Biomass conversion factors (density and carbon concentration) by decay classes for dead wood of Pinus sylvestris, Picea abies and Betula spp. in boreal forests of Sweden

FRIDA SANDSTRÖM, HANS PETERSSON, NICHOLAS KRUYS & GÖRAN STÅHL

FRIDA SANDSTRÖM
Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Sciences, Umeå, Sweden.

HANS PETERSSON
Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Sciences, Umeå, Sweden.

NICHOLAS KRUYS
Swedish council for sustainable development, Umeå, Sweden.

GÖRAN STÅHL
Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Sciences, Umeå, Sweden.

Corresponding author (also potential proofs should be sent to this address):
Hans Petersson
Department of Forest Resource Management and Geomatics
Swedish University of Agricultural Sciences
S-901 83 Umeå, Sweden
Tel: +46 90 786 85 01
Fax: +46 90 77 81 16
E-mail: Hans.Petersson@resgeom.slu.se

Abstract
For estimating the amount of carbon (C) in dead wood, conversion factors from raw volume per decay class to dry weight were developed using three different classification systems for the species Norway spruce (Picea abies L. Karst), Scots pine (Pinus sylvestris L.) and birch (Betula pendula Roth and B. pubescens Ehrh) in Sweden. Also the C concentration in dead wood (dry weight) was studied. About 2500 discs were collected from logs in managed forests located on 289 temporary National Forest Inventory (NFI) sample plots and in 11 strips located in preserved forests. The conversion factors were based on an extensive data compilation with a wide representation of different site-, stand-, species- and dead wood properties and were assumed to represent the population of fallen dead wood in Sweden. The density decreased significantly by decay class and the range in density for decay classes was widest for the NFI decay classification system, suggesting this to be the most suitable. The C concentration in dead wood biomass increased with increasing decay class and in average Norway spruce (Picea abies) showed a lower C concentration than Scots pine (Pinus sylvestris). The average dead wood C store of Swedish forests was estimated to 0.85 Mg C/ha.

Keywords
biomass, boreal forest**,** carbon concentration, coarse woody debris, decay stage, density, Sweden

Introduction

The interest in dead wood is both related to biological diversity aspects (Esseen et al., 1997; Siitonen, 2001) and to atmospheric carbon (C) cycle issues (Harmon and Hua, 1991; Krankina and Harmon, 1995; Naesset, 1999a).

The United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol are international treaties agreed upon 1992 and 1997, respectively, to achieve worldwide reduction of greenhouse gas emissions (Schulze et al., 2002). For the Land Use, Land Use Change and Forestry sector, all parties are bound to report removals and emissions by different C pools annually. The pools are: the C in aboveground biomass, belowground biomass, litter, dead wood and soil organic C (Anonymous, 2003).

The northern boreal and temperate forests are considered to be an overall C sink, i.e. the forests sequester more than they emit (Harmon and Hua, 1991; Kauppi et al., 1992; Dixon et al., 1994). Goodale et al. (2002) report that these forests together provided a net sink of 0.6-0.7 Pg of C per year during the early 1990s, of which 0.15 Pg C per year in dead wood. Earlier estimations of the C sequestration have lately shown to be too low). (Goodale et al., 2002). A large part of this underestimation is probably due to the lack of existing reporting methods of coarse woody debris. Since the dead wood in the boreal forest is a significant component of the ecosystems, often accounting for 18-40% in old growth forest (Siitonen, 2001), this can be a part of the missing sink. In addition, the slow decomposition rates suggest that woody debris serves as a C pool for up to many decades (Brown et al., 1996). It is therefore necessary to get reliable figures of the C mass of dead wood in the northern boreal and temperate forests.

Compared to many other countries, Sweden is relatively well equipped with monitoring programs that repeatedly measure C pools (Ståhl et al., 2003). The Swedish National Forest Inventory (NFI) forms a good basis for covering most of the reporting requirements of the Kyoto Protocol (Ståhl et al., 2004). The NFI is an annual, stratified systematic cluster sample inventory of Swedish forests (Ranneby et al., 1987). In 1994 an inventory of the volume per decay class of dead wood was integrated in the NFI (Fridman and Walheim, 2000). The NFI-design includes both permanent and temporary circular sample plots that are clustered into tracts. Using the permanent plots is a reliable way of estimating the change in the dead wood stock. In the future, the C reporting will be based on approximately 30 000 permanent sample plots inventoried within a five-year cycle.

Estimation of the C mass in dead wood is somewhat complicated, since the density varies depending on decomposition stage of the wood. The decomposition stage of dead wood is often estimated with some sort of decay class system (Pyle and Brown, 1998). The decomposition stages are subjectively determined mainly by visual characteristics that correlate to the degree of decay, e.g. change in structure of the bark and softness of the wood. To be able to determine the amount of C in the dead wood it is therefore necessary to have conversion factors from volume per decay class to biomass and to C concentration of the biomass. A considerable number of studies have been carried out on decomposition rates (Sollins, 1982; Harmon et al., 1987; Harmon and Hua, 1991; Krankina and Harmon, 1995; Stone et al., 1998; Naesset, 1999b; Ranius et al., 2004) of coarse woody debris but little is known about conversion factors relating decay class to C concentration. In particular, it is hard to find more than one study made on a certain decay class system. However, Harmon et al. (1987) studied American coniferous tree species and wood density in four decay classes. Changes in C concentration and density by decay class were reported for three species and unidentified species in coastal British Columbia (Preston et al., 1998). The total C concentration increased with increasing decay class, and using solid-state C-13 NMR spectroscopy showed that the increase in C concentration was probably linked to the loss of carbohydrate and relative increase in lignin in higher decay classes. Naesset (1999a) investigated the relationship between wood density of Norway spruce (Picea abies) logs and three different decomposition systems. Two studies with calculated C concentration in five different decay classes of Scots pine (Pinus sylvestris) and Norway spruce (Picea abies) have been carried out in Russian forests (Krankina and Harmon, 1995; Yatskov et al., 2003).

Many different decay class systems with different class definitions are used (e.g. Arnborg, 1942; Pyle and Brown, 1998, 1999; Naesset, 1999a). Three decay class systems are commonly used in Sweden. These are the National Forest Inventory system (Anonymous, 1994) and systems constructed by Söderström (Söderström, 1988) and Renvall (Renvall, 1995).

Objectives

The objective of this study was to assess the relationships between volume, biomass and C in dead wood per decay class for Norway spruce, Scots pine and birch, the most common tree species in Scandinavia. For different fields of application, conversion factors, from raw volume to dry weight, were developed for three different classification systems. To represent the population of fallen dead wood (not snags) in Swedish forests, the derivation data were selected from both managed (divided in four age classes) and preserved forests (belonging to the highest age-class). The C concentration in dead wood biomass was estimated and the dead wood C mass per land area of Swedish forests was quantified in a case study.

Materials and Methods

To represent the population of fallen dead wood (not snags) in Sweden, 289 sample plots distributed over the whole country were inventoried. The areas were located in forestland (i.e. land which hosts a potential yield of stem-wood exceeding one cubic meter per hectare and year) ─ both in forests managed for timber production and in forests preserved mainly for nature conservation.

Managed forests

In July to August 2002, dead wood was sampled on or in the vicinity to 289 sample plots previously surveyed by the Swedish National Forest Inventory (NFI). The NFI is an annual, systematic cluster sample inventory of Sweden’s forests. Each year about 1400 survey sample clusters are inventoried in the field. About 2/3 of the clusters are permanent and 1/3 are temporary. The clusters are distributed throughout the country in a pattern that is denser in the southern part of Sweden than in the north. The clusters are square-shaped with sample plots along each side. The number of sample plots in each cluster is between four and twelve, depending on geographical region (Ranneby et al., 1987).

Sample stands were selected by the following procedure:

1. All temporary sample plots of the NFI, years 1997-2000 were included for selection
2. Sweden was divided into 100 km^2 squares
3. Only plots where the NFI previously had registered dead wood were considered
4. Only plots where Scots pine or Norway spruce were by volume the dominating living tree species were considered
5. Up to 8 plots, representing two tree species times four stand age classes (0-40, 41-100, 101-140 and 141- years), were randomly selected per square

Assuming that properties influencing the density of dead wood might be different between strata, the stratification by squares and stand age classes was made to obtain an efficient sample.

Preserved forests

The anthropogenic influence on dead wood in preserved forests is probably quite limited in comparison with managed forests. Therefore, it is reasonable to believe that the population of dead wood in preserved forest might differ from the population in managed forests. Before year 2003, preserved forests were not inventoried by the NFI and to represent preserved forest, one nature reserve dominated by Norway spruce and one dominated by Scots pine were subjectively selected in each of the six northernmost counties of Sweden, where most natural forest reserves (Hermansson and Nilsson, 2005) are found. Within the reserves a total of 11 stands (no Scots pine stand was surveyed in the county of Norrbotten) were selected by simple random sampling and inventoried in September 2003. All stands in preserved forests belonged to the highest stand age class (141- years).

The distribution and summary statistics of the inventoried sample plots are found in Figure 1 and Table 1.

Table 1: Summery statistics of the inventoried managed forests (289 sample plots, inventoried 2002) and preserved forest (11 strips, inventoried 2003).

		Managed forest	**Preserved forest**
Number of areas visited in different stand age classes	**0-40**	63	-
	41-100	75	-
	101-141	73	-
	>141	78	11
Swedish grid (RT90) (Range E -W)		1260504 - 1868556	1328358 – 1747779
Swedish grid (RT90) (Range S - N)		6204176 - 7570956	6814825 – 7402955
Elevation (m)		10-800 (average 244)	280-640 (average 452)
Size of Nature reserves (ha)		-	15-27 000 (average 3070)
Size of sample area (m)		Radius 10-40 (average 11)	Strip length 300-1220 (average 770)
Number of inventoried logs (number of discs within brackets)	**Birch** (Betula pendula and B. pubescens)	71 (193)	-
	Norway spruce (Picea abies)	321 (902)	107 (286)
	Scots pine (Pinus sylvestris)	356 (967)	75 (198)
	Total	748 (2062)	182 (484)
Length of logs (m)		1.3-37 (average 9.2)	1.3-31 (average 10.5)
Diameter of logs 1.3 m from base (cm)		10-46 (average 18)	10-63 (average 21)

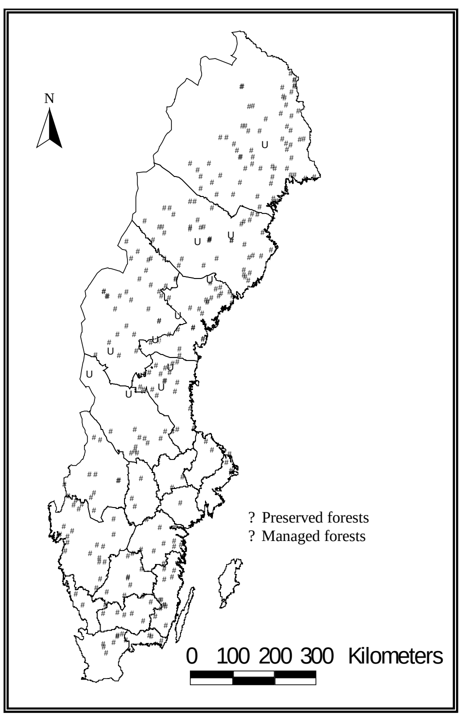

Figure 1: The distribution of the sample plots in managed and preserved boreal forests in Sweden.

Inventory design in field

In the selected NFI sample stands, plots with radius of 10 m were laid out. Depending on the frequency of dead wood the radius was increased to up to 40 m, within the same stand, until at least three pieces of dead wood were found.

The dead wood in the preserved forest was inventoried by a strip survey and each strip had a subjectively located starting point. The strip width was always 10 m and the strip lengths varied between 300 and 1220 m depending on the frequency of dead wood (the sampling in the strips continued until at least 14 pieces of dead wood were found).

The reason for changing design from circular plots to a strip survey for preserved forests was esthetical. Damage caused by collecting samples in plots was assumed to have a higher esthetical impact than a strip survey. Furthermore, a limit was set so that the distance between inventoried dead wood should be at least 10 m.

Dead wood was defined as dead biomass of boles with a minimum length of at least 1.3 m and with diameters of at least 10 cm at the small end of the piece. Only fallen dead wood of Norway spruce (Picea abies) and Scots pine (Pinus sylvestris) were inventoried in preserved forests, and for managed forests also birch (Betula pendula and B. pubescens). The fallen trees could be either stem broken, uprooted or cut. The pieces of dead wood were treated as point objects and to be inventoried the pith at their base had to be located within the plot or within the strip.

One decay stage for each piece of dead wood was determined according to three different decay classification systems described below in Tables 2-4.

For further analysis, three discs, 5 – 10 cm wide, were selected and removed with a bow saw from each log. The first disc was selected close to the base. The second and the third disc were selected to represent the middle and upper part of the log. Two diameter measurements were made, perpendicularly to each other, at the point where the discs were sampled. The mid disc was weighed in field for comparison with the corresponding weight at the laboratory; the reason was to control that sample discs do not loose weight and/or shrink during transport from forest to lab. Due to the high decomposition grade, it was not always possible to collect all three discs. The three extracted discs were placed in paper bags and sent to the laboratory.

Table 2: The **NFI** classification system of dead wood per decay class (Swedish University of Agricultural Sciences, 1994)

Decay class	The **NFI** classification system
0	Raw wood. Trees that recently died, not yet dried up.
1	Solid dead wood. The volume of the stem consists to more than 90% of solid wood and the stem has a hard exterior surface. The wood is to small extent affected by wood decaying organisms.
2	Somewhat decayed wood. The volume of the stem consists to 10-25% of soft wood. The remaining wood is solid.
3	Decayed dead wood. The volume of the stem consists to 26-75% of soft or very soft wood.
4	Very decayed dead wood. The volume of the stem consists to 76-100% soft or very soft wood. A tool can be pressed through the stem. However, a solid core can occur.

Table 3: The **Söderström** classification system of dead wood per decay class (modified from Söderström, 1988)

Decay class	The **Söderström** classification system
1	Wood hard, bark remaining intact
2	Wood hard, more than 50% bark remaining
3	Wood hard, less than 50% bark remaining
4	Wood has started to soften
5	Wood soft, with small crevices and small pieces lost
6	Wood fragments lost so the outline of the trunk is deformed
7	The outer surface of the log is hard to define, possibly with a core of harder wood

Table 4: The **Renvall** classification system of dead wood per decay class (modified from Renvall, 1995)

Decay class	The **Renvall** classification system
1	Wood hard, a knife penetrates only a few millimeters into the wood
2	Wood fairly hard, a knife penetrates ca 1-2 centimeters into the wood
3	Wood fairly soft, knife penetrates fairly easily half-way through the wood (3-5 cm)
4	Wood soft, the shape of the trunk is deformed, the whole blade of the knife easily penetrates into the wood

Analysis at the laboratory

The volume of each disc was estimated by multiplying the cross section area by the width. All cross sections were photographed and the areas were measured using the computer program Image Tool 3.00 (Wilcox et al., 1996). If bark still was attached, it was included in the area estimate. The width was measured by a sliding caliper [mm] and estimated as the average width of four to eight measurements, systematically distributed on the cross section. For a proportion of discs, the cross section area in field (based on cross callipered discs) was compared with the cross section area at laboratory (based on photographs). The comparison indicated no shrinking and we therefore assumed the volume in field and at laboratory to be the same. For a few samples, it was not possible to estimate the volume due to a high decomposition.

The discs were dried for 48 hours (85° C) to constant weight and thereafter weighed by a Mettler PE 4000 electronic balance [0.1g]. Random sectors of the discs were selected, ground and analyzed for carbon (C) by the “flash combustion method” with the Nitrogen Analyzer NA 1500. The 51 analyzed sub-samples were subjectively selected to represent Norway spruce and Scots pine in both managed and preserved forests. The sub samples were approximately evenly distributed among the five NFI decay classes.

Calculations

With constant density (dry weight/raw volume) within and between logs, the average density (d_{ij}) could be estimated as:

$$d_{ij} = \frac{\sum dry\,weight_{ijk}}{\sum raw\,volume_{ijk}} \qquad (1)$$

where *i* is species, *j* is decay class and *k* is disc number of a piece of dead wood; the sum is taken over all discs within a decay class per species. In case the density varies within and between logs, this approach to estimate the density would be rather crude and different weights should be given to different logs and discs based on the sampling scheme used. Thus, to study the appropriateness of formula 1, the density of the base, middle and upper discs was compared for all logs. This resulted in the average densities: 0.245, 0.228 and 0.236 g/cm^3 and we concluded that no weighting was needed.
Studies were made to compare the log densities of different sub-populations. In these studies, SEs (Standard Error) were estimated using standard formulas and potential differences in conversion factors between paired classes were tested using the following formula:

$$(d_{ij} - d_{ij+1}) \pm 1{,}96 * \sqrt{SE_{ij}^2 + SE_{ij+1}^2} \qquad (2)$$

where d_{ij} and d_{ij+1} were the average densities (conversion factors) for two compared classes, with a confidence interval based on the corresponding SEs. The differences between densities based on the NFI system were tested for the following combinations: the differences between managed and preserved forests for both Scots pine and Norway spruce; the differences between all combinations of decay classes within species; and differences between species (all classes together).

For each species and decay class, the weight of C per hectare (C_{ij}) in dead wood was estimated for Swedish forests as:

$$C_{ij} = v_{ij} * d_{ij} * 0.5 \qquad (3)$$

where v_{ij} is the volume per hectare obtained from the Swedish NFI, d_{ij} is the density from equation (1) and 0.5 is the rounded C conversion factor derived in this study (0.5 is also recommended by the IPCC, the International Panel on Climate change; Anonymous., 1996). The estimates were based on NFI data (v_{ij}) derived from permanent sample plots of the years 1998-2002. The decay class "0" was introduced in the NFI year 2003 and thus data of decay classes "0" and "1" have been merged to one class in the calculations. The densities for birch were used in the calculations for all deciduous dead wood and the densities for logs were also used for snags.

Results

Density (Conversion factors)

Tables 5-7 show the dead wood densities or conversion factors from volume to biomass for Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and birch (Betula pendula and B. pubescens) according to three different decay class systems. Per species when decay classes were arranged into an array, significant differences were found between all consecutive decay classes for the NFI classification system. This was not always the case for the Söderström and Renvall systems. The density decreased by decay class for the NFI and the Renvall classification systems, but not always for the Söderström system.

The range in density for the decay classes was wider for the NFI system than for the Renvall system (Tables 5-7). For the purpose of converting estimates of volume to biomass, this indicated that the NFI system was to be preferred.

Significant differences ($^{*}P<0.05$) were found between the average densities for managed and preserved forests for Norway spruce but not for Scots pine: Significant differences were also found in the average densities between species.

Table 8 shows the densities of dead wood for different stand age classes for Scots pine, Norway spruce and birch according to the NFI decay class system. The densities increase with increasing stand age, except between class 3 and 4 for birch. Per species and for all species, the differences between class 1 and 3 and 1 and 4 were significant. Norway spruce and all species together showed a significant difference between class 1 and 2. The differences between classes 2 and 3, and 3 and 4 were only significant for birch and differences between classes 2 and 4 were only significant for Scots pine. Table 9 shows the densities of dead wood by latitude (Swedish grid system: RT90) for Scots pine, Norway spruce and birch. A slight trend was found, showing a decreasing density by increasing latitude.

Table 5: Dead wood densities (g/cm^3) (dry weight/raw volume) for Scots pine (Pinus sylvestris) in managed and preserved forests according to three different decay classification systems. SE (Standard Error) within brackets. A few logs, were not classified by all three systems.

	Density [g/cm^3]		
Decay class	**Scots pine all**	**Scots pine managed**	**Scots pine preserved**
NFI			
0	0.3343 (0.009)	0.3360 (0.008)	0.3273 (0.029)
1	0.3078 (0.005)	0.3128 (0.006)	0.2812 (0.011)
2	0.2502 (0.006)	0.2521 (0.006)	0.2434 (0.015)
3	0.2287 (0.007)	0.2226 (0.008)	0.2685 (0.013)
4	0.1687 (0.008)	0.1577 (0.009)	0.2077 (0.012)
All classes	0.2389 (0.004)	0.2384 (0.004)	0.2411 (0.011)
Söderström			
1	0.2748 (0.045)	0.3340 (0.008)	0.1425 (0.069)
2	0.2932 (0.009)	0.2932 (0.009)	No data
3	0.3003 (0.007)	0.3078 (0.007)	0.2644 (0.019)
4	0.2618 (0.005)	0.2616 (0.006)	0.2623 (0.007)
5	0.2316 (0.006)	0.2314 (0.007)	0.2323 (0.017)
6	0.1996 (0.008)	0.1931 (0.008)	0.2404 (0.016)
7	0.1520 (0.017)	0.1291 (0.016)	0.2356 (0.022)
All classes	0.2389 (0.004)	0.2384 (0.004)	0.2411 (0.011)
Renvall			
1	0.2673 (0.008)	0.2701 (0.007)	0.2507 (0.032)
2	0.2444 (0.006)	0.2433 (0.007)	0.2482 (0.012)
3	0.2171 (0.008)	0.2111 (0.009)	0.2441 (0.014)
4	0.1939 (0.010)	0.1929 (0.012)	0.1989 (0.015)
All classes	0.2396 (0.004)	0.2393 (0.004)	0.2411 (0.011)

Table 6: Dead wood densities (g/cm^3) (dry weight/raw volume) for Norway spruce (Picea abies) in managed and preserved forests according to three different decay classification systems. SE (Standard Error) within brackets. A few logs, were not classified by all three systems.

		Density [g/cm^3]	
Decay class	**Norway spruce all**	**Norway spruce managed**	**Norway spruce preserved**
NFI			
0	0.3042 (0.007)	0.3060 (0.008)	0.2980 (0.014)
1	0.2884 (0.003)	0.2915 (0.003)	0.2773 (0.008)
2	0.2320 (0.005)	0.2412 (0.006)	0.2173 (0.007)
3	0.1726 (0.005)	0.1748 (0.007)	0.1694 (0.006)
4	0.1367 (0.006)	0.1311 (0.007)	0.1548 (0.009)
All classes	0.2259 (0.003)	0.2322 (0.004)	0.2118 (0.005)
Söderström			
1	0.3088 (0.004)	0.3015 (0.004)	0.3194 (0.009)
2	0.2793 (0.004)	0.2850 (0.005)	0.2654 (0.009)
3	0.2846 (0.005)	0.2884 (0.005)	0.2788 (0.016)
4	0.2147 (0.005)	0.2295 (0.006)	0.1977 (0.006)
5	0.1718 (0.005)	0.1732 (0.007)	0.1695 (0.006)
6	0.1334 (0.009)	0.1319 (0.010)	0.1443 (0.022)
7	0.1420 (0.015)	0.1407 (0.015)	No data
All classes	0.2269 (0.003)	0.2337 (0.004)	0.2118 (0.005)
Renvall			
1	0.2549 (0.005)	0.2508 (0.005)	0.2699 (0.009)
2	0.2194 (0.005)	0.2335 (0.007)	0.2012 (0.006)
3	0.1926 (0.008)	0.2105 (0.012)	0.1660 (0.007)
4	0.1727 (0.012)	0.1826 (0.016)	0.1435 (0.011)
All classes	0.2274 (0.003)	0.2347 (0.004)	0.2118 (0.005)

Table 7: Dead wood densities (g/cm^3) (dry weight/raw volume) for birch (Betula pendula and B. pubescens) in managed forests according to three different decay classification systems. SE (Standard Error) within brackets. A few logs. were not classified by all three systems.

Decay class	Density [g/cm^3] Birch
NFI-system	
0	0.4745 (0.009)
1	0.3646 (0.014)
2	0.2699 (0.014)
3	0.1931 (0.017)
4	0.1215 (0.016)
All classes	0.2746 (0.011)
Söderström	
1	0.4133 (0.019)
2	0.3838 (0.014)
3	0.3486 (0.017)
4	0.2106 (0.028)
5	0.2370 (0.015)
6	0.1505 (0.014)
7	No data
All classes	0.2952 (0.013)
Renvall	
1	0.2872 (0.018)
2	0.3148 (0.018)
3	0.2488 (0.032)
4	0.2093 (0.036)
All classes	0.2803 (0.013)

Table 8: Dead wood densities (g/cm^3) (dry weight/raw volume) by stand age classes for Scots pine (Pinus sylvestris). Norway spruce (Picea abies) and birch (Betula pendula and B. pubescens) according to the NFI decay class system. SE (Standard Error) within brackets.

Stand age class	Corresponding ages [years]	Density [g/cm^3] Scots pine	Norway spruce	Birch	All species
1	**0-40**	0.2170 (0.009)	0.1769 (0.012)	0.2134 (0.021)	0.2058 (0.007)
2	**41-100**	0.2315 (0.007)	0.2331 (0.006)	0.2396 (0.017)	0.2327 (0.004)
3	**101-141**	0.2425 (0.009)	0.2369 (0.008)	0.3489 (0.020)	0.2471 (0.006)
4	**>141**	0.2569 (0.008)	0.2515 (0.006)	0.2845 (0.019)	0.2564 (0.005)

Table 9: Dead wood densities (g/cm^3) (dry weight/raw volume) by latitude (Swedish grid: RT90) for Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and birch (Betula pendula and B. pubescens). SE (Standard Error) within brackets.

Latitude RT90 [m]	Density [g/cm^3] Scots pine	Norway spruce	Birch	All species
6468324	0.2665 (0.007)	0.2950 (0.005)	0.3031 (0.027)	0.2849 (0.004)
6834561	0.2829 (0.005)	0.2762 (0.005)	0.2850 (0.015)	0.2802 (0.004)
7114810	0.2679 (0.006)	0.2474 (0.005)	0.3309 (0.015)	0.2643 (0.004)
7387296	0.2466 (0.006)	0.2338 (0.008)	0.2804 (0.018)	0.2464 (0.005)

Carbon concentration

For 51 sub-samples, the C concentration in the dead wood (dry weight) increased by decay class for both species. The C concentration was lower for Norway spruce than for Scots pine (Table 10). The difference between the lowest and highest decay class is about the same for both species, i.e. about 2%.

Carbon content in Swedish forests

The amount of C in dead wood per hectare, including logs and snags, was estimated to 0.85 Mg C/ha of which the largest quantities were found in coniferous species and in decay class 0 and 1 (Table 11).

Table 10: Carbon concentration (%)in dead wood (dry weight) of Scots pine (Pinus sylvestris) and Norway spruce (Picea abies).

Decay class NFI-system	Carbon concentration (%) Scots pine	Norway spruce
0	50.32	49.22
1	50.52	49.17
2	51.46	49.68
3	51.46	50.81
4	52.23	51.27
All classes	51.20	50.03

Table 11: The carbon content of dead wood including logs and snags per area (Mg C/ha).of Scots pine (Pinus sylvestris). Norway spruce (Picea abies) and Deciduous tree species. in Swedish managed forests. (Estimates are based on average NFI data from years 1998-2002. Only permanent sample plots were used.)

Decay class NFI-system	Carbon content (Mg C/ha)		
	Scots pine	**Norway spruce**	**Deciduous**
0 and 1	0.157	0.210	0.118
2	0.053	0.040	0.048
3	0.074	0.026	0.025
4	0.055	0.025	0.014
All classes	0.340	0.302	0.205

Discussion

The decay stage and the C concentration of a piece of dead wood probably depend on time since death, wood properties, the occurrence of wood decaying organisms and on the microclimate (Harmon et al., 1986). The design for selecting sample plots were adapted to, in the best possible way, cover the population of fallen dead wood in Sweden. This was made by geographically distributing a large number of sample plots over the country and by representing a wide range of site-, stand- and dead wood conditions (Figure 1). To, at application, further minimize the risk of bias, the same definition of dead wood was used at the derivation and at the intended NFI-application, i.e. the NFI-definition. For the same reason, also the sample design was imitating the design of the NFI.

A potential problem at application might be that the conversion factors are based on volumes calculated from the actual cross section area of the logs but will be applied to volumes based on the cross callipered cross section area. The actual cross section area was estimated to be 3.7% smaller than the cross callipered one and to avoid overestimating biomass in dead wood this has to be considered.

From a statistical point of view for the purpose of converting estimates of volume to biomass, the NFI system was assumed to be preferred. The NFI system is incorporated in the NFI inventory design to monitor the decomposition stage and the habitat quality of dead wood. The Renvall system is not adapted to the sampling design of the NFI and it is possible that, after some modification, the predictive properties of this system might be improved. However, the Söderström system is probably more useful for other fields of application such as for the purpose of monitoring biological diversity aspects. However, only the purpose of converting estimates of volume to biomass was evaluated.

The decrease in density with increasing decay class coincides with other studies. Krankina and Harmon (1995) classified Norway spruce, Scots pine and birch logs according to a decay class system with five classes and reported a pattern of decreasing density over decay classes. Two other studies in Russia (Harmon et al., 2000; Yatskov et al., 2003) also report decreasing dead wood density of Scots pine, Norway spruce and birch with increasing decomposition. Similar trends have been reported for American coniferous tree species (Means et al., 1985; Harmon et al., 1987). Naesset (1999a) made a study were the relationship between wood density and decay classes of Norway spruce logs were studied in open areas. The results of the average wood density of logs using the Söderström decay classes 2-6 were: 0.39, 0.36, 0.27, 0.21, 0.17 g/cm^3, respectively. Our corresponding results in closed forests show lower densities in all classes and not the straightforward decrease in density (Table 6).

Significant differences in density were found also between species and, for Norway spruce, between managed and preserved forests. Furthermore, there was a tendency of lower dead wood density of Norway spruce than of Scots pine, which corresponds to that Pinus species generally have a higher resistance to decay (Scheffer and Cowling, 1966; Table 5 and 6). Important implications are the need to inventory dead wood by species and maybe separately for managed and preserved forests.

The densities showed a significant difference between stand age class 1 and 3 and between class 1 and 4 for all species (Table 8). The transition from natural regeneration systems to the clear cutting system in the mid 20th century has led to a continuous increasing average growth rate and consequently to a lower wood density (Nylinder and Hägglund, 1954). The increasing dead wood density with increasing stand age of the forest corresponds to results reported by Krankina et al. (1999) who found an increase from 0.155 g/cm^3 in forests 10-20 years old to 0.272 g/cm^3 in old growth forests.

The dead wood C concentration of Scots pine and Norway spruce increased by decay class. The increase was about 2% from the lowest to the highest decay class for both species (Table 10). The tendency of consistent increasing C concentration with increasing decomposition contradict to the results by Harmon et al. (1987) that found no consistent change with decay class in coniferous tree species in California, USA. However, their reported average C concentration of 0.51 is corresponding with the average C concentration in this study. In average Norway spruce showed lower C concentration than Scots pine, 0.500 and 0.512, respectively. Thörnkvist (1985) reported C concentrations of 0.500 for Norway spruce and 0.508 for Scots pine for living trees which is somewhat lower than the results for the least decayed dead wood in this study.

In the case study, a restricted data material derived the C concentrations and therefore we used the rounded factor 0.5 for the conversion from biomass to C. This factor is the same as the standard factor by IPCC (Anonymous, 1996). In Swedish forests the dead wood C store were estimated to 0.85 Mg C/ha (Table 11). The corresponding results from a study in Russia is 1-8 Mg C/ha in managed stands and 17 Mg C/ha in old-growth forests (Krankina and Harmon, 1995).

Conclusions

The densities (conversion factors) are based on an extensive data material with a wide representation of different site-, stand-, species- and dead wood properties and are therefore assumed to represent the population of fallen dead wood in Sweden. For the purpose of converting estimates of volume to C of dead wood, the NFI decay classification system appeared to be the most suitable system tested. Moreover, the use of different conversion factors for different circumstances (e.g. species, management) is suggested since significant differences were found for most comparisons of densities. In this study, the C concentration increased with increasing decay class and in average Norway spruce showed a lower C concentration than Scots pine. Compared to a study made in Russia, the dead wood C store of 0.85 Mg C/ha in Swedish forest was found quite low.

Acknowledgements

This study was financially supported by the Swedish Research Council for Environment, the Agricultural Sciences and Spatial Planning (FORMAS) and The Swedish Energy Agency (STEM). The authors are deeply grateful to the county administrations for cooperation and the access to dead wood samples from preserved forests.

References

Anonymous, 1994. Riksinventeringen av skog (RIS) 1994 – Fältinstruktion. SLU, Umeå (in Swedish).

Anonymous, 1996. IPCC Guidelines for National Greenhouse Gas Inventories. Volume 3. Greenhouse Gas Inventory reference manual. (Rev. ed.). In: Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J., Callender, B.A. (Eds.). (1996). IPCC. UK Meteorological Office, Bracknell, UK.

Anonymous, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry. In: Penman, J., Gytarsky, M., Hiraishi, T., Krug T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., Wagner, F. (Eds.). IPCC/OECD/IEA/IGES, Hayama, Japan.

Arnborg, T., 1942. Lågaföryngringen i en syd-lappländsk granurskog. Sver. Skogsv. Tids. 40, 47-78 (In Swedish).

Brown, S., Mo, J. M., McPherson, J. K., Bell, D. T., 1996. Decomposition of woody debris in Western Australian forests. Can. J. For. Res. 26, 954-966.

Dixon, R.K., Brown, S., Houghton, R.A., Solomon, A.M., Trexler, M.C., Wisniewski, J., 1994. Carbon pools and flux of global forest ecosystems. Science. 263, 185-190.

Esseen, P.A., Ehnström, B., Ericson, L., Sjöberg, K., 1997. Boreal Forest. Ecol. Bull. 46, 16-47.

Fridman, J., Walheim, M., 2000. Amount, structure and dynamics of dead wood on managed forestland in Sweden. For. Ecol. Manage. 131, 23-36.

Goodale, C.L., Apps, M.J., Birdsey, R.A., Field, C.B., Heath, L.S., Houghton, R.A., Jenkins, J.C., Kohlmaier, G.H., Kurz, W., Liu, S., Nabuurs, G-J., Nilsson, S., Shvidenko, Anatoly, Z., 2002. Forest carbon sinks in the Northern hemisphere. Ecol. Appl. 12(3), 891-899.

Harmon, M.E., Hua, C., 1991. Coarse woody debris dynamics in two old growth eco-systems. BioScience. 41, 604-610.

Harmon, M.E., Cromack, K., Smith, B.G., 1987. Coarse woody debris in mixed-conifer forests, Sequoia National Park, California. Can. J. For. Res. 17, 1265-1272.

Harmon, M.E., Krankina, O.N., Sexton, J., 2000. Decomposition vectors: a new approach to estimating woody detritius decomposition dynamics. Can. J. For. Res. 30, 76-84.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J. D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Cummins, K.W., 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. 15, 133-302.

Hermansson, G., Nilsson, M., 2005. Sveriges Rikes lag, Miljöbalken (1998: 808). (126th ed.). Nordstedts juridik AB Stockholm, Sweden (in Swedish).

Kauppi, P.E., Mielikainen, K., Kuusela, K., 1992. Biomass and carbon budget of European forests, 1971 to 1990. Science. 256, 70-74.

Krankina, O.N., Harmon, M.E., 1995. Dynamics of the dead wood carbon pool in Northwestern Russian boreal forests. Wat. air soil poll. 82(1-2), 227-238.

Krankina, O.N., Harmon, M.E., Griazkin, A.V., 1999. Nutrient stores and dynamics of woody detritus in a boreal forest: modeling potential implications at the stand level. Can. J. For. Res. 29, 20-32.

Means, J.E., Cromack, K., MacMillan, P.C., 1985. Comparison of decomposition models using wood density of Douglas-fir logs. Can. J. For. Res. 15, 1092-1098.

Naesset, E., 1999a. Relationship between relative wood density of Picea abies logs and simple classification systems of decayed coarse woody debris. Can. J. For. Res. 14, 454-461.

Naesset, E., 1999b. Decomposition rate constants of Picea abies logs in southeastern Norway. Can. J. For. Res. 29, 372-381.

Nylinder, P., Hägglund, E., 1954. Ståndorts- och trädegenskapers inverkan på utbyte och kvalitet vid framställning av sulfitmassa av gran. Medd. Stat. Skogsf. (in Swedish).

Preston, C.M., Trofymow, J.A., Niu, J., Fyfe, C.A., 1998. ^{13}CPMAS-NMRA spectroscopy and chemical analyses of coarse woody debris in coastal forests of Vancouver Island. For. Ecol. Manage. 111, 51-68.

Pyle, C., Brown, M.M., 1998. A rapid system of decay classification for hardwood logs of the eastern deciduous forest floor. J. Torr. Bot. Soc. 125, 237-245.

Pyle, C., Brown, M.M., 1999. Heterogeneity of wood decay classes within hardwood logs. For. Ecol. Manage. 114, 253-259.

Ranius, T., Jonsson, B.G., Kruys, N., 2004. Modeling dead wood in Fennoscandian old-growth forests dominated by Norway spruce. Can. J. For. Res. 34, 1025-1034.

Ranneby, B., Cruse, T., Hägglund, B., Jonasson, H., Swärd, J., 1987. Designing a new national forest survey for Sweden. Stud. For. Suec. 177.

Renvall, P., 1995. Community structure and dynamics of wood-rotting Basidiomycetes on decomposing conifer trunks in northern Finland. Karstenia. 35, 1–51.

Scheffer, T.C., Cowling, E.B., 1966. Natural resistance of wood to microbial deterioration. Ann. Rev. Phyt. 4, 147-170.

Schulze, E.D., Valentini, R., Sanz, M.J., 2002. The long way from Kyoto to Marrakesh: Implications of the Kyoto Protocol negotiations for global ecology. Glob. Change Biol. 8, 505-518.

Siitonen, J., 2001. Forest management, coarse woody debris and saproxylic organisms: Fennoscandian boreal forests as an example. Ecol. Bull. 49, 11-41.

Söderström, L., 1988. Sequence of bryophytes and lichens in relation to substrate variables of decaying coniferous wood in Northern Sweden. Nord. J Bot. 8, 89-97.

Sollins, P., 1982. Input and decay of coarse woody debris in coniferous stands in western Oregon and Washington. Can. J. For. Res. 12, 18-28.

Ståhl, G., Andrén, O., Klemedtsson, L., Kätterer, T., Nilsson, M., Olsson, H., Petersson, H., 2003. Preparing for Swedens reporting of emissions and removals of greenhouse gases in the LULUCF sector under the Kyoto Protocol. A report prepared for the Swedish Environmental Protection Agency. Report 5357.

Ståhl, G., Boström, B., Lindqvist, H., Lindroth, A., Nilsson, J., Olsson, M., 2004. Methodological options for quantifying changes in carbon pools in Swedish forests. Stud. For. Suec. 214.

Stone, J.N., MacKinnon, A., Parminter, V., Lertzman, K.P., 1998. Coarse woody debris decomposition documented over 65 years on southern Vancouver Island. Can. J. For. Res. 28: 788-793.

Thörnqvist, T., 1985. Trädbränslekvalitet – vad är det? Swed. Univ. Agric. Sci., SIMS, Uppsala, 14. (in Swedish).

Wilcox, D., Dove, B., McDavid, D., Greer, D., 1996. UTHSCSA Image Tool for Windows (version 3.00) [Computer software]. San Antonio, The University of Texas Health Science Center. Retrieved October 1, 2002. http://ddsdx.uthscsa.edu/

Yatskov, M., Harmon, M.E., Krankina, O., 2003. A chronosequence of wood decomposition in the boreal forests of Russia. Can. J. For. Res., 33, 1211-1226.