). Instead of tree height, any measured continuously or ordinally scaled tree attribute can be chosen as the z-coordinate.

The SCI is defined as the surface area of the TIN in three dimensional space divided by the area covered by its projection on a plane surface. If all trees have the same z-value (e.g. all trees have the same height or basal area as in an even aged plantation) the SCI equals 1, the lower limit of the SCI. For structurally more complex forest stands the SCI is >1.

Fig. 13 Structural Complexity Index (SCI) of the plot Steinkreuz visualized as a triangulated irregular network (TIN) with dbh (a) and height (b) as selected tree attribute

Competition indices

Indices of spatial competition are commonly based on the nearest-neighbour (NN) concept where the immediate neighbours surrounding a subject tree are likely to have a competitive effect (Schneider et al. 2006). Using this approach, a competition index is calculated for each tree as a measure of the competition intensity exerted by neighbouring trees.

Competition index values typically are associated with the point locations of the subject trees. By contrast a different approach producing spatial competition fields has been developed where potential competition pressure is known for every point in a research plot. Such competition kernels are functions that describe how biological processes such as growth, survival and reproduction of an individual depend on its own size and the size of and distance to other individuals (Snyder and Chesson 2004; Vogt et al. 2010).

In our plots we quantified tree-tree competition by using a combination of a traditional competition index and a competition kernel as suggested by Pommerening and Maleki (2014). First we defined a zone of influence (ZOI) and then derived the actual competition index (CI) sensu stricto. We assumed that the ZOI is a circular area around a tree in which it predominantly draws on resources like light, water and nutrients (Berger and Hildenbrandt 2000). Where the ZOIs overlap, trees interact via competition for resources (Grimm and Railsback 2005). In this context, we considered symmetric competition as an equal sharing of resources among individuals whereas asymmetric competition is an unequal sharing of resources resulting from larger individuals having a competitive advantage over smaller ones (Schwinning and Weiner 1998; Freckleton and Watkinson 2001; Begon et al. 2006). Hence, we adapted an approach described in Pommerening and Maleki (2014) and calculated the radius of the Competition Zone (r_{CZ}) for each tree:

$$rCZ = \frac{\propto \times\ dbh}{\beta + dbh} \quad \text{(eq.3)}$$

where dbh is tree diameter at 1.3 m and α and β are parameters defined by species.

The Competition Index (*CI*) for every tree was calculated as follows:

$$CI = \frac{1}{dbh} \times \sum_{t \in C} \frac{dbh_t}{d_t} \quad \text{(eq.4)}$$

where dbh is diameter for a given tree, d_t is distance between the given tree and another tree in the plot, C is a set of trees which competition zones overlap with the competition zone of a given tree:

$$C = \{t \in T \dashv | \ d_\downarrow t < rCZ + rCZ_\downarrow t\} \quad \text{(eq. 5)}$$

T is a set of living trees in the plot.

Another way of displaying the space available for each tree and hence indirectly where competition is high, is the dual graph of the Delaunay tessellation: we used Voronoi diagrams to make changes after interventions visible (Fig. 14).
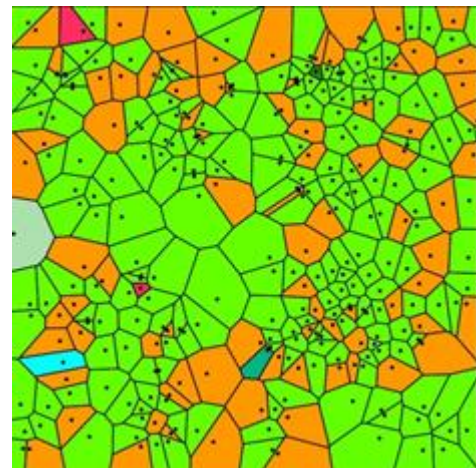

Fig. 14 Voronoi diagram of the Steinkreuz plot.

Concluding remarks

For all of the above applications, we used tree selection results from exercises performed in different Marteloscopes. Those exercises allowed us to test in how far they are suitable for practical silvicultural training or how they may be further applied in research activities. We encourage the reader interested in our work and the practical application of Marteloscopes to contact the authors for more information or support.

Acknowledgements

Author details

[1]Chair of Silviculture, University of Freiburg, Tennenbacherstr. 4, 79085 Freiburg im Breisgau, Germany, [2]European Forest Institute EFI, Yliopistokatu 6, 80100 Joensuu, Finland, [3]Swiss Federal Research Institute WSL, Zürcherstrasse 111, CH-8903 Birmensdorf, Switzerland, [4]Swiss Federal Research Institute WSL, EPFL, Bât. GR Station 2, ECOS, 1015 Lausanne–Ecublens, Switzerland, [5]Irstea, UR EMGR, Centre de Grenoble, F-38402 St-Martin-d'Hères, France, [6]INRA, UMR1201 DYNAFOR, Chemin de Borde Rouge, Auzeville, CS 52627, 31326 Castanet Tolosan Cedex, France, [7]CRPF-Occitanie, 7 chemin de la Lacade, 31320 Auzeville Tolosane, France, [8]BaySF, Forstbetrieb Ebrach, Marktplatz 2, 96157 Ebrach, Germany, [9]Landesforsten Rheinland-Pfalz, Le Quartier Hornbach 9, 67433 Neustadt an der Weinstraße, Germany, [10] Department of Forest Ecosystem Science and Management, Penn State University, University Park 16801, PA, USA

References

Assmann, E. 1970. The Principles of Forest Yield Study. Pergamon Press, Oxford.

Bässler, C. and Müller, J. 2010. Importance of natural disturbance for recovery of the rare polypore Antrodiella citrinella Niemela & Ryvarden. Fungal Biology 114:129–133.

Begon, M., Harper, J.L., Townsend, C.R. 1996. Ecology. Blackwell Science, Oxford.

Berger, U., Hildenbrandt, H. 2000. A new approach to spatially explicit modelling of forest dynamics: spacing, ageing and neighbourhood competition of mangrove trees. Ecol. Model. 132, 287–302.

Bouget, C., Larrieu, L., Brin, A. 2014. Key features for saproxylic biodiversity from rapid habitat assessment in temperate forests Ecological Indicators 36: 656–664.

Bouget C.; Larrieu L.; Parmain G.; Nusillard B. 2013. In search of the best local habitat drivers for saproxylic beetle diversity in temperate deciduous forests. Biodiversity and Conservation 22:2111–2130.

Bruciamacchie, M. 2006. Le marteloscope, un outil pour apprendre la gestion durable – exemple d'évaluation de différents scénarios au marteloscope de Zittersheim (Vosges du Nord). In: Valauri D, André J, Dodelin B, Eynard Machet R, Rambaud D, editors. Bois mort et à cavités – une clé. pour des forêts vivantes.

Paris: Lavoisier. pp. 237–252.

Courbaud B., Pupin C, Letort A., Cabanettes A., Larrieu L. 2017. Modelling the probability of microhabitat formation on trees using cross-sectional data. Methods in Ecology and Evolution, 8 (10), 1347-1359.

Courbaud, B., Lafond, V., Lagarrigues, G., Vieilledent, G., Cordonnier, T., Jabot, F., De Coligny, F. 2015. Applying ecological model evaludation: lessons learned with the forest dynamics model Samsara2. Ecological Modelling 314: 1-14.

Courbaud, B., de Coligny, F., Cordonnier, T. 2003. Simulating radiation distributionin a heterogeneous Norway spruce forest on a slope. Agric. For. Meteorol. 116,1–18.

Dajoz, R. 2007. Les insectes des forêts. Rôle et diversité des insectes dans le milieu forestier. Tec et Doc Lavoisier, Paris.

de Coligny, F., Ancelin, P., Cornu, G., Courbaud, B., Dreyfus, P., Goreaud, F.,Gourlet-Fleury, S., Meredieu, C., Saint-André, L. 2003. CAPSIS: Computer-Aided Projection for Strategies in Silviculture: advantages of a shared forest modelling platform. In: Amaro, A., Reed, D., Soares, P. (Eds.), Modelling Forest Systems.CABI Publishing, Wallingford, UK, pp. 319–323.

Delaunay, B. 1934. Sur la sphère vide. In: Bulletin of Academy of Sciences of the USSR. 7: 6, 793–800.

Dufour-Kowalski, S., Courbaud, B., Dreyfus, P., Meredieu, C., de Coligny, F. 2012. Capsis: an open software framework and community for forest growth modelling. Ann. For. Sci. 69 (2), 221–233.

Freckleton, R.P., Watkinson, A.R. 2001. Asymmetric competition between plant species. Funct. Ecol. 15, 615–623.

Gossner M.M., Lade P., Rohland A., Sichardt N., Kahl T., Bauhus J., Weisser W.W., Petermann J. S. 2015. Effects of management on aquatic tree-hole communities in temperate forests are mediated by detritus amount and water chemistry. J Anim Ecol. 85(1):213-26.

Gouix, N. 2011. Gestion forestière et Biodiversité, les enjeux de conservation d'une espèce parapluie :Limoniscus violaceus (Coleoptera). Thèse de doctorat de l'Université P. & M. Curie.

Grimm, V., Railsback, S.F. 2005. Individual-Based Modeling and Ecology. PrincetonU.P., Princeton.

Juutilainen, K., Halme, P., Kotiranta, H. and Monkkonen, M. 2011.Size matters in studies of dead wood and wood-inhabiting fungi. Fungal Ecology 4:342–349

Hosmer D.W., Lemeshow S., May S. 2008. Model development. In: Hosmer D.W., Lemeshow S., May S. (eds). Applied survival analysis. Regression modeling of time-to-event data, 2nd edn. Wileyinterscience, New Jersey, pp 132–168

Hunter, M.L. 1990. Wildlife, Forests, and Forestry: Principles of Managing Forests for Biological Diversity. Englewood Cliffs, New Jersey: Prentice-Hall.

Jonsson B.G., Kruys N., Ranius T. 2005. Ecology of Species Living on Dead Wood – Lessons for Dead Wood Management. Silva Fennica 39 (2): 289-309.

Kimmins, J. 2005. Forest ecology: A foundation for sustainable forest management and environmental ethics in forestry (3rd ed.). Upper Saddle River, NJ: Prentice Hall.

Kraus D., Krumm F. (eds). 2013 Integrative approaches as an opportunity for the conservation of forest biodiversity. European Forest Institute, 284 pp.

Kraus D., Mergner U., Schuck A., Krumm F., Haußmann T. 2016a. Integrate+: Wieviel Naturschutz kann der bewirtschaftete Wald leisten? Der Dauerwald 54, 33-38.

Kraus, D., Bütler, R., Krumm, F., Lachat, T., Larrieu, L., Mergner, U., Paillet, Y., Rydkvist, T., Schuck, A., and Winter, S. 2016b. Catalogue of tree microhabitats – Reference field list. Integrate+ Technical Paper 13. 16 p.

Kraus, D., Bebi, P., Buetler, R., Heintz, W., Krumm, F., Lachat, T., Larrieu, L., Lehnerova, L., Levin, M., Mergner, U., Pach, M., Paillet, Y., Pyttel, P., Rydkvist, T., Santopuoli, G., Sever, K., Sturm, K., Vandekerkhove, K., Winter, S., Witz, M., and Schuck, A. 2017. Spatially explicit database of tree related microhabitats (TreMs). Version 1.2. Integrate+ project. GBIF Dataset repository.

Lafond, V., Cordonnier, T., de Coligny, F., Courbaud, B. 2012. Reconstructing harvest-ing diameter distribution from aggregate data. Ann. For. Sci. 69, 235–243.

Lafond, V., Lagarrigues, G., Cordonnier, T., Courbaud, B. 2014. Uneven-aged man-agement options to promote forest resilience for climate change adaptation:effects of group selection and harvesting intensity. Ann. For. Sci. 71 (2), 173–186.

Larrieu, L., Paillet, Y, Winter, S., Bütler, R., Kraus, D., Krumm, F, Lachat, T, Michel, A., Regnery, B., Vandekerkhove, K. 2018. Tree related microhabitats in temperate and Mediterranean European forests: A hierarchical typology for inventory standardization. Ecological Indicators 84: 194–207 .

Larrieu L., Cabanettes A., Sarthou JP. 2015. Hoverfly richness and abundance strongly decrease, in montane beech-fir forest, as stand heterogeneity decrease. European Journal of Entomology 112(4): 755–769.

Lassauce, A., Paillet, Y., Jactel, H. and Bouget, C. 2011. Deadwood as a surrogate for forest biodiversity: Meta-analysis of correlations between deadwood volume and species richness of saproxylic organisms. Ecological Indicators 11:1027–103.

Le Louarn H., Quéré P.J. 2003. Les rongeurs de France - Faunistique et biologie, 2ème édition. INRA ed.

Lindenmayer, D. B., W. Blanchard, L. McBurney, D. Blair, S. Banks, G. E. Likens, J. F. Franklin, W. F. Laurance, J. A. R. Stein, and P. Gibbons. 2012. Interacting factors driving a major loss of large trees with cavities in a forest ecosystem. PLoS ONE 7 (1): 1–16.

Meeker, W.Q. and Escobar, L.A. 1998. Statistical Methods for Reliability Data. Wiley, New York.

Möller, G. 2005. Habitatstrukturen holz-bewohnender Insekten und Pilze. In Biodiversität im Wald, LöBF-Mitteilungen 03: S. 30-35.

Müller, J. and Bütler, R. 2010. A review of habitat thresholds for dead wood: a baseline for management recommendations in European forests. European Journal of Forest Research 129:981–992.

Müller, J., Bussler, H., Bense, U., Brustel, H., Flechtner, G., Fowles, A., Kahlen, M., Möller, G., Mühle, H., Schmidl, J. and Zabransky, P. 2005. Urwald relict species – Saproxylic beetles indicating structural qualities and habitat tradition. Waldökologie online 2:106–1.

Pommerening, A. and Maleki, K. 2014. Differences between competition kernels and traditional size-ratio based competition indices used in forest ecology. Forest Ecology and Management 331, 135–143.

Pommerening, A., Vítková, L., Zhao, X., Pallarés Ramos, C. 2015. Towards Understanding Human Tree Selection Behaviour. Forest Facts - Results from the Swedish University of Agricultural Sciences. Nr. 9 2015. 6 p.

Poore, A. 2011. The marteloscope – a training aid for continuous cover forest management. Woodland Heritage 2011, 28–29.

Pretzsch, H. 2009. Forest dynamics, growth and yield: From meas- urement to model. Berlin: Springer Verlag.

Puettmann K., Coates D., Messier C. 2009. A critique of silviculture: managing for complexity. Island Press, Washington, 200 p.

Regnery, B., Couvet, D., Kubarek, L., Julien, J.F., Kerbiriou, C. 2013. Tree microhabitats as indicators of bird and bat communities in Mediterranean forests. Ecol. Indic. 34, 221-230.

Schneider, M.K., Law, R., Illian, J.B., 2006. Quantification of neighborhood-dependent plant growth by Bayesian hierarchical modelling. J. Ecol. 94, 310–321.

Schuck, A., Kraus, D., Krumm, F., Held, A., Schmitt, H., 2015. Integrate+ Marteloscopes – Calibrating silvicultural decision making. Integrate+ Technical Paper No. 1. 12 p.

Schütz, J.P. 1997. Sylviculture 2. La gestion des forêts irrégulières et mélangées.Presses Polytechniques et Universitaires Romandes, Lauzane.

Schwinning, S., Weiner, J. 1998. Mechanisms determining the degree of size asymmetry in competition among plants. Oecologia 113, 447–455.

Snyder, R.E., Chesson, P. 2004. How the spatial scales of dispersal, competition and environmental heterogeneity interact to affect coexistence. Am. Nat. 164, 633–650.

Spinelli, R., Magagnotti, N., Pali, L., Soucy, M. 2016. Comparing Tree Selection as Performed by Different Professional Figures. Forest Sci 62, 213-219.

Tews J., Brose U., Grimm V., Tielbörger K., Wichmann M.C., Schwager M., Jeltsch F. 2004. Animal species diversity driven by habitat heterogeneity/diversity: the importance of keystone structures. J. Biogeogr. 31, 79–92

Vieilledent, G., Courbaud, B., Kunstler, G., Dhôte, J.F., Clark, J.S. 2010. Individual variability in tree allometries determines light resourceallocation in forest ecosystems—a hierarchical Bayes approach. Oecologia163, 759–773.

Vitkova, L., Dhubhain, A.N., Pommerening, A. 2016. Agreement in Tree Marking: What Is the Uncertainty of Human Tree Selection in Selective Forest Management? Forest Sci 62, 288-296.

Vogt, D.R., Murrell, D.J., Stoll, P. 2010. Testing spatial theories of plant coexistence: no consistent differences in intra- and interspecific interaction distances. Am. Nat. 175, 73–84.

Winter, S., Möller, G.C. 2008. Microhabitats in lowland beech forests as monitoring tool for nature conservation. Forest Ecol Manag 255, 1251-1261.

Zenner, E., Hibbs, D. 2000. A new method for modeling the heterogeneity of forest structure. Forest Ecology and Management, 129, 75-87.

Additional file

Annex I: Integrate+ Marteloscope plot information sheets (COM-I+ 26:3)