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Dead wood availability in managed Swedish forests – Policy outcomes and implications for biodiversity

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A B S T R A C T

Dead wood is a critical resource for forest biodiversity and widely used as an indicator for sustainable forest management. Based on data from the Swedish National Forest Inventory we provide baseline information and analyze trends in volume and distribution of dead wood in Swedish managed forests during 15 years. The data are based on ≈30,000 sample plots inventoried during three periods (1994–1998; 2003–2007 and 2008–2012). The forest policy has since 1994 emphasized the need to increase the amount of dead wood in Swedish forests. The average volume of dead wood in Sweden has increased by 25% (from 6.1 to 7.6 m^3 ha^{-1}) since the mid-1990s, but patterns differed among regions and tree species. The volume of conifer dead wood (mainly from *Picea abies*) has increased in the southern part of the country, but remained stable or decreased in the northern part. Heterogeneity of dead wood types was low in terms of species, diameter and decay classes, potentially negatively impacting on biodiversity. Overall, we found only minor effects of the current forest policy since most of the increase can be attributed to storm events creating a pulse of hard dead wood. Therefore, the implementation of established policy instruments (e.g. legislation and voluntary certification schemes) need to be revisited. In addition to the retention of dead trees during forestry operations, policy makers should consider calling for more large-scale targeted creation of dead trees and management methods with longer rotation cycles.

1. Introduction

Dead wood is the most important factor influencing forest biodiversity in boreal (Esseen et al., 1997), temperate (Paillet et al., 2010) and tropical forests (Grove, 2002). Around 7500 forest species in the Nordic countries are known to be dependent on dead trees during whole or part of their life cycles (Stokland et al., 2012), i.e. defined as being saproxylic (Speight, 1989; Stokland et al., 2012). This corresponds to 20–25% of all forest species (mainly fungi and invertebrates) in the region (Siitonen, 2001). As a consequence of modern forestry, the volume of dead wood has decreased significantly as pristine forests have been converted into managed stands. Throughout Europe, the current volumes of dead wood in managed forests are normally less than 10% of natural levels (Stokland et al., 2012). Along with the decrease in volume, the composition in terms of tree species, diameter distribution and decay classes has changed dramatically (Jönsson and Jonsson, 2007; Blaser et al., 2013). With significant habitat loss, it is not surprising that many saproxylic forest species are declining. For example, more than 700 species of the 2000 red-listed forest species in Sweden are dependent on dead wood (Larsson, 2011).

A significant amount of research is available on the strong dependence between the occurrence of saproxylic species and specific dead wood types (see reviews by Harmon et al., 1986; Jonsson et al., 2005; Stokland et al., 2012). This particularly concerns habitat specificity of species with regard to tree species, tree size, substrate type, and decay stage, with a superimposed role of the environmental conditions provided by the forest stand itself (Stokland et al., 2012). The Swedish Species Information Centre provides online data (http://artfakta.artdatabanken.se/, accessed in October 2015) on the requirements of red-listed species, showing the number of species dependent on different tree species. The data includes around 750 saproxylic red-listed species. Their habitat demands partly mirror the general abundance of the different

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tree species as a significant number of them are dependent on the dominant species (*Pinus sylvestris* L. and *Picea abies* (L.) Karst.). However, the data also highlights the importance of temperate deciduous tree species (see below), which have the highest number of associated red-listed species. Lack of dead wood from deciduous trees is one of the most important factors limiting biodiversity in the Swedish forest landscape. Attempts to estimate threshold levels for dead wood have been made. In a review of European forest ecosystems, Müller and Bütler (2010) conclude that the thresholds for occurrence of many saproxylic species are within the range of 20–50 m^3 of dead wood per hectare. Such estimates serve as a bench mark for evaluating existing volumes in managed forests and as management guidelines. However, these values only concern species frequent enough to allow statistical analysis of their occurrence. Relevant data allowing for analyses of the specific demands of rare species are largely lacking.

In 2011 the European Union (EU) established its Biodiversity Strategy, aiming to halt biodiversity loss by 2020. Among agreed targets and actions, Action 12 in the strategy relates to integrating biodiversity measures in forest management plans, and states that one measure is "to maintain optimal levels of dead wood" (Anon., 2011). The strategy does not define "optimal levels" in quantitative terms, but explicitly refers to the EU Species and Habitat Directive that calls for "Favorable Conservation Status" (FCS) for listed habitat types and species. This highlights the need for better baseline information on dead wood availability in different forest types and setting the current volumes in relation to the demands of saproxylic species (Travaglini et al., 2007).

Since the early 1990s Swedish forest management has begun to show greater environmental concern during its forestry operations (Simonsson et al., 2015). This is reflected in the Forestry Act from 1993, and also in the voluntary forest certification schemes (Angelstam et al., 2013; Johansson et al., 2013) that currently certifies a large portion of the Swedish forest landscape. Both the Forestry Act and the certification schemes highlight the importance of dead wood for forest biodiversity and the recommendations also include quantitative statements. For instance, the FSC standard requests, in addition to a general statement of retaining dead wood during forestry operations, that at least three high stumps or girdled trees per hectare should be created at final harvest, striving to include different tree species (Anon., 2014a). In addition to these sectorial policies, the Swedish government adopted a set of national environmental quality objectives in 1999 (Anon., 2001), including an objective of "Sustainable forests". This objective included increasing the volume of hard dead wood (<10% of the volume decayed) by at least 40% throughout the country and considerably more in areas where biological diversity is particularly at risk. In later revisions of the objectives, hard dead wood was also included as a critical indicator for sustainable forestry. Therefore, given the policy focus on dead wood during the past 15 years it is reasonable to expect that the volumes of dead wood should have increased in Sweden's forests.

Although it is well established that the volume of dead wood is generally low in managed forests (e.g. Stokland et al., 2012; Kebli et al., 2012), we have surprisingly little detailed information about the composition and structure of dead wood. Usually, at national level only crude averages over large regions and wood types are reported (but see Fridman and Walheim, 2000; Kruys et al., 2013). Although this does provide information on general habitat loss and current trends, it lacks the detail required to devise practical recommendations for managers to improve conditions for biodiversity. Critical questions such as, how much and what types of dead wood to protect and to potentially create (Jonsson et al., 2005) cannot be addressed based on current information.

Since the 1920s the Swedish National Forest Inventory (NFI) describes the state of and changes in Sweden's forests (Fridman et al., 2014). The information is used as a basis for forest and environmental policy and planning. On an annual basis around 7000 permanent plots are inventoried throughout the country, and include since 1994 detailed estimates of dead wood. Hence, large amounts of data on dead wood in Swedish forests is available from the last 15 years. Fridman and Walheim (2000) made an initial analysis based on data from 1994 to 1996 and found a national average of 6.1 $m^3\,ha^{-1}$, but with significant geographical variation. In a recent study Kruys et al. (2013) analyzed structural changes in young forest stands (0–10 years old), including estimates of dead wood. They found a general increase of dead wood in young forests during the last 10 years, but similarly to Fridman and Walheim (2000) also large geographical variation. Besides these studies, the NFI annually reports total volumes in different counties for two decay classes (<10% or >10% of the wood volume decayed) and three groups of tree species (*P. sylvestris*, *P. abies* and deciduous trees). The current reporting scheme does not fully utilize the wealth of data available and there are strong reasons to extend the analyses made by Fridman and Walheim (2000) and Kruys et al. (2013) based on a longer time period and the significantly larger data set now available. The current analysis will provide forest and conservation management with a better understanding on the current dead wood resources and its impact on biodiversity in managed forests. The analysis will further emphasize the potential to use national forest monitoring to evaluate the effects of changed management guidelines.

This study aims to provide baseline data and estimates of trends in the availability of dead wood in Swedish forests and to evaluate the effects of the changes in forest policy related to dead wood since 1994. As such it represents a case on how ambitious conservation policies may or may not result in changes supporting forest biodiversity. The analyses are based on sample plot data from the NFI and will highlight variation in volumes with regard to

- Changes in dead wood volumes during a 15 year period in five regions.
- Dead wood volumes in different forest types according to habitat types defined within the European Species and Habitats Directive, i.e. the so called Natura 2000 habitats.
- Dead wood distribution among tree species, decay classes, and stem diameters within different regions.

2. Material and methods

2.1. Study area

Two thirds of Sweden are covered by forests (based on the FAO forest definition; FAO, 1998), mainly composed of boreal forests dominated by conifers. The area of the productive forest land (defined as producing more than 1 $m^3\,ha^{-1}$ per year) comprises 23.2 million hectares. This study is based on data from all managed, productive forests (excluding formally protected areas) in Sweden, except for the belt of mountain birch forests along the Scandes Mountains in the northwest part. The area of protected forests is unevenly distributed and only 3.6% of the productive forest land is formally protected (Anon., 2014b). This means that our analysis includes more than 96% of the productive forest.

Most of the study area has been subject to industrial forestry, starting on a larger scale in the southernmost part from the early 1800s and expanding northwards through the whole country during the 19th century (Östlund et al., 1997; Axelsson et al., 2002). The first wave of forest extraction targeted large diameter classes for saw timber and other purposes, which reduced growing stock (volume of live trees) significantly up to early 20th century. Forest management developed during this time period and the growing stock has increased with 104% since the 1920s (Anon., 2015). Clearcutting

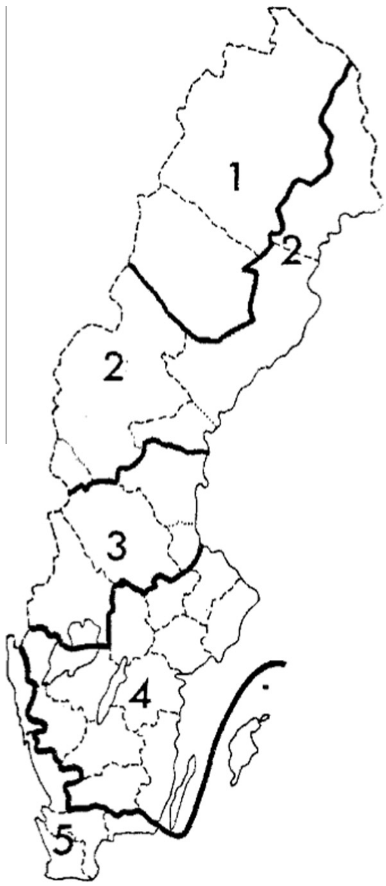

Fig. 1. Regional delineation of Sweden in the National Forest Inventory. Regions 1–3 spans from southern boreal to northern boreal zone, region 4 belongs to the hemiboreal zone and region 5 is mainly temperate (nemoral).

occurred in the early 20th century, but became the dominant method from the 1950s and onwards. Since 1950 more than 60% of the Swedish forest land has been clearcut (Anon., 2015). Management practices include soil preparation, planting, precommercial thinning, commercial thinning and in many cases also fertilization. This has created forests with high growth rates, dominated by cohorts of single tree species (mainly *P. abies* or *P. sylvestris*) with a strong reduction of old, dying and dead trees. It is estimated that current dead wood volumes are generally below 10% of volumes common in natural forests (Jönsson and Jonsson, 2007).

The regional delineation of Sweden (Fig. 1) in the Swedish NFI broadly follows the main biogeographical zones, spanning from temperate (nemoral) forest in the south to mountain forest and the northern boreal zone in the north. Although not strictly adhering to the vegetation zones of Ahti et al. (1968), the delineation corresponds well to their description of vegetation – climate relations in northern Europe.

2.2. Data sources and definitions

The included data sets are from the three full NFI cycles; 1994–1998, 2003–2007 and 2008–2012. The total number of analyzed plots is 35,975, 30,127 and 29,892, respectively for the three cycles and include the permanent plots of the NFI. These plots are clustered into quadratic tracts with 8 circular sample plots with a 10 m's radius (314 m^2), located evenly along the tract sides. The length of the tract sides varies, from 300 m in the south to 1800 m in the north. For further details on the NFI see Fridman et al. (2014).

A large range of variables are collected in each plot. These includes both general description of the forest stand and detailed information on individual dead wood units. For the present analysis we have included; volume of live trees, region (see Fig. 1), classification of Natura 2000 habitats, and stand age (basal area weighted mean tree age). Variables for each dead wood unit (>10 cm in basal diameter and >1.3 m in length) were tree species (see below), size (maximum basal diameter), decay stage (see below) and position (standing or downed). A standing dead tree is defined as being any stump or snag higher than 1.3 m and is recorded separately from downed logs originating from the same tree.

Based on specific criteria (Gardfjell and Hagner, 2014), all sample plots within the NFI are evaluated in the field to determine whether they qualify as being defined as Natura 2000 habitats according to the EU Habitats directive or not. These criteria include; natural regeneration, no forest management the last 25 years, forest age (>40 years above recommended harvest age), presence of dead wood, multilayered forest structure and specific criteria for particular habitat types. In total, 6.5% of the plots (N = 1957) where classified as Natura 2000 habitats in the third study period. Several of the habitats are very rare, restricting the possibility for detailed analyses. Therefore, were grouped into five broader categories in the analysis; Mires and wet forests (N = 390; eight habitat types); Taiga expanded (N = 1479; five habitat types); Deciduous forests and meadows (N = 62; seven habitat types); Mountain birch forest (N = 15; one habitat); Dunes and rising shores (N = 11; three habitat types).

In the NFI, a total of 28 different tree species have recorded as dead trees. Many of these are very rare and so the analysis groups the tree species into five categories; (1) *P. sylvestris* L., (2) *P. abies* (L. Karst.), (3) *Betula* spp., (4) Temperate deciduous trees (*Quercus* spp., *Fagus sylvatica* L., *Fraxinus excelsior* L., *Ulmus* spp., *Tilia cordata* Mill., *Acer platanoides* L., *Carpinus betulus* L., and *Prunus avium* L.) and, (5) Other deciduous trees (*Populus tremula* L., *Salix caprea* L., *Alnus* spp., *Sorbus* spp.). A few non-native exotic tree species (e.g. *Pinus contorta* Douglas ex Loudon, *Abies* spp.) are recorded in the NFI, but excluded from the analysis as their share of the volume of dead wood is insignificant throughout the country (<0.05 $m^3\ ha^{-1}$).

All dead trees (standing and downed) are classified in five decay stages:

Decay stage 0. Fresh dead wood (with green needles or leaves, and/or with fresh cambium)
Decay stage 1. Hard dead wood (<10% of the wood decayed)
Decay stage 2. Slightly decayed (10–25% of the wood decayed)
Decay stage 3. Decayed dead wood (26–75% of the wood decayed)
Decay stage 4. Strongly decayed wood (76–100% of the wood decayed)

During the first study period (1994–1998) decay stages 0 and 1 were not separated and hence reported collectively. The distinction between decay stages in the field is straightforward and based on calibration by field personnel. However, decay stage 4 includes a decision on when a dead tree is fully decayed and no longer recorded – a decision that is partly subjective. Downed log volumes are based on Smalian's formula, while the volumes of standing dead trees are based on species specific form height functions (Näslund, 1947; Eriksson, 1973).

2.3. Statistical approaches

In order to estimate averages and their corresponding standard errors we consider the design as a cluster-plot design where each cluster of plots (tract) is an independent observation. Although the clusters are systematically distributed in order to maximize the precision of the estimates, we estimated the standard errors through assuming simple random sampling. This is a normal procedure that typically overestimates the standard errors slightly. The assumption has no impact on the estimated mean values.

The national estimator need to account for varying sampling intensity in different regions, i.e. the stratified sampling. The composite estimator for dead wood volume ($\widehat{Y}$) is obtained by:

$$\widehat{Y} = \sum_{h=1}^{5} \widehat{Y}_h, \quad (1)$$

where $\widehat{Y}_h$ is the estimated total dead wood volume in region h. The mean volume per hectare is estimated as the ratio between the estimated total volume and the estimated total forest area, i.e.:

$$\widehat{\widehat{Y}} = \frac{\sum_{h=1}^{5} \widehat{Y}_h}{\sum_{h=1}^{5} \widehat{A}_h}, \quad (2)$$

where $\widehat{A}_h$ is the estimated area of region h. These procedures for deriving mean values and standard errors follow the standard methods applied in the Swedish NFI and are further presented in Fridman and Walheim (2000), and Toet et al. (2007).

Although many comparisons are theoretically possible we have refrained from statistically testing for differences in dead wood availability among regions, time periods, and dead wood categories. Given that the NFI is based on a large number of sample plots, most differences are highly statistically significant while not necessarily biologically relevant. Hence, the analyses focus on providing estimates on dead wood volumes upon which we qualitatively evaluate to what extent any observed difference is ecologically relevant. We statistically evaluated changes in dead wood volumes by calculating confidence intervals for the change in each region.

3. Results

3.1. Total volume of dead wood in Sweden

Across Sweden, the total volume of dead wood in managed forests has increased by 25%, from 6.1 to 7.6 $m^3\ ha^{-1}$ during the studied 15-year period (Table 1). However, the trends differed among regions. Volumes decreased in the northwest (region 1), remained relatively stable in regions 2 and 3 and increased in regions 4 and 5. The change between the two last time periods are generally small except for region 4 where volumes have increased slightly

Table 1
Average volume of dead wood (downed and standing; $m^3\ ha^{-1}$) in Swedish managed forests outside formally protected areas. Regions are shown in Fig. 1.

Region	Period						
	1994–1998		2003–2007		2008–2012		
	Mean ± SE	%[a]	Mean ± SE	%[a]	Mean ± SE	%[a]	No. of plots[b]
1	9.94 ± 0.58	14.1	8.68 ± 0.50	11.1	8.25 ± 0.48	9.9	2673
2	6.97 ± 0.23	6.6	7.87 ± 0.26	7.2	7.87 ± 0.26	6.8	8199
3	5.16 ± 0.20	4.2	6.35 ± 0.25	4.7	6.63 ± 0.26	4.7	6511
4	3.80 ± 0.13	2.3	6.50 ± 0.21	3.9	7.51 ± 0.25	4.4	9970
5	3.80 ± 0.23	2.2	8.53 ± 0.52	4.6	8.17 ± 0.50	4.4	2539
1–5	6.08 ± 0.13	5.0	7.38 ± 0.16	5.7	7.60 ± 0.17	5.7	29,892

[a] Percentage of dead wood in relation to live tree volume.
[b] The number of plots in each region is given for period 3 (2008–2012). The total number of plots was 35,975 in period 1 (1994–1998) and 30,127 in period 2 (2003–2007), with similar distribution among regions as in period 3.

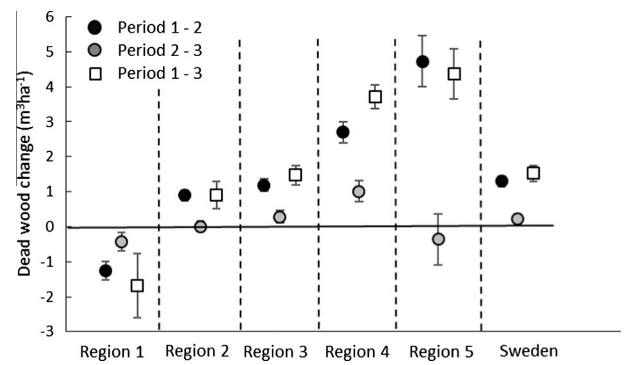

Fig. 2. Average change (with 95% confidence intervals) in dead wood volumes between the study periods. Regions are shown in Fig. 1.

(Fig. 2). The dead wood volume 2008–2012 relative to live tree volume was on average 5.7%, being lowest in region 5 (4.4%) and highest in region 1 (9.9%). Since the mid-1990s the proportion of dead wood has increased in all regions except for region 1 (Table 1).

Downed dead wood dominates in the Swedish forest landscape, but the fraction of standing dead trees has increased during the study period, from below 30% in the mid-1990s to 40% in the last period (Table 2). In general the fraction of standing dead trees increase from the north to the south. However, while the fraction of standing dead trees increase in the three northernmost regions, the fraction has been more or less constant in the south.

3.2. Dead wood in Natura 2000 habitats

The volumes of dead wood were generally significantly higher in plots located within sites classified as belonging to Natura 2000 habitats than outside such habitats (Table 3). On average the dead wood volumes were about three times higher (20.3 $m^3\ ha^{-1}$) within Natura 2000 habitats compared to plots not classified as habitats (6.7 $m^3\ ha^{-1}$). Besides the rare habitat group "Dunes and Rising shores", the highest volumes of dead wood were found within "Taiga expanded" and "Deciduous forests and Meadows". The low productive forest types included in the habitat groups "Mires and Wet forests" and "Mountain birch" forests have significantly less dead wood.

3.3. Dead wood by tree species

The volume of dead wood was dominated by conifers in all regions, with temperate deciduous trees only occurring in the two southernmost regions. The trends over time varied both among regions and tree species (Fig. 3). In region 1 (northwestern Sweden) the volume of dead pines decreased from the mid-1990s to the two last periods, while other tree species remained stable. In contrast conifers in general and spruce in particular increased during the two last time periods in region 4 and 5 (and partly also in region 3). Other tree species remained stable, except for an increase in the volume of temperate deciduous trees in region 5, which increased from 0.3 $m^3\ ha^{-1}$ in the mid-1990s to 1.1 $m^3\ ha^{-1}$ during the two last time periods.

3.4. Dead wood by forest age class

The dead wood volume increased with stand age in all regions (Fig. 4), and was generally above 9 $m^3\ ha^{-1}$ in forests older than 100 years. The maximum was reached in forests older than 150 years in regions 1–4 (>14 $m^3\ ha^{-1}$), with a highest recorded value of 22.4 $m^3\ ha^{-1}$ in region 1. In region 5 the volume was highest in forests aged between 125 and 150 years. However, the

Table 2
Average volume of standing dead wood (m^3 ha^{-1}) in Swedish managed forests outside formally protected areas. Sample size given in Table 1 and Regions are shown in Fig. 1.

Region	Period					
	1994–1998		2003–2007		2008–2012	
	Mean ± SE	%[a]	Mean ± SE	%[a]	Mean ± SE	%[a]
1	2.09 ± 0.17	21.0%	2.64 ± 0.21	30.4%	2.59 ± 0.21	31.5%
2	1.80 ± 0.08	25.9%	2.85 ± 0.13	36.3%	3.04 ± 0.14	38.6%
3	1.54 ± 0.08	29.8%	2.46 ± 0.14	38.8%	2.77 ± 0.15	41.8%
4	1.60 ± 0.08	42.2%	2.74 ± 0.13	42.2%	3.40 ± 0.16	45.2%
5	1.70 ± 0.16	44.8%	3.68 ± 0.35	43.2%	3.66 ± 0.35	44.7%
1–5	1.74 ± 0.05	28.6%	2.76 ± 0.08	37.4%	3.04 ± 0.09	40.0%

[a] Fraction of standing dead wood to total dead wood volume.

lowest recorded volume in forests older than 150 years in region 5 is likely an artefact of few sample plots (only 19 plots) in this category. By comparison the volume of dead wood in region 5 during the second period (2003–2007) was 10.2 m^3 ha^{-1} in forests older than 150 years; more in line with volumes in older forests in other regions.

3.5. Dead wood by decay stage

Wood in decay stage 1 (hard dead wood) dominated in all regions while fresh dead wood (decay stage 0) was least prevalent (Fig. 5). There were no distinct differences among regions, except slightly higher volumes of decay classes 0 and 1 in regions 4 and 5 and slightly higher volumes of more decayed wood in regions 1 and 2. The volume of dead trees in decay classes 0 and 1 has almost doubled between the mid-1990s and the last period (2008–2012), from 2.1 to 4.0 m^3 with a highest recorded ha^{-1}, resulting in a corresponding increase in the fraction of dead wood in these classes, from 34% to 53%.

3.6. Number and diameter of dead trees

The number of dead trees per hectare showed only minor variation among regions, with a national average of 57, ranging from 50 (region 3) to 64 (region 1). During the last study period (2008–2012) 63% of all dead trees were downed while 37% were standing. There was limited variation among different tree species but with a slightly higher fraction (44%) of dead temperate trees remaining standing. The fraction of standing dead trees was similar among the studied regions, however, the fraction of standing dead trees was clearly lower in the mid-1990s (27% standing).

The vast majority of dead trees in all regions are in small diameter classes and more than 70% of all dead trees was less than 20 cm in base diameter in all regions (Fig. 6). This pattern was consistent among tree species (data not shown). Less than 10% of dead trees were larger than 30 cm in base diameter.

4. Discussion

4.1. Changes over time

The national average of dead wood in managed Swedish forests based on the latest NFI cycle was 7.6 m^3 ha^{-1}. This is in between the neighboring boreal countries Finland and Norway, where the latest reported national averages are 5.9 and 10.6 m^3 ha^{-1}, respectively (Parviainen and Västilä, 2011; Storaunet and Rolstad, 2015). During the studied 15-year period, the volume of dead trees in managed Swedish forests has increased with on average 1.5 m^3 ha^{-1}. This corresponds to a 25% increase given the low initial volumes. Most of the increase occured between the first two time periods (mid-1990s to mid-2000s) while the most recent increase was small. By comparison, the dead wood volumes increased twice as much (2.9 m^3 ha^{-1}) in Norway during the same time period (Storaunet and Rolstad, 2015). The situation in Finland partly mirrors Sweden with an increase in the southern part and a decrease in the northern part of the country (Parviainen and Västilä, 2011). Forest management practices in these three countries are broadly similar and the role of dead wood for biodiversity is well established in national forest policies. The reasons for the different trend in Norway (significant increase) compared to Finland and Sweden (minor increase) merits further study. However, it is notable that the role of forestry in the national economy differs among countries which potentially influence the implementation of the policies. In 2006 the forest sector contributed to 3.8 and 5.7% of the Gross Domestic Product (GDP) in Sweden and Finland, respectively, but only 0.8% in Norway (FAO, 2008). Moreover, the share of bioenergy of total primary energy consumption is only about 6% in Norway while it is around 20% in Sweden and Finland (Scarlat et al., 2011).

Our results indicate that the increase of dead wood across managed Swedish forests has slowed down in recent years (Fig. 2). This seems logical given that a balance between input (natural mortality) and loss of dead wood due to decay will eventually be reached. In a simulation study on dead wood dynamics in forests managed by the FSC standard, Ranius et al. (2003) estimated that Swedish spruce forests would have on average 10.2 m^3 ha^{-1} seen over a full forest rotation. Although the simulation study focused only on spruce forests, the estimates are most likely relevant for a large part of the Swedish forest landscape. This suggests that with current forest management practices, dead wood levels are slowly approaching what can be expected without additional silvicultural interventions that directly increase dead wood volumes (e.g. Bauhus et al., 2009).

The data shows a distinct increase of dead wood in decay stages 0 and 1 (fresh and hard dead wood) in the two southernmost

Table 3
Average volume of dead wood (downed and standing; m^3 ha^{-1}) in plots classified as Natura 2000 habitats (for groups see Methods) and plots not classified as Natura 2000 habitats for the time period 2008–2012. Regions are shown in Fig. 1.

Region	Natura 2000 Habitat group					
	Mire and wet forest Mean ± SE	Taiga expanded Mean ± SE	Deciduous forests and meadows Mean ± SE	Mountain birch forests Mean ± SE	Dunes and Rising shores Mean ± SE	Not classified Mean ± SE
1	8.35 ± 0.94	25.09 ± 1.81	–	11.02 ± 0.49	–	6.14 ± 0.32
2	7.69 ± 0.97	23.31 ± 1.45	–	27.68±[a]	35.99 ± 3.89	6.74 ± 0.22
3	7.28 ± 1.14	20.28 ± 2.41	1.73 ± 0.03	–	38.56 ± 1.12	6.10 ± 0.23
4	16.21 ± 0.91	12.72 ± 1.12	21.95 ± 1.58	–	–	7.26 ± 0.25
5	10.78 ± 1.08	16.48 ± 4.05	17.74 ± 1.90	–	0±[a]	7.79 ± 0.42
1–5	10.90 ± 0.60	22.52 ± 1.08	19.23 ± 1.44	13.94 ± 0.52	27.56 ± 5.98	6.72 ± 0.13

[a] Too few observations are available for computing an estimate of standard error.

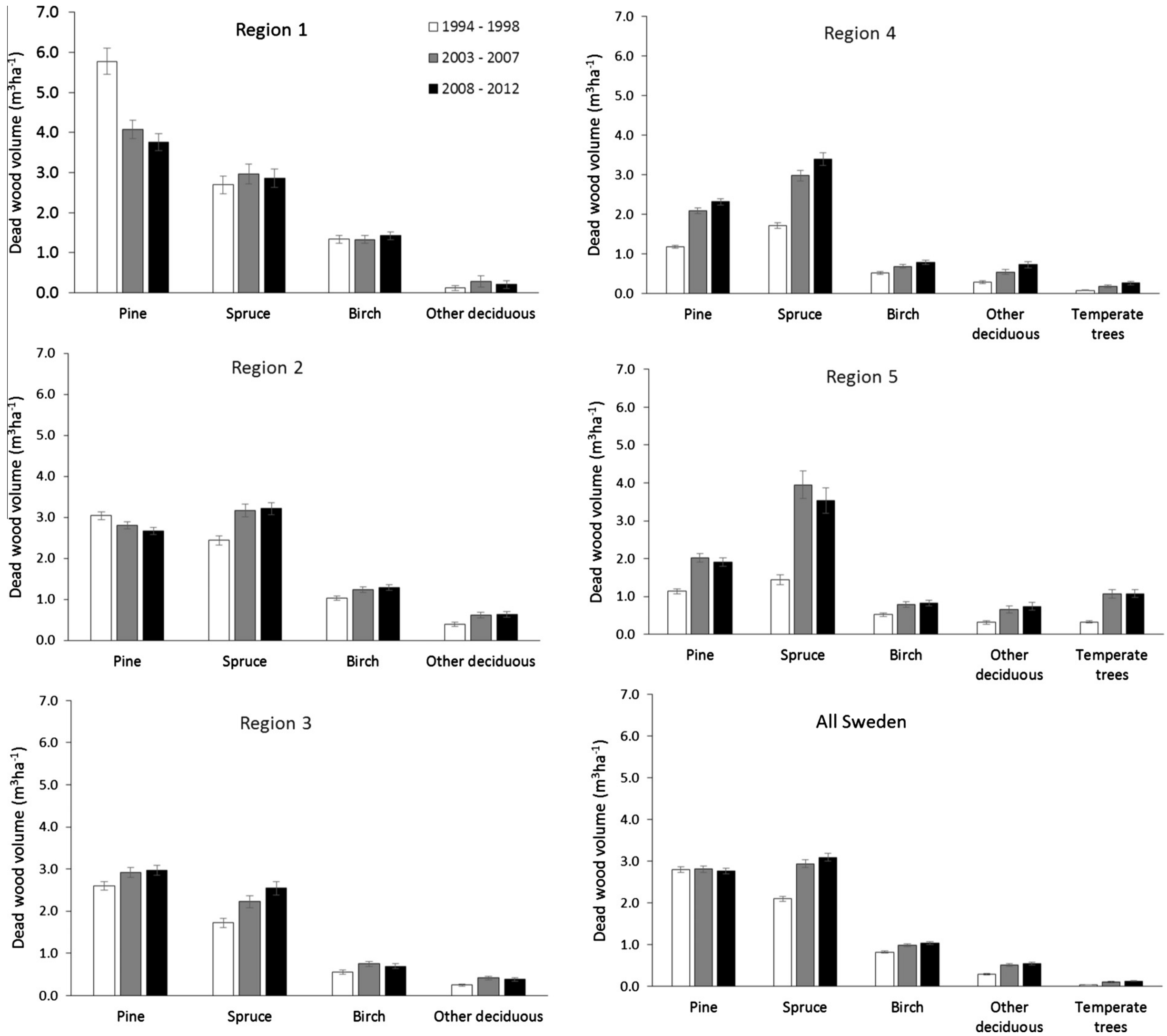

Fig. 3. Dead wood volumes (mean ± SE) in Swedish managed forests. Tree species groups are defined in the Methods and regions are shown in Fig. 1.

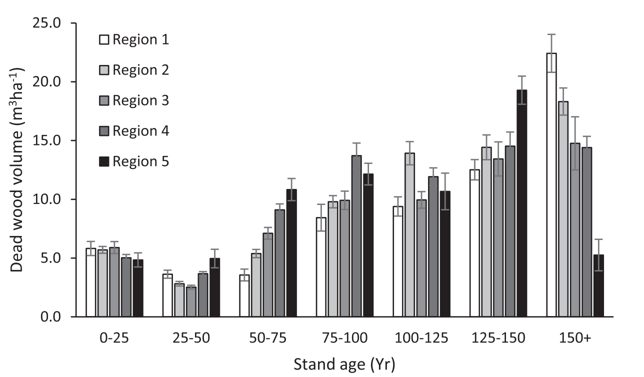

Fig. 4. Dead wood volumes (mean ± SE) in forests of different age classes in Swedish managed forests during the period 2008–2012. Regions are shown in Fig. 1.

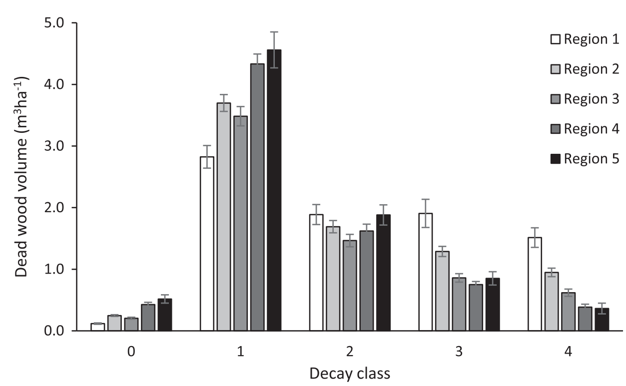

Fig. 5. Decay stage distribution of dead wood volumes (mean ± SE) in Swedish managed forests during the period 2008–2012. Decay stages are defined in the Methods and regions shown in Fig. 1.

regions during the two last time periods, when compared to the first period. This coincides well with the dramatic storm "Gudrun", that struck southern Sweden in January 8–9, 2005, severely damaging 0.27 million ha forest over a total area of 4.8 million ha. During this storm about 75 million m^3 of trees were blown down, of which Norway spruce constituted 80% (Anon., 2006a). This corresponds to an average of 15 m^3 ha^{-1} of fresh dead wood added across the affected region in a single event. Although significant salvage logging occurred, it spanned over several years it was not possible to extract all the dead wood. This pulse of dead wood is seen as higher volumes of dead wood in decay stage 1 during the

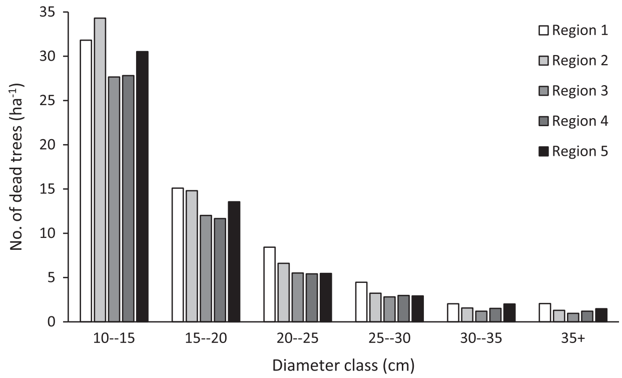

Fig. 6. Diameter distribution of dead wood in Swedish managed forests during the period 2008–2012. Regions are shown in Fig. 1.

last time period. Although it is conceivable that current forest policies have influenced the level of salvage logging to some extent, we conclude that during the studied 15-year period, natural events seem to have played a larger role than management actions directed to increase dead wood volumes. This is supported by the limited increase or even decrease (region 1) in dead wood volumes in northern Sweden which was not affected by the storm in 2005. Similar results were reported by Kruys et al. (2013). They studied dead wood in young forests (<10 years) and showed that dead wood volumes more than tripled in the time period around 2005 in southern Sweden (our region 5 and the major part of region 4), while there was no significant increase in northern Sweden (our region 1 and parts of region 2).

4.2. Comparison with natural forests

Compared to natural forests, our estimate of 7.6 $m^3\,ha^{-1}$ of dead wood, and less than 60 dead trees per hectare, are far below natural levels and only represent 5.7% of the volume of live trees in Swedish forests. In many natural forests, the volume of dead wood ranges between 10 and 40% of the volume of live trees (see references in Nilsson et al., 2002; Stokland et al., 2012). The global record in reported volumes of dead wood comes from the Pacific Northwest in North America with single stands exceeding 1000 $m^3\,ha^{-1}$ (Harmon et al., 1986). However, this is likely a global exception and a range of both empirical and simulation studies indicate that natural forests in boreal regions should contain in the range of 80–120 $m^3\,ha^{-1}$ dead wood (e.g. Siitonen, 2001; Ranius et al., 2004) and up to several hundreds of dead trees per hectare (Nilsson et al., 2002). From boreal forests in European Russia, Shorohova and Kapitsa (2015) reports dead wood volumes from natural forests with different disturbance regimes. Dead wood volumes varied strongly depending on dominant disturbance dynamics, ranging from 50 to 200 $m^3\,ha^{-1}$ and with dead/living volume ratio varying from 29 to 102%. In central European forests, even higher volumes of dead wood (exceeding 200 $m^3\,ha^{-1}$) are common in old-growth forests (Burrascano et al., 2013).

With current forest management guidelines in Sweden, which stress the importance of leaving and creating dead wood, our results suggest that dead wood volumes will hardly reach more than 10% of the volumes in natural forest ecosystems; a level that is likely to be too low for many saproxylic species (Müller and Bütler, 2010). At present, even in the oldest forests in region 1 the total volume of dead wood does not reach more than around 20% of the natural levels.

The situation is more promising for forest stands classified as Natura 2000 habitats according to the EU species and habitat directives (20.3 $m^3\,ha^{-1}$) and also for protected forests in Sweden where dead wood volumes are estimated to be 23.7 $m^3\,ha^{-1}$ (Anon., 2006b). These forest stands constitute a minor fraction of the landscape, but should clearly be targeted for conservation of saproxylic species. The current analysis does not allow for evaluating the biodiversity status of the Natura 2000 habitats beyond volumes of dead wood. However, since dead wood is regularly considered as a key indicator of forest biodiversity (e.g. Travaglini et al., 2007; Lassauce et al., 2011; EEA, 2012) and as the occurrence of saproxylic species strongly correlates with dead wood volumes (Jonsson et al., 2005) it is reasonable to see the Natura 2000 habitats as key target areas for conservation. In these forests, natural levels of dead wood are easier to obtain and dead wood biota is likely to be best represented.

4.3. Dead wood qualities and distribution

Beyond crude volumes, the actual composition of dead wood is also critical for the associated biota (Stokland et al., 2012; Blaser et al., 2013; Kebli et al., 2012). In their study on dead wood monitoring in Europe, Travaglini et al. (2007) show that dead wood volumes do not differ significatly among forest types. However, there was considerable structural differences among forest types when analyzing e.g. diameter distribution and fraction of standing dead wood. More coarse dead wood occurred in European coniferous forests and a higher fraction of downed wood compared to Mediterranean and oak-dominated forests.

The quality aspects of dead wood reflected the composition of the tree layer. The dead wood was dominated by conifers (pine and spruce), and diameter distribution reflected a general dominance of small trees in Swedish forests (Anon., 2014b). Similarly the decay stage distribution mainly reflects the time logs spend in each decay class, although the accumulation in class 1 is likely an effect of the recent pulse of dead spruce trees. Although this is logical, it stresses a main conservation concern, namely that many of the threatened saproxylic species prefer very specific types of dead trees, such as large stemmed trees and in later stages of decay (Jonsson et al., 2005; Stokland et al., 2012). In particular we note the relatively low volumes of dead temperate deciduous trees. This is a major conservation problem as temperate trees host the largest number of Red-listed species.

The recommendations in the FSC certification standards (Anon., 2014a) states that, forest managers are expected to create high stumps (or girdled trees) in harvested areas. The standard states that at least three such standing dead trees per hectares should be created with an aim to include a range of tree species. As these recommendations and regulations were initiated during the mid-1990s it is reasonable to assume that the increased fraction of dead standing trees and increased total volume (cf. Table 2) is a result of these policies. It should be noted, however, that the fraction of standing dead trees has not increased in the southernmost regions affected by the storm Gudrun.

4.4. Reliability of the NFI data

The data available from the NFI allow for detailed analysis of dead wood at both a regional and national scales. However, given the diversity of dead wood types (tree species, sizes and decay stages) and specific forest conditions, even large scale monitoring may fail to provide accurate estimates of specific dead wood qualities in particular forest types. This is evident in the analysis of separate Natura 2000 habitats, for which estimates of single habitat types could not be done. As a result, we lack critical information on the conservation status of many forest habitats in the Natura 2000 system. Overall, however, the NFI is a unique source of data about type and volume of dead wood across the Swedish landscape. Following the introduction of dead wood measurements in the Swedish NFI in the 1990s, most NFIs nowadays include such measurements (Rondeux et al., 2012), although harmonization to assure comparability between countries remains a challenge (Woodall et al., 2009).

4.5. Implications for biodiversity

Data from the Swedish NFI show an increase in the volume of dead wood mainly in early decay stages and in the southern parts of the country. Although the changes satisfy the environmental target of increasing hard dead wood (decay classes 0 and 1) by 40% (Anon., 2001), the increase can mainly be attributed to natural disturbance events like the 2005 major storm "Gudrun" (southern Sweden). Hence, despite two decades of focus on the role of dead wood, as expressed in the Swedish Forestry Act, forest certification standards and national environmental objectives, we see limited direct effects of these policy ambitions on the ground. Higher volumes of dead wood are only found in forest stands defined as belonging to some of the Natura 2000 habitats defined in the EU species and habitats directives. However, even in these stands the volumes are in most cases below what is considered as the threshold for viable populations of most saproxylic species (Müller and Bütler, 2010).

Future policy discussions need to consider not merely advocating the retention of dead trees during forestry operations, but also to call for more targeted creation of dead trees. Given the mismatch between species requirement and available dead wood, such management and restoration efforts should primarily be directed to temperate deciduous trees (southern Sweden) and large diameter, preferably pre-rotten conifers (northern Sweden). However, it is unlikely that biologically significant higher volumes of dead trees will accumulate with current management practices based on clearcutting with short rotations. In order to further improve the conditions for species dependent on dead trees, other management methods with longer rotation periods and increased levels of retention might be needed (Bauhus et al., 2009; Kuuluvainen et al., 2012; Fedrowitz et al., 2014). Our results further suggests that the role of protected areas and remnant stands with high natural values (such as areas fulfilling the EUs habitats and species directives) will continue to have a crucial role for conserving forest biodiversity associated with dead trees.

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