Forest Ecology and Management 429 (2018) 394–405

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Deadwood management in Central European forests: Key considerations for practical implementation

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ARTICLE INFO

Keywords:
Long-term retention
Saproxylic diversity
Microhabitats
Forest management

ABSTRACT

A substantial amount of literature on the importance of deadwood in Central European forests has been available providing partial recommendations to enhance deadwood-dependent biodiversity. However, a comprehensive review of science- and forestry experts-based recommendations effectively enhancing deadwood bearing in mind operational implications has not been presented in international literature. Therefore, this paper compiles the key aspects regarding the implementation of deadwood management in managed forests where the aim is to favour biodiversity without compromising or negatively affecting operational and commercial aspects of forest management. Simple deadwood management guidelines rooted in science and forestry expertise aiding decision-making in the efforts to effectively enhance biodiversity without compromising other management objectives are thus provided. Specifically, long-term retention of individual trees or tree groups and the retention of already existing deadwood (e.g. snags, coarse woody debris, uprooted, snapped, and sun-exposed trees) as well as artificial creation of deadwood (e.g. tree girdling) are presented here as we identified them as the key approaches to successful deadwood management. The major advantages and disadvantages of individual deadwood management approaches in terms of biological and operational/commercial aspects are also emphasised in order to assist forest managers in their decision-making. Furthermore, the key factors that should be considered when applying ecologically and economically efficient deadwood management are discussed; i.e. retention of trees with microhabitats, size of retained trees, position and arrangement, and decay stage. The main points regarding these factors are also addressed in the light of supporting realistic implementation of individual deadwood management approaches.

1. Introduction

Biodiversity is considered a fundamental driver of high intrinsic value that steers forest ecosystem functionality and facilitates for key ecosystem processes and services (Mori et al., 2017). An increasing amount of evidence supporting the significance of deadwood for biodiversity has been available. Although the significance of deadwood as a support for biodiversity has been widely recognised (e.g. Vandekerkhove et al., 2005; Bütler et al., 2007; Lassauce et al., 2011; Lachat et al., 2013; Bouget et al., 2014a, 2014b, etc.), deadwood was also reported to be important for carbon storage (Kueppers et al., 2004; Woodall and Liknes, 2008; Olajuyigbe et al., 2011), nutrient cycling (Laiho and Prescott, 2004; Yuan et al., 2017), soil forming processes and hydrology (Harmon et al., 1986), etc. Deadwood volumes in forests greatly vary depending on forest type (Christensen et al., 2005), tree species (Debeljak, 2006), stand age (Ekbom et al., 2006), geographical location (Stokland et al., 2012) as well as other factors. However, forest management and natural disturbance history also alter the volume of deadwood as well as its type and distribution throughout the forest.

Deadwood is generally present in rather low volumes in conventionally managed forests in comparison to natural forests (Siitonen et al., 2000; Pedlar et al., 2002; Debeljak, 2006; Larrieu et al., 2012; Dieler et al., 2017; Nagel et al., 2017). This is mainly due to the harvesting of trees once they reach the target diameter for felling, which allows to retain only a small amount of deadwood typically in a form of short stumps, small twigs and branches resulting in the absence of snags or large logs (Kruys et al., 1999). However, larger segments of deadwood are particularly important as they remain longer in the forest ecosystem continuously providing habitat as opposed to deadwood of small dimensions offering habitat only temporarily (Lachat et al., 2013). It is also essential to manage for diversity in the retained deadwood; i.e. a range of sizes, decay stages, tree species, locations, etc.

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https://doi.org/10.1016/j.foreco.2018.07.034
Received 19 April 2018; Received in revised form 17 July 2018; Accepted 18 July 2018

in order to provide suitable environment for a variety of deadwood-dependent species. Deadwood in natural forests results from tree mortality caused by senescence processes or by competition. Alternatively, deadwood may be created by natural disturbances whose quantity and type is rather variable (Rahman et al., 2008) similarly as the deadwood types and quantities it creates (e.g. splintered stems, snapped or broken stems and branches, uprooted trees, etc.). The structure and function of the deadwood changes over time following the natural disturbances (McComb and Lindenmayer, 1999) also depending if any silvicultural interventions are consequently applied. Salvage logging, for instance, tends to remove most of the deadwood substantially reducing the overall deadwood quantities (Priewasser et al., 2013, Michalová et al., 2017).

To a limited extend, the concept of deadwood management has been a part of forest management of some state forest enterprises as well as for some private forest properties in e.g. Germany, Switzerland, France, Italy, Austria, Sweden and Denmark. Life and Life+ projects reports also provided relevant information on some of the practical cases of deadwood management (i.e. Cavalli and Mason, 2003; Mason et al., 2003) with NATURA 2000 reports also delivering information on deadwood management in some of the above-mentioned European countries (European Commission, 2015). Nonetheless, outcomes of forest management practices focusing on the enhancement of deadwood quantity and quality have not been available in published international literature with only some exceptions (e.g. Doerfler et al. (2017) focusing on the success of a deadwood enrichment strategy in production forests in Germany). Although deadwood volumes are assessed on a 5-years basis across European Union (e.g. Forests Europe, 2015), detailed information on deadwood quantities of different types and stages of decay in production forests is unavailable in many countries since the management practices aiming at deadwood enhancement have been applied only for the last 20 years. This period is too short to allow us to record sufficient data on the development of deadwood over time. Besides, detailed deadwood monitoring that would normally yield valuable data on deadwood quantities and qualities has not been part of national forest inventories in some countries. However, although strategies to increase the deadwood qualities in managed forests have been implemented in the light of biodiversity enhancement and certified sustainable forest management (e.g. PEFC, 2010; FSC, 2013) and they have been monitored as a part of National Forest Inventories in some countries (e.g. Germany, Switzerland, the Netherlands), their success have been largely under-reported across Europe (Doerfler et al., 2017). Nonetheless, deadwood has been stated as one of the indicators of sustainable forest management.

Maintenance of sufficient deadwood quantities comprising of a variety of deadwood types does not only locally increase saproxylic species diversity. It also reduces the risk of the saproxylic species becoming extinct thanks to the presence of suitable habitat and thus their viable population. Maintaining sufficient population also reduces the risk of undesirable loss of genes, which occurs during prolonged reduction in population due to ecological and stochastic reasons (Økland et al., 1996). A variety of deadwood types shall be also encouraged, with the same applying to the diversity of deadwood's spatial distribution and stages of decay supporting a range of habitats since different species require different conditions (Bouget et al., 2013). The importance of the presence of old trees and continuous deadwood supply in the conservation of red-listed species was also highlighted especially since the occurrence of relict saproxylic species correlates with the continuity in forest cover containing such features (Buse, 2012). The retention of trees bearing microhabitats and deadwood should be thoughtfully planned in order to ensure long-lasting habitat continuity (Bütler et al., 2013).

A substantial amount of literature on various aspects of deadwood providing and summarising valuable information on deadwood diversity and volume but also the importance of deadwood for ecology of saproxylic species has been available among other topics (Heilmann-Clausen and Christensen, 2003; Heilmann-Clausen et al., 2005; Müller and Bütler, 2010; Lassace et al., 2011; Bouget et al., 2012, 2013; Dittrich et al., 2014; Müller et al., 2015a; Gossner et al., 2016; Doerfler et al., 2017). Individual recommendations supporting specific deadwood management approaches have also been offered; i.e. the necessity to have certain deadwood quantity and/or quality (dimension, position, tree species, etc.) (e.g. Kappes et al., 2009; Müller and Bütler, 2010; Doerfler et al., 2017). However, international literature concisely compiling and presenting a combination of science- and expertise-based recommendations guiding the enhancement of deadwood volumes and diversity in managed temperate forests of Central Europe has not been available; especially when considering commercial feasibility of individual approaches but still bearing in mind the biodiversity enhancement. Although deadwood-related literature often concludes with recommending the increase in deadwood volumes and/or deadwood diversity (e.g. Bunnell and Houde, 2010; Müller and Bütler, 2010), a range of specific, simple and feasible operational approaches that can be implemented to achieve these deadwood management recommendations is rarely mentioned. Especially, if the balance between the deadwood management benefits biodiversity with operational and commercial aspects also taken into an account.

Therefore, the major aim of this paper is to concisely present the key deadwood management approaches – based on scientific findings and expertise - that can be considered in public and private temperate forests of Central Europe. This is conducted in the efforts to effectively enhance deadwood volume and its diversity without compromising other management objectives or increasing operational costs. The major factors necessary to be considered when applying an effective deadwood management are also included in order to support its realistic implementation in practice. We further emphasise the major benefits and drawbacks of individual deadwood management approaches in order to provide a representative picture of its application bearing in mind operational feasibility and commercial viability of these approaches.

2. Approaches to forest management enhancing deadwood

Based on the vast amount of literature published on deadwood as an important biodiversity indicator as well as on existing expertise, several approaches that can be used to increase deadwood quantities and types in managed forest were identified; i.e. the retention of single trees or groups of live trees or the retention of snags and already existing deadwood. Although these methods reflect research concerning the functional effectiveness of measures to promote biodiversity (e.g. Fedrowitz et al., 2014; Hämäläinen et al., 2014), other methods such as retention of lying logs following harvesting, retention of uprooted trees or artificial creation of deadwood by generating high tree stumps or killing of targeted trees (e.g. girdling) can also be considered. Combination of individual deadwood management approaches is also considered a suitable concept for deadwood management in order to achieve greater volume and diversity of deadwood (Ranius et al., 2005).

Opting for deadwood enhancement approaches can increase the diversity (decay stage and dimensions) of deadwood, which is more important for biodiversity than the actual deadwood quantity (Rimle et al., 2017). It is important to work with natural processes that create deadwood but also to improve linkages between existing deadwood features by artificially generating additional deadwood as well as protecting already existing deadwood (Humphrey and Bailey, 2012). Deadwood management is challenging and presents numerous trade-offs between biodiversity enhancement and operational or commercial aspects. Therefore, some of the major advantages and disadvantages of selected deadwood management approaches forest managers are likely to encounter when adopting deadwood management are demonstrated in Tables 1 and 2. Although some efforts towards tree retention already takes place in many commercial forests, it is important to bear in mind

Table 1
The main advantages and disadvantages of major biological aspects of selected deadwood management approaches aiming at deadwood enhancement in managed forests.

Management approach	Advantages	Disadvantages
Individual (live) tree retention	Creates important stepping stones and microhabitat for saproxylic beetles; provides key microhabitat for future development of standing and consequently lying deadwood; provides continuous supply of seeds; supports the development of old-growth elements in the forests	If retained trees are too small, once decayed, they may not form a suitable habitat for saproxylic species requiring larger segments of deadwood
(Live) tree group retention	Creates important microhabitat for saproxylic fungi or epixylic bryophytes; forms buffering effect - microclimate; provides key substrate for future development of standing and consequently lying deadwood; provides continuous supply of seeds; supports the development of old-growth elements in the forests	If retained trees are too small, once decayed, they may not form a suitable habitat for saproxylic species requiring larger segments of deadwood
Retention of existing deadwood	Already existing deadwood of advanced stages of decay provides microhabitats for saproxylic organisms; supports the development of old-growth elements in the forests	May be a source of pests in the case of susceptible species (e.g. Norway spruce and bark beetle); freshly created snags may require longer time to become suitably decayed
Retention of uprooted trees	Provides microhabitats for saproxylic species; supports the development of old-growth elements in the forests	Freshly uprooted trees require longer time to become suitably decayed for some saproxylic species; possible entry point or a source of pests in case of susceptible species (e.g. Norway spruce and bark beetle)
High stump retention/ creation	Provides suitable substrate for the development of short snags and microhabitats for saproxylic organisms	Depending on the height of the stump, the decay and disintegration can be rapid
Live trees girdling	Supports the creation of deadwood and consequently microhabitats for saproxylic organisms; supports the development of old-growth elements in the forests	Girdled area may be an entry point for unwanted tree pests and diseases
Retention of deadwood of desired tree species	Supports (not only) specialist saproxylic species bound to deadwood of particular tree species	Potential source of pests in the case susceptible species are retained (e.g. Norway spruce and bark beetle)
Retention of trees of specific diameter	Creates substrate for the development of deadwood of dimensions suitable for (not only) specialist saproxylic species bound to deadwood of specific tree species; supports the development of old-growth elements in the forests	If the retained trees are too small, saproxylic species requiring large deadwood segments may not be able to colonise (and vice versa); retention of small trees results in their rapid decay
Retaining sun-exposed trees and deadwood	Creates substrate for the development of deadwood with suitable properties for specialist saproxylic species requiring warm and sun-exposed conditions; supports the development of old-growth elements in the forests	If the retained trees are too small, saproxylic species requiring large deadwood segments may not be able to colonise (and vice versa); retention of small trees results in their rapid decay

that the resulting deadwood volumes should be within a recommended range considering the state of forest stand, forest management history, species composition, stand age, etc. (e.g. Müller and Bütler, 2010). In the following sections, we present some of the major practices that can be employed to enhance deadwood that, at the same time, reflect decisions likely faced when adopting effective deadwood management.

2.1. Retention of living single trees and tree groups

Allowing individual trees or small groups of trees to reach the end of their life span is an effective measure to increase the amount of deadwood. The retained individual trees or tree groups can reach the stage of veteran trees that eventually develop into snags (unless damaged by wind and consequently fallen on the ground) that decay disintegrating

Table 2
The major operational/commercial aspects of individual management approaches aiming at deadwood enhancement in managed forests where the main advantages and disadvantages are presented.

Management approach	Advantages	Disadvantages
Individual (live) tree or tree group retention	Reduces harvesting and logging cost if the retained trees are located in areas with difficult access (extreme slopes, rugged terrain, etc.)	Potential loss of financial revenue as the retention of individual trees or tree groups may involve trees of larger diameters aimed at timber production
Retention of existing deadwood	Reduces harvesting or tending costs as decaying trees are of low or no commercial value for timber or fuel wood production or are located in an area with difficult access	May form obstacles to logging operations or to access routes or on roads and paths, etc.; possible health and safety risk to public if close to roads, paths, etc.
Retention of uprooted trees	Reduces harvesting or tending costs as uprooted trees are of low commercial value for timber production or located in an area with difficult access	May pose health and safety risk to forest workers or may create an obstacle when located close to roads, paths, etc.
High stump retention/ creation	Creating high stump from a tree of poor form at its base does not decrease quality of the harvested log; easier in the mountain forests	Additional costs involved as trained and skilled staff is necessary to carry out the operation
Live trees girdling	If poor quality trees are retained for girdling, the overall quality of harvested timber is not decreased. Could be used to kill non-native species	Additional costs involved as trained and skilled staff is necessary to carry out the operation especially if carried out repeatedly across larger areas
Retention of deadwood of desired tree species	Undesirable species for timber production are retained to reduce the harvesting and transport costs especially if located in an area with difficult access	Possible loss of financial revenue as the retention may involve trees aimed at timber production
Retention of trees of specific diameter	Trees of undesirable dimensions are retained, which reduces the harvesting and transport costs, especially if located in an area with difficult access	Potential loss of financial revenue since the retention of individual trees of larger dimensions may be aimed at timber or fuel wood production
Retaining sun-exposed trees and deadwood	Retention of poor quality trees or those located in an area with difficult access that are exposed to sun reduces the harvesting and transport costs, especially if located in an area with difficult access	If under denser canopy, heavier thinning may be required in the close proximity of the retained tree(s) to create more light accessing the tree

into coarse woody debris with progressing time. The decay rate increases with e.g. rising air humidity and temperatures or the length of vegetative period. Priority should be given to the oldest and largest trees, preferably those with already existing microhabitats (for detail see Section 3) and with some extent of deadwood (Bouget et al., 2014a, 2014b; Müller et al., 2014). When choosing trees to be retained and left for snag formation, trees with the presence of microhabitats or defects found within the first 2 m of the bole should be prioritised. Healthy logs and stems with the diameter < 30 cm should be used for retention only if there are no other options since it is beneficial to keep larger segments of deadwood due to their longer residence time (Bače and Svoboda, 2015).

There are several options in tree retention; the group of trees or individual trees can be marked and retained in production forests with the remaining stand being subjected to usual silvicultural interventions. Alternatively, trees can be located at more open site with direct light reaching the retained trees. An area between the forest stand and a meadow, field, water body, etc. may be also considered a suitable place without the necessity to excessively open the canopy and therefore minimise the loss of timber production and quality of future stands within the area. It is possible to use deforested areas in continuously wooded landscapes, such as electricity pylon routes, abandoned forest tracks, rides or pastures, etc.

A combination of dispersed and aggregated patterns can be used when retaining individual trees and tree groups (Bütler et al., 2013). The retention of aggregated tree groups was reported to provide suitable sites for birds than in the case of dispersed retention (Bütler et al., 2013). Similarly, lichens perform better within a small group of retained trees as opposed to dispersed individuals (Nascimbene et al., 2013). Thorn et al. (2017) reported that this is the case for the majority of saproxylic species. The retention of sun-exposed scattered trees, on the other hand supports umbrella species such as great Capricorn beetle (*Cerambyx cerdo* L.) (Buse et al., 2007; Albert et al., 2012) or long-horned beetle (*Rosalia alpina* L.) (Russo et al., 2011).

2.2. Retention of existing deadwood

If deadwood of various decay stages and sizes already exists at a site of interest (e.g. snags, fallen deadwood or uprooted trees), it is favourable to preserve it. If any standing dead trees or snags of preferably large dimensions are available, they should be retained in full. However, exceptions may include snags that pose an imminent risk to the health and safety of public (i.e. snags near publicly accessible roads and paths, places with increased recreational activities) and forest workers (tending operations, marking, etc.) or if they form a major obstacle for harvesting. Nonetheless, if a snag needs to be felled, its remnants should be left where the felling took place, if possible.

Similarly, as in the case of snags, as far as possible, already existing lying deadwood shall be retained. Lying deadwood resulting from natural disturbances (uprooted trees and trees broken by wind/snow) tend to be subjected to salvage logging. Should deadwood resulting from natural disturbances pose no risk to the production forests in terms of generating greater pest outbreaks, some of the uprooted or snapped trees can be retained. Uprooted trees create favourable conditions for natural regeneration in the form of exposed mineral soil and pit-and-mound topography, while being important for natural soil development (Šamonil et al., 2010, 2014). Displaced root plates should be prevented from returning to their initial position following the disturbance. Logging practices (careless winging or skidding) damaging already existing deadwood or uprooted trees should be also prevented.

2.3. Artificial creation of deadwood

Retaining thick crown branches or entire crowns after felling operations is considered a suitable tool to increase the amount of lying deadwood along with the retention of poorer quality stems after harvesting (Doerfler et al., 2017). Implementation of such deadwood enhancing strategy is considered an achievable way to promote biodiversity in the production forests (Doerfler et al., 2017). Uprooted trees, high stumps, snags as well as standing and leaning dead trees can be created artificially (e.g. Cavalli and Mason, 2003; Nordén et al., 2004; Brin et al., 2013; Mason and Zapponi, 2015). Active creation of these deadwood features usually include tree girdling, felling and pulling, inoculation with fungal pathogens or combination of these techniques by skilled chainsaw operators (Lewis, 1998; Kuuluvainen et al., 2004).

Trees with microhabitats also bearing deadwood can be generated using some of the above-mentioned approaches along with de-limbing and active creation of cavities and basal pockets of various sizes (Lewis, 1998). The nesting cavities can be created by cutting and extracting a wood block from the tree 1–4 m above the ground and cutting a thin slice to make a lid to close the cavity (Zapponi et al., 2015). Basal pockets, on the other hand, can be made by creating slits using a chainsaw (Zapponi et al., 2015). Pollarding (i.e. the periodical removal of the upper branches of a tree by pruning; Thomas, 2000) was reported to lead to the rapid formation of cavities and is thus considered an important technique in cavities-dependent species and saproxilic habitats restoration (Sebek et al., 2013). Other microhabitats such as stem splintering and various injuries further developing into microhabitats can be also generated using a chainsaw.

Beside additional costs and the necessity to employ specially trained staff the above-mentioned practices may be limited by legislation in some countries. However, the benefits of these deadwood-enhancing practices also leading to creation of crucial microhabitats and thus greatly facilitating for biodiversity are likely to offset the costs and efforts involved.

3. Key factors to be considered as a part of deadwood management

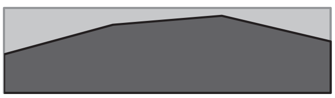
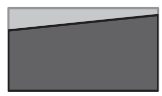
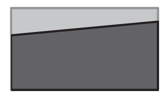
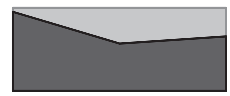
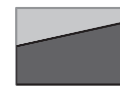
A range of factors affects deadwood management causing differences in the trends of species diversity in different species groups. In order to support the key factors that shall be considered in deadwood management, selected key factors are presented in Table 3 in order to demonstrate the differences in the trends of selected deadwood-dependent species groups such as lichens, bryophytes, fungi, beetles, vertebrates and invertebrates.

3.1. Retaining trees with microhabitats

If available, trees harbouring microhabitats shall be favoured for retention when making a decision on retaining a group of trees or individual trees (Bouget et al., 2014a, 2014b; Müller et al., 2014; Fig. 1, Table 3). Trees with microhabitats often bear some amount of deadwood providing necessary habitats for a range of species (or groups of species) to grow, nest or forage as a part of their life cycle (Winter and Möller, 2008; Vuidot et al., 2011; Larrieu et al., 2014; Paillet et al., 2017; Larrieu et al., 2018; Kozák et al., 2018). The retention focus shall be also made on individuals with the potential to develop fully functioning microhabitats over time (e.g. presence of injuries, harvesting damage, etc.). Such trees shall be selected early; if necessary, they should be released from competition by means of thinning to prevent suppressed crown and root system ensuring the full development of microhabitats and deadwood (Krása, 2015). If information is available on individual's age, attempts should be made to give the priority to the oldest trees as they often feature well-developed microhabitats (Winter and Möller, 2008; Michel and Winter, 2009; Vuidot et al., 2011).

The number of trees bearing microhabitats is minimised in production forests since conventional silvicultural approaches remove trees with microhabitats as such trees are considered of poor quality in terms of timber production. The trees bearing microhabitats are rarely fully developed in production forests due to relatively short rotation periods and harvesting of trees once they reach target diameter as opposed to

Table 3
Trends of the differences in species diversity given different deadwood factors; figures represent the proportion of particular taxon in relation to the maximum number of species given the level of particular factor - the scales of individual parameters were united to simplify their interpretation. The description of decay stages is detailed in Appendix A.

Taxon	Factors												
	Stage of decay				Position		Mean size		Light exposure			Tree species	
	0	1	2	3	Standing	Lying	10–20 cm	> 20 cm	Direct light	Semi-shade	Full shade	Conif.	Broadl.
Lichens[1,2]	0.40	0.73	0.88	0.38	1.00	0.25	0.55	1.00	0.80	1.00	0.80	–	–
Bryophytes[1,2]	0.13	0.63	0.70	0.65	0.00	1.00	0.65	1.00	0.10	0.50	1.00		–
Fungi[1,2]	0.33	0.70	0.80	0.73	0.30	1.00	0.80	1.00	0.25	0.80	1.00		–
Beetles[2,3,4]	0.70	1.00	0.85	0.10	1.00	0.70	0.95	1.00	0.97	0.95	0.47		–
Vertebrates[1]	1.00	1.00	0.75	0.30	–	–	–	–	–	–	–	–	–
Invertebrates[4]	0.30	0.40	0.70	0.95	–	–	0.85	1.00	1.00	0.80	0.80	–	–
All species[5,6]	0.45	0.88	0.90	0.35	0.83	0.95	0.75	1.00	1.00	0.15	0.35	0.60	1.00
Weighted average	0.50	0.88	1.00	0.67	0.80	1.00	0.80	1.00	1.00	0.60	0.69	0.60	1.00
Trend (weighted average)													

[1] Bunnell and Houde (2010).
[2] Jonsson et al. (2010).
[3] Lindhe et al. (2005).
[4] Jonsell et al. (2004).
[5] Stokland et al. (2004).
[6] Stokland and Meyke (2008).

leaving them to reach the end of their life span as in natural forests. This was confirmed by studies comparing the abundance of microhabitats in production and natural unmanaged forests (Winter and Möller, 2008; Vuidot et al., 2011; Regnery et al., 2013; Paillet et al., 2017). Although microhabitats are found in production forests, their diversity is usually rather limited to e.g. bark loss, dendrothelms, cavities, etc. (Larrieu et al., 2012). However, it is still favourable to focus on retention of trees that bear such microhabitats. In addition, the retention of trees of different sizes, species and decays stages that bear microhabitats shall be conducted at a range of sites; i.e. sites with special designation/

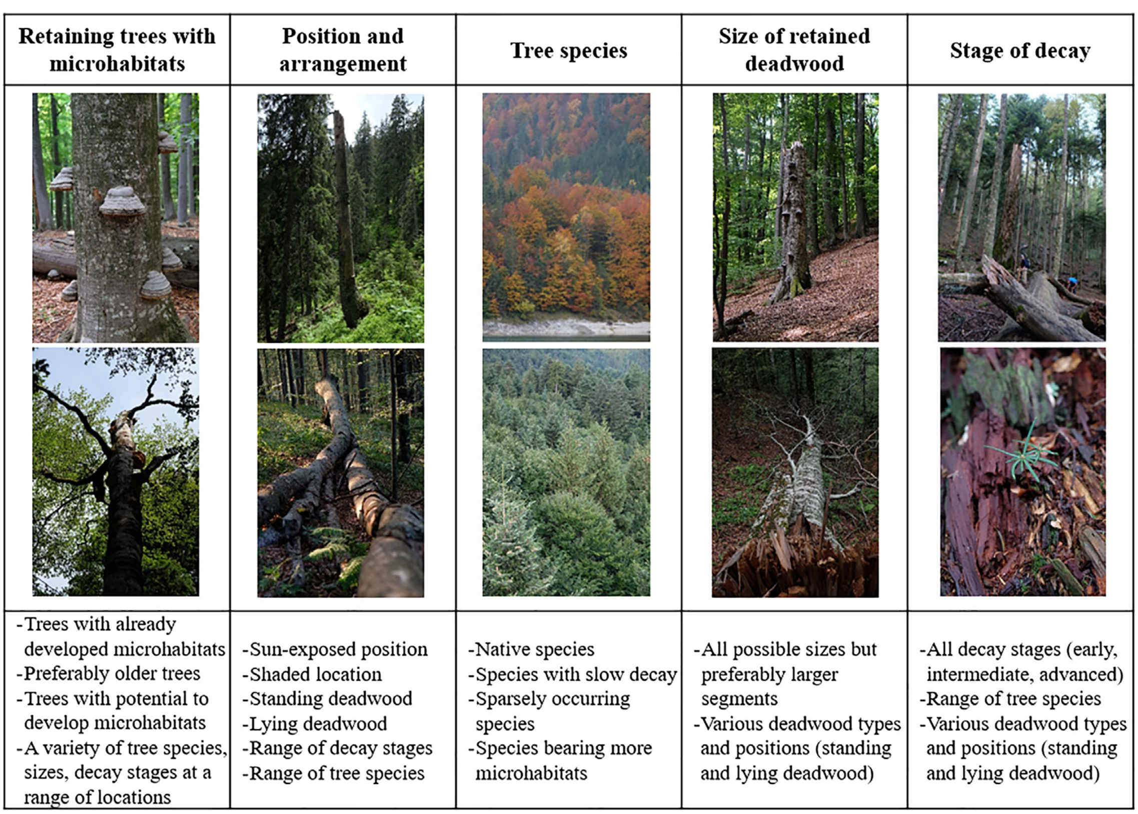


Fig. 1. Key factors of deadwood management along with the major points worth bearing in mind when considering deadwood management.

protection status, commercially productive as well as unproductive sites, different forest types, diverse altitudes, etc.

3.2. Size of retained deadwood

Enhancing the occurrence of deadwood of large dimensions was reported to have positive effects on biodiversity (e.g. Økland et al., 1996; Gossner et al., 2013; Svensson et al., 2014; Juutilainen et al., 2014; Seibold et al., 2014). The presence of large segments of deadwood is considered a more important factor in comparison to, for example, the position of deadwood (standing/lying) in explaining the occurring species diversity (Bouget et al., 2012) (Fig. 1, Table 3). Large segments of deadwood are also favoured since greater tree diameter correlates with thicker bark with diverse features (e.g. increased level of cracks and rugged texture of the outer bark) (Bače and Svoboda, 2015) or a long-term provision of nutrients (Herrmann and Bauhus, 2018). Larger dimensions contribute to longer decay time and thus longer period for the suitable habitat to be available (Heilmann-Clausen and Christensen, 2004). In addition, deadwood of greater volume has a smaller surface area/volume ratio, which results in a greater stability of temperature and moisture in deadwood (Bače and Svoboda, 2015).

Large logs cannot be replaced with the equal volume of smaller logs in the light of supporting the enhancement of biodiversity since many species only require deadwood of larger proportions (Kraus and Krumm, 2013). Although the retention of high stumps was reported to be more beneficial in comparison to brash retention, the combination of both brash and high tree stumps retention was stated as a suitable option in terms of economy and functional effectiveness for biodiversity (Ranius et al., 2014). The presence of deadwood of large dimensions can be considered as a good indicator of continuity since their wood decomposition is rather slow. The continuity of deadwood is of high importance as it facilitates for better connectivity and allows organisms to better disperse, interact, and access resources (North and Keeton, 2008).

Unlike deadwood of large dimensions, deadwood of small dimensions in a form of small branches and small stems can be found in production forests (Fridman and Walheim, 2000; Bače and Svoboda, 2012). If forest management measures incorporating deadwood enhancement are adopted, it is necessary to enhance the diversity of deadwood dimensions and actively focus on the development of large segments of deadwood. However, smaller deadwood segments are also necessary since some saproxylic species require smaller stem or branch thickness (Ódor et al., 2006; Juutilainen et al., 2014).

3.3. Tree species

It is appropriate to retain native species whose occurrence is sparse (Økland et al., 1996) in order to support local species communities and thus achieve a greater diversity in deadwood of native species composition. Tree species with slow rate of decay should be prioritised for retention since the rate of decay varies amongst individual species; oaks (*Quercus* spp.) have a slower decomposition rate in comparison to spruces (*Picea* spp.), pines (*Pinus* spp.), and European beech (*Fagus sylvatica* L.) that decompose 1.4, 1.6 and 1.8 times faster than oaks, respectively (Rock et al., 2008). Moreover, broadleaved species tend to bear more microhabitats, which should be considered when choosing which trees to retain (Larrieu et al., 2012). It is important to include late successional species such as European beech as well as pioneer species e.g. birch (*Betula* spp.), poplar (*Populus* spp.), and willow (*Salix* spp.) where possible (Fig. 1, Table 3).

Although it is also important to enhance deadwood in coniferous forests, conifers tend to support less microhabitats, which is the case for various geographical locations in Europe. This is due to multiple reasons such as natural lack of certain microhabitats in conifers due to evolution in the mountain areas, their use in plantation forestry where they rarely reach the senescence age when microhabitats are formed, etc. More microhabitats were reported on European beech in comparison to silver fir (*Abies alba* Mill.) in beech-fir forests in central Pyrenees where fir bears no microhabitats below the diameter of 68 cm (Larrieu et al., 2012). In Scandinavian forests, deadwood of broadleaved species generally supports a greater diversity of saproxylic species than deadwood of coniferous species (e.g. Stokland et al., 2004). The oak genus should be emphasized in particular; pedunculate (*Quercus robur* L.) and sessile oaks (*Quercus petraea* (Matt.) Liebl.) are important for biodiversity of saproxylic invertebrates in Central Europe (Vodka et al., 2009; Bouget et al., 2011). In Sweden, for instance, 32% (i.e. 174) of Red-listed saproxylic species are bound to oak species (Jonsell et al., 1998). In the case of Central Europe, many saproxylic beetles are attracted to hornbeam (*Carpinus betulus* L.) in the first years of its wood decomposition, even if left in the shade (Müller et al., 2015b). In contrast to hornbeam, although also supporting some specialised lichen and moss species, ash (*Fraxinus excelsior* L.) trees do not host that many saproxylic species, which is perhaps linked to specific chemistry of its wood (Müller et al., 2015b). Sycamore (*Acer pseudoplatanus* L.), however, another broadleaved tree species, is significant for the biodiversity of lichens, particularly at higher elevations (Bače and Svoboda, 2015).

3.4. Position and arrangement

The position of deadwood influences its properties since many fungi and bryophytes are favoured by shaded moist conditions while dry and warmer conditions are generally suitable for saproxylic beetles and lichens (Lachat et al., 2013) (Fig. 1, Table 3). Therefore, it is important to retain sun-exposed trees in gaps or under more open canopy as a part of deadwood enhancing management (Rosenwald and Löhmus, 2008; Gustafsson et al., 2010; Parmain and Bouget, 2018) as such features support valuable microhabitats favouring saproxylic umbrella species (Buse et al., 2007; Albert et al., 2012; Russo et al., 2011). Moreover, the sun-exposed and warm conditions in gaps may appeal to shade-intolerant beetle species that are attracted by the openness as opposed to the actual microhabitat trees bearing deadwood (Koch Widerberg et al., 2012). Deadwood with elevated moisture, on the other hand, showed greater fungal community succession, which was especially pronounced in advanced stages of decay (Rajala et al., 2012).

It is necessary to consider diversity of deadwood types when retaining particular trees or tree groups in order to correctly meet the deadwood management objectives. In some cases, standing deadwood hosts more saproxylic species than lying deadwood as demonstrated on e.g. oak snags that facilitate a higher number of individuals of saproxylic beetles than lying logs (Bouget et al., 2012). Lying deadwood on the other hand tends to host a greater number of fungi and bryophytes in comparison to standing deadwood (Jonsson et al., 2010). It is also important to note that similar substrates at different locations, e.g. forest floor, tree stem or canopy branches, can facilitate conditions for different species; snags, for instance, accommodated for species that were absent from lying logs (Bouget et al., 2012).

3.5. Decay stage

Saproxylic species richness and the occurrence of rare saproxylic species is determined by the presence of deadwood that is, amongst other factors such as deadwood size, determined by the decay stage (Heilmann-Clausen and Christensen, 2004; Sefidi and Etemad, 2015). Therefore, enhancing diversity of deadwood types in different stages of decay (retention of existing deadwood and creation of new segments) is considered a viable management option to increase biodiversity in forests (Ódor and Standovár, 2001) (Fig. 1, Table 3). Decaying wood hosts a large number of lichens, bryophytes, fungi and invertebrates whose occurrence is influenced by the decay stage (Ódor and Standovár, 2001; Ódor and van Hees, 2004; Penttilã et al., 2004; Siitonen et al., 2000). Intermediate and advanced decay stages appear to be the most favourable for many species of fungi, with the more progressed intermediated stage being particularly favourable for some Red-listed species (Heilmann-Clausen and Christensen, 2003; Persiani et al., 2015; Sefidi and Etemad, 2015). Small vertebrates, on the other hand, seek earlier stages of decay for foraging (Bunnell and Houde, 2010).

Different deadwood types vary in their decay dynamics; i.e. the decay rates of standing deadwood tend to be slower than in the case of lying deadwood (Jomura et al., 2008; Bouget et al., 2012). It is thus necessary to retain or create different types of deadwood as part of forest management to support a range of decay stages that host a variety of not only saproxylic species. Apart from its significance for saproxylic diversity, decaying wood also supports natural regeneration especially in mountain forests as deadwood as a substrate favours the occurrence and survival success of natural regeneration of e.g. Norway spruce (Zielonka, 2006; Bujoczek et al., 2015). A study from Šumava National Park (south-eastern Czech Republic) showed that most Norway spruce seedlings grew on lying deadwood of intermediate and advanced decay stages (Čížková et al., 2011). This was attributed to diverse and rugged surface of the deadwood but especially to the stable hydrological conditions and better accumulation of water in the deadwood offering suitable microhabitat conditions for Norway spruce seedlings.

4. Suitable settings for an effective deadwood management

Individual forests comprise of diverse site conditions of different value when initiating deadwood management. Therefore, several considerations need to be taken into an account when planning the application of deadwood management. Prior to the deadwood management application, it is important to consider several aspects in the light of assessing the site's suitability to particular deadwood enhancing approach: (i) current levels of deadwood on site, (ii) continuity and diversity of deadwood habitats over time, (iii) interest in conservation of specific saproxylic, (iv) ecological connectivity and (v) history of management (Humphrey and Bailey, 2012).

It is important to preserve deadwood in parts of forests of higher ecological value where deadwood already occurs. Nonetheless, deadwood should also be enhanced in areas where it is absent since even a small increase in deadwood quantity may be a positive prerequisite for some saproxylic species to occur. The implementation of different approaches aiming at deadwood enhancement should ensure uneven distribution of deadwood across the forest with the efforts to increase the proportion of deadwood in places where it is absent. However, the decision-making should be case-specific due to a large variation in site conditions; an example of the potential to implement deadwood management is demonstrated in Fig. 2; a case study of a forest property commonly found in Central Europe.

Natural forests are, by definition, rich in deadwood, in comparison to production forests, and may serve as refugia of specialist saproxylic species that have an increased demand on the amount of deadwood (Gossner et al., 2013). Forest reserves or forests stands where harvesting was abandoned were also studied to show the growing amounts of deadwood providing valuable habitats (Vandekerkhove et al., 2009; Meyer and Schmidt, 2011; Paillet et al., 2015). If there are natural reserves around the area where higher quantities of deadwood already occur, priority should be given to retaining deadwood near such sites in order to create 'stepping stones' and thus support suitable conditions for the populations of saproxylic species and their potential to spread further. In order to create similar deadwood hotspots in managed forests, it is favourable to focus the deadwood enhancing practices in areas not desired or suitable for timber production such as waterlogged depressions, rocky slopes and buffer zones along watercourses. Refraining from timber harvesting in such places or in difficult terrain also reduces the harvesting costs.

There are several cases where the deadwood enhancement should be avoided or carefully planned due to health and safety reasons. The retention should be restricted near frequently used routes such as marked hiking and cycling trails, where the retained or created deadwood may present an increased risk to the safety of forest visitors. Another such example is where the tree retention forms an obstacle to harvesting or tending operations or transport routes. Tree retention should be carefully planned if the retained tree or tree group is located immediately next to a fenced area in order to avoid or minimise damage to the fence due to a fall or a breakage of a fragment of the retained group. In addition, retention of tree species susceptible to insect outbreaks shall be limited; e.g. refrain from retaining Norway spruce (*Picea abies* L. Karst.) near stands dominated by this commercially important coniferous species due to its susceptibility to bark beetle (*Ips typographus* Linnaeus, 1758) outbreak. We have to be cautious especially in the case of larger amounts of early stages of deadwood in single species plantations of Norway spruce. However, this effect is much less pronounced in forests with mixed species composition of structurally heterogeneous stands.

The key measure allowing single trees or groups of trees to reach the end of their life span does not have to be strictly applied under all circumstances. In order to minimise the financial loss, priority should be given to retention of trees whose preservation produces smaller economic loss. If an ideal deadwood type - known to greatly enhance

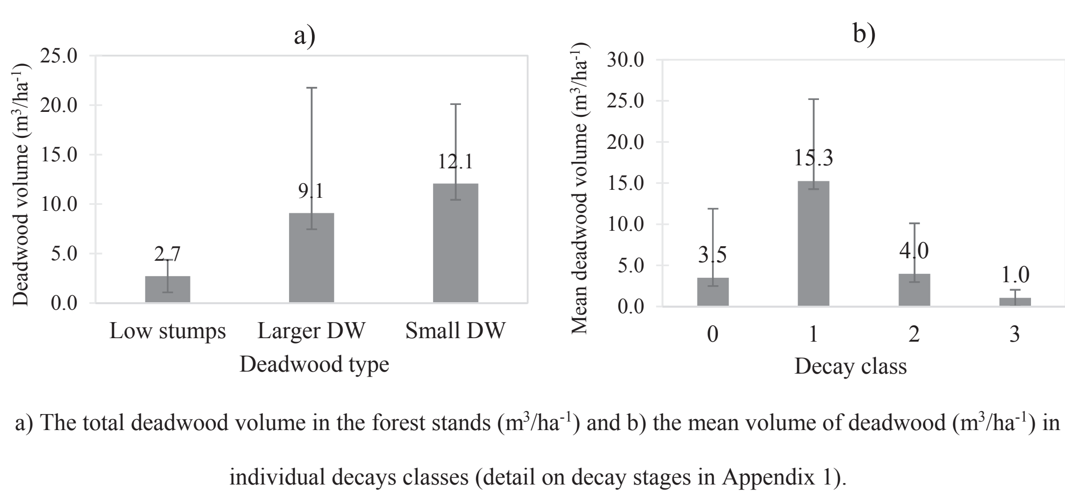


Fig. 2. Case study of the potential of deadwood management in traditional commercially managed Central European forest property – the University forest Kostelec nad Černými lesy, in central Bohemia, Czech Republic. (a) The total deadwood volume in the forest stands (m^3/ha^{-1}) and (b) the mean volume of deadwood (m^3/ha^{-1}) in individual decays classes (detail on decay stages in Appendix A).

biodiversity - is absent from the forests and its creation is difficult, generating different types of deadwood that supports other species with different demands is also favourable. Deadwood retention with a minimum financial loss may also be applied in areas where the access by transport vehicles is difficult or not possible due to extreme slopes, rugged terrain or where the area of interest is enclosed by properties of other owners. Another case when retention may cause little financial loss is when the trees subjected to retention are of poor quality (e.g. trees showing irregular growth or poor form). Trees that already bear certain stage of decay or harbour microhabitats may also be subjected to retention at little financial loss. Trees found on the fringes of farmland not utilised for farming that are adjacent to forests shall also be considered for long-term retention in the light of deadwood formation.

Kostelec nad Černými lesy (6900 ha) is a sustainably managed forest that is used here to exemplify deadwood volumes and types in a typical commercially-managed Central European forest property focusing on the production of construction timber, fuel wood, chips, bark, and biomass. Norway spruce dominates half of the forest area with additional 18 and 11% accounting for Scots pine and European beech, respectively, with the reminder comprising of other broadleaved and coniferous species. Inventory data from 2011 showed that deadwood volume varied across the forest with the mean deadwood volume reaching $23.9\,m^3/ha^{-1}$ (a) with the younger decay stage (b; no. 1, Appendix A) being the most commonly represented throughout the forest. However, considering the total deadwood volume of $23.9\,m^3/ha^{-1}$ may be misleading since only the category of 'larger deadwood' (snags and lying deadwood with the length > 1 m and with the diameter at a smaller end > 7 cm) forming $9.1\,m^3/ha^{-1}$ can be considered as a suitable habitat for saproxylic species considered in this paper. The reminding $14.8\,m^3/ha^{-1}$ account for small stumps (< 15 cm in diameter at the height of 20–30 cm) and small deadwood (deadwood < 7 cm in diameter at a smaller end) that do not form an appropriate habitat for the saproxylic species targeted by the deadwood management approaches described here.

Given sufficient time and dedicated forest management efforts, it is possible to achieve internationally recommended deadwood volumes i.e. $35\,m^3/ha^{-1}$ (e.g. Müller and Bütler, 2010) in this typical Central European commercial forest, if the timber assortments of poor quality of larger sizes are retained. However, it is necessary to aim for greater diversity of deadwood types, especially larger deadwood segments in order to satisfy the saproxylic beetles requiring larger fragments of deadwood as opposed to retaining smaller deadwood segments; i.e. stumps and stems or branches < 7 cm in diameter.

5. Discussion

Developing deadwood management recommendations requires a good comprehension of the relationships between deadwood characteristics and the ecology of species depending on it as part of their life cycle (Brin et al., 2011). Certain deadwood management guidelines were created on institutional levels in some countries or presented in grey literature written in local languages. However, only a limited number of publications reported on the outcomes of deadwood management in Central Europe. Although we did not present any novel insights into the topic of deadwood in production forests, we were the first to concisely compile the key basic deadwood enhancement recommendations that are based on scientific findings and practical experience in the light of introducing the concept of feasible deadwood management in production forests of Central Europe. The presented concept of deadwood management demonstrates the balance between the deadwood management benefits on biodiversity and the implementation of necessary deadwood management approaches not compromising operational costs.

We provided a set of simple deadwood management approaches with a minimum management input mainly focusing on the enhancement or creation of natural features in managed forests facilitating – not only – saproxylic species. Although the disadvantages of deadwood management are apparent (e.g. conflict with timber production), deadwood management is a relatively low maintenance approach. If individual deadwood enhancing methods present certain costs (i.e. artificial creation of deadwood), we believe such cost are sufficiently balanced by the benefits of individual deadwood management approaches on biodiversity. Since most forests include areas that are not particularly suitable for timber production (e.g. waterlogged soil, difficult access, poor quality trees), such areas can be subjected to deadwood retention without additional harvesting costs involved as they are good candidates to maintain structural attributes. However, deadwood management shall be applied in the whole forest in order to achieve the presence of deadwood across the entire forest site. It is encouraging to include some form of deadwood management practices in the business-as-usual forest management in public forests but also in forest properties owned by communities and private owners since little or no cost is involved.

The willingness of forest managers to apply deadwood management and impartially explain to private forest owners the pros and cons of this approach influences the forest owners to opt for deadwood management with the aim to enhance biodiversity. Private owners may be stimulated to use some form of deadwood management since the deadwood management approaches included here require minimum costs but provide considerable enhancement of biodiversity. Therefore, such approaches are unlikely to hinder the management aims focusing on timber production, which, in contrary, are frequently seen as the reason not to opt for deadwood management. Nonetheless, virtual didactic tools such as marteloscopes can be utilised for exercising particular forestry practices (Kraus et al., 2018). Such virtual training facilities allow forestry professionals to carry out particular management approaches (e.g. tree retention for deadwood creation) in order to see the outcomes without the necessity to retain or cut the selected trees. Such exercise helps build confidence in using alternative or unfamiliar practices.

Forestry in Central Europe is a conservative discipline with deeply rooted use of traditional silvicultural practices, some of which aim to reduce heterogeneity in forests, which is, however, the key factor supporting biodiversity. In order to include what appears to be the novel management concepts integrating multiple ecosystem services into traditional forest management - such as deadwood enhancement - the mind set of many foresters requires a substantial renaissance. This is mainly due to the conflict between practising traditional silviculture and accepting, and consequently incorporating, new approaches that sometimes override the traditional and widely accepted silvicultural concepts. In other words, retaining trees reaching target diameter for harvesting in order to create deadwood may be considered as one of the compromises between biodiversity enhancement (in a form of deadwood creation) and traditional forest management approaches the foresters ought to accept.

Deadwood management may as well be considered a novel approach for some foresters. Recent research on the adoption of new forest management practices revealed that implementation of innovative approaches may be challenging due to overriding reliance on familiar and widely-recognised techniques and due to the lack of agreement amongst forestry professionals on the choice of trees for specific purpose (e.g. Vítková et al., 2016; Pommerening et al., 2018). Since such findings are also applicable to choice of trees to be retained as a part of deadwood management, a full appreciation of multiple forest functions would help forest managers to be more open-minded and include some form of deadwood enhancement to better accommodate for a wider range of forest services. Since certain certification standards require some level of deadwood retention for the purpose of biodiversity conservation, enforcing certification standards to certain extent positively stimulates the use of deadwood management.

It is also important to note that the growing societal demands and increasing awareness of public regarding the quality of environment have already made many forest managers to apply approaches effectively accommodating for multiple ecosystem services. Employing deadwood management is believed to help achieve this by means of balancing biodiversity enhancement and timber production. While biodiversity is generally positively evaluated by public, the actual presence of deadwood does not always get such a positive appraisal. This is mainly attributed to aesthetical values of deadwood as high amounts of deadwood in the forest are not often viewed as aesthetically pleasing but instead as messy, chaotic or abandoned. Such emotional aspects should be also kept in mind by the practising forest managers when implementing deadwood management strategies in order to minimise any potential conflicts with the members of public. In addition, in poorer regions where firewood is considered an important energy resource, the application of deadwood management may be seen as a waste of valuable energy resource.

Certain aspects of deadwood, such as its position or decay stage, that are related to the occurrence of iconic or easily recognised species, have been subjected to more research in comparison to e.g. economic aspects of deadwood management where only a small amount of data has been available. It is therefore necessary to carry out economic assessment in order to gain evidence on economic feasibility of individual deadwood management approaches. For instance, cost-benefit analyses providing information on the retention of single trees or groups of trees or on the artificial creation of deadwood would allow us to apply the most convenient forest management approach suited to the particular site that balances interventions aiming at biodiversity enhancement with those aiming at generating revenue from timber production. This would facilitate for the 'win-win' situation where we manage for biodiversity at minimum cost; i.e. reduce harvesting cost by retaining tree groups located in places with difficult access.

Health and safety in forests is another important point to be considered as a part of deadwood management; especially, since forest workers are often in a close contact with deadwood that may injure them. Individual deadwood management approaches shall be therefore well planned and carefully executed in order to minimise any health and safety risks. Suitable methodology and practice policies are to be applied or developed and an appropriate risk assessment shall be carried out prior to undertaking any work that ought to be carefully supervised and guided, if necessary. In addition, the risk of any injury to the members of public or damage of their property shall be also minimised. However, the risk of injuries to forest visitors is generally low due to any dangerous deadwood segments being removed from within a close proximity to public paths and roads in the forests due to a regular assessment of public areas and issuing cautions by means of informative sign posts.

6. Conclusion

Incorporation of deadwood management into conventional forest management in production forests is a feasible forest management approach that facilitates for biodiversity maintenance while simultaneously allowing for timber production. However, individual deadwood management approaches need to be carefully selected in order to suit the given forest conditions and management aims without accepting unnecessary compromises. Although deadwood is an important feature supporting forest biodiversity, only a limited number of forestry practitioners in Central Europe have actively engaged in approaches that effectively enhance deadwood to recommended levels in forests where the major aim is timber production. Therefore, we highlighted the main practically feasible deadwood management approaches that can be used by forest managers in the forests of Central Europe to enhance deadwood diversity and consequently overall forest biodiversity. The major factors relating to deadwood management discussed in this paper, i.e. retention of trees with microhabitats, size of retained trees, position and arrangement, and decay stage, were highlighted as they shall be considered in order to carry out successful deadwood management.

As a part of effective deadwood management practice, it is necessary to retain as much of already existing deadwood (e.g. snags, fallen or lying deadwood, or uprooted and snapped trees) as possible. Retaining at least certain proportion of deadwood resulting from natural disturbances that is usually subjected to salvage logging is also favourable for enhancing volume but most importantly also for deadwood diversity. Most conventionally used silvicultural practices in Central European forests do not actively engage in deadwood creation. Therefore, incorporating the retention of preferably sun-exposed single trees or tree groups by means of allowing single trees or tree groups to reach the end of their life span eventually developing into snags that decay and disintegrate into coarse woody debris is essential. In addition, artificial creation of deadwood where practices such as girdling, felling and pulling, inoculation with fungal pathogens or combination of these techniques are employed are also valuable options for the enhancement of deadwood diversity and volume.

Since tree size, its arrangement and position, but also the decay rate and tree species affect deadwood diversity and volume, considering these key factors greatly aids the decision-making on the choice of particular deadwood management approach. Moreover, bearing in mind these factors allows us to ensure that, given time, recommended deadwood volume is achieved and that its composition is diverse with a range of deadwood types, sizes, and decay stages. Large deadwood segments, preferably standing and sun-exposed, for instance, shall be present in the forests since they have longer residence time and support greater number of saproxylic species. Heterogeneous spatial distribution of deadwood of various types is also important in order to achieve variability in spatial arrangement of deadwood. The focus on deadwood formed by native species is advocated in the light of native biodiversity enhancement.

Deadwood management presents some disadvantages on operational/commercial level such as the potential loss of financial revenue from timber harvesting, possible health and safety hazards or the necessity to employ only costly specially trained staff to carry out the operations. Disadvantages on biological level nonetheless also persist; i.e. unsuitable location or position of deadwood, the presence of unsuitable tree species with a fast decay rate, long time required until suitable decay stage is reached or deadwood presents a potential source of pests and diseases. However, careful planning of deadwood management is required in order to eliminate the disadvantages and secure cost-effective choice of particular approach. Therefore, given careful choice of deadwood management approach and sufficient time, in the case any disadvantages remain, they are believed to be compensated by the positive effects individual deadwood management approaches have on biodiversity.

Acknowledgement

Radek Bače was supported by project CIGA No. 20164310 and project LTC17055 financed by the Czech Ministry of Education, Youth and Sport project. Miroslav Svoboda was funded by project EVA4.0 No. CZ.02.1.01/0.0/0.0/16_019/0000803 financed by the Czech Ministry of Education, Youth and Sport. We also wish to thank to Péter Ódor, Yoan Paillet and an anonymous reviewer for their valuable comments that improved this paper.

Appendix A

Decay classes used to demonstrate the volumes of deadwood found in the forest of Kostelec nad Černými lesy. The decay classes are based on the methodology of Marušák et al. (2009) that is used for deadwood evaluation in the Czech Republic and is comparable to other decay classes grading system such those used in Siitonen et al., 2000, Heilmann-Clausen (2001), Nordén and Paltto (2001), Ódor and van Hees (2004), and Müller-Using and Bartsch (2009), etc.

0: The tree recently died; its stem either collapsed or it is still standing; the wood is fresh, hard, with an absence of rot; the entire stem is covered by bark; the diameter of the smallest twigs is < 1 cm.

1: The wood remains hard with fungi already appearing; the stem is either in a contact with the ground or it slants without ground contact as it is supported by its branches; majority of the stem is covered by bark in most cases; the diameter of the smallest twigs is > 1 cm.

2: The wood is soft in places with pieces of decaying wood disintegrating; only thick branches are present; the stem in one piece and in a contact with the ground incompletely copying the ground surface; large clusters of epiphytic vegetation cover the stem; bark is absent in most cases.

3: The wood is very soft and disintegrating; the stem lies in a close contact with the ground intimately copying the ground surface; the surface of the stem is covered with deep furrows with the presence of epiphytes and fungi; bark is absent in most cases.

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