

Dead wood volume to dead wood carbon: the issue of conversion factors

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Abstract Requirements for emission reporting under the Kyoto protocol demand an estimate of the dead wood carbon pool in forests. The volume of dead wood consists of coarse woody debris, smaller woody debris and dead roots. The measurement of dead wood volume was included in the most recent National Forest Inventory in Switzerland. To convert dead wood volume into carbon two conversion factors are required: (a) carbon (C) concentration and (b) wood density. So far internationally accepted default values for C concentration (50%) and for wood density (density of alive trees) were used as default values to estimate dead wood carbon, since local measurements were lacking. However, in a field study at 34 sites in Switzerland, the C concentration and density of CWD from *Picea abies* and *Fagus sylvatica* of four decay classes were measured recently. The results showed that C concentration in CWD differed significantly between species but did not change due to decay class. The density of CWD decreased significantly with an increase in decay class and it also differed between species. The decrease in CWD density was more pronounced for *F. sylvatica* than for *P. abies*. We assessed correlations between climate attributes and CWD density using regression analysis. The modeled densities and measured C concentrations were then expanded with

the help of CWD volume data from the NFI3. Spruce CWD and thus spruce CWD carbon is much more abundant in Swiss forests than beech CWD carbon. The majority of spruce CWD is located in the Alps and Pre-Alps. The CWD volume from *P. abies* was 10 times higher than that from *F. sylvatica*. Thus, changes in conversion factors for *P. abies* CWD affected the overall estimate of dead wood carbon in Swiss forests much more than changes in conversion factors for *F. sylvatica* CWD. Current improvements in CWD conversion factors decreased the estimated amount of spruce CWD carbon by 23.1% and that of beech by 47.6%. The estimated amount of CWD carbon in Swiss forests is decreased by 31%. Since improved estimation methods are currently not applied to smaller woody debris and dead root material, the estimated amount of dead wood carbon is only reduced by 15%. Improving conversion factors for all dead wood fractions would presumably decrease the amount of dead wood carbon by additional 16%.

Keywords Carbon · Coarse woody debris · Wood density · *Picea abies* · *Fagus sylvatica* · Dead wood carbon · Conversion factors · Green house gas accounting

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Introduction

Many countries, such as Switzerland, have joined the United Nations Framework Convention on Climate Change (UNFCCC) and ratified the additional Kyoto Protocol that regulates emission reduction commitments. Requirements for emission reporting have been defined in the Convention and the Kyoto Protocol. Thus, Switzerland is required to report annual emissions from many sectors including Land use, Land use change and Forestry (LULUCF). In the

LULUCF section countries have to report removals or sinks of greenhouse gas (GHG) under Article 3.3 (afforestation and deforestation) and can elect to do so under Article 3.4 (forest management) of the Kyoto protocol. Switzerland has decided to include forest management under Article 3.4 in their accounting of anthropogenic GHG emission and removal and needs to provide the required reporting under this section. For this report, changes of carbon in plants, dead wood and soil must be estimated for managed forest, which have been established prior to 1990. The quantity of carbon in dead organic matter is a significant reservoir in many of the world's forests (IPCC 2003). So far measurement of dead wood is less established in National Forest Inventories (NFI) than measurement of alive trees (Tomppo et al. 2010; Woodall et al. 2009). Until now knowledge about dead wood volume in Swiss Forests was limited because criteria for coarse woody debris and the minimum diameter for coarse woody debris was altered over time to serve a shift in demand for information (Böhl and Brändli 2007).

The dead wood pool consists of different fractions such as woody debris from fallen stems, standing dead trees, dead coarse roots and other dead material not included in the litter or soil carbon pools (IPCC 2003). For practical reasons, the Swiss NFI distinguishes between (a) bigger size woody debris that includes fallen dead trees and snags ($d > 12$ cm), (b) smaller woody debris ($7 < d < 12$ cm) and (c) dead coarse roots. A comprehensive measurement of those dead wood volumes was included in the most recent NFI for Switzerland (Böhl and Brändli 2007; Cioldi et al. 2010). Those three dead wood fractions contain dead wood volume approximately in the ratio 2:1:1 (Cioldi et al. 2010).

To convert volume measurements into carbon, two conversion factors are necessary: (1) C concentration and (2) density. If local measurements for those factors are not available, the IPCC good practice guidance (IPCC 2003) supplies default values. The default value for C concentration of wood is 50%, for instance. The default value for dead wood density is the density of alive wood from *Picea abies* (0.40 g cm^{-3}) and *Fagus sylvatica* (0.58 g cm^{-3}). Very similar default values from local studies of alive wood (Assmann 1961) were used so far to calculate dead wood carbon in the Swiss GHG inventory (FOEN 2009). However, Lamlon and Savidge (2003) found that C content varies substantially among species and that a 50% generic value is an oversimplification of limited application in relation to global warming and the concept of carbon credits. Furthermore, density of dead wood is likely to be dependent on its state of decay (Harmon et al. 1987, 1986). Harmon et al. (1986) stated that if dead wood volume is multiplied with the default wood density of fresh wood then the carbon content of this part of the ecosystem is

usually overestimated. For more accurate estimates of dead wood carbon, the decay rate-specific dead wood density for all major tree species needs to be established under local conditions. Decay class-specific C concentration and density values were measured recently for spruce and beech coarse woody debris at 34 sites in Switzerland (Jüngling, pers. com.). These measurements need to be extrapolated to the whole forest area of Switzerland. One method to apply the measured coarse woody debris-density values to the NFI database is by using decay class-specific density values, irrespective of local differences. Alternatively, measured density values can be used to establish a model that predicts site-specific coarse woody debris-density values on the basis of local climate attributes, provided correlations between climate attributes and wood density can be found.

The key factors that influence the decay process and thus wood density are (1) the environment and (2) substrate quality (Laiho and Prescott 2004). A number of models have been established to predict litter decay on the basis of climate attributes (Kurz-Besson et al. 2006; Meentemeyer 1978), and a few models have been established to predict CWD decay (Mackensen et al. 2003; Yin 1999). Major climate attributes used in models vary between studies. Mean annual temperature was often found to determine woody debris decomposition (Gough et al. 2007; Liski et al. 2003; Mackensen et al. 2003; Meentemeyer 1978). For leaf litter decay, it was found that temperature and a factor for drought can explain a majority of the variability in decay (Liski et al. 2003; Meentemeyer 1978). Rainfall and the resulting water content of wood were also shown to increase their decay rates (Gough et al. 2007). Explanatory variables in models can vary due to the state of decay. Heim and Frey (2004) found that the early stages of leaf litter decay were determined by litter quality parameters whereas later stages were determined by climate attributes. All those studies found some correlations between climate attributes and debris decay. At least in the first three phases of wood decay, also wood density decreases significantly over time (Müller-Using and Bartsch 2009). Hence, it appears possible that CWD density, as a surrogate for CWD decay, could be modeled on the basis of climate attributes for the notable time span that dead wood remains within one decay class.

The volume of dead wood can depend on a range of factors, such as tree species, climate and management, to name the most important ones (Fig. 1). The volume of coarse woody debris in mixed forests of Switzerland, as provided by the NFI3, was found to be on average $21.5 \text{ m}^3 \text{ ha}^{-1}$ and is considered high in European comparison (Brändli et al. 2010). Spruce (*P. abies*) and beech (*F. sylvatica*) are the two major species in Swiss forest, together equating to about 60% of the forest biomass

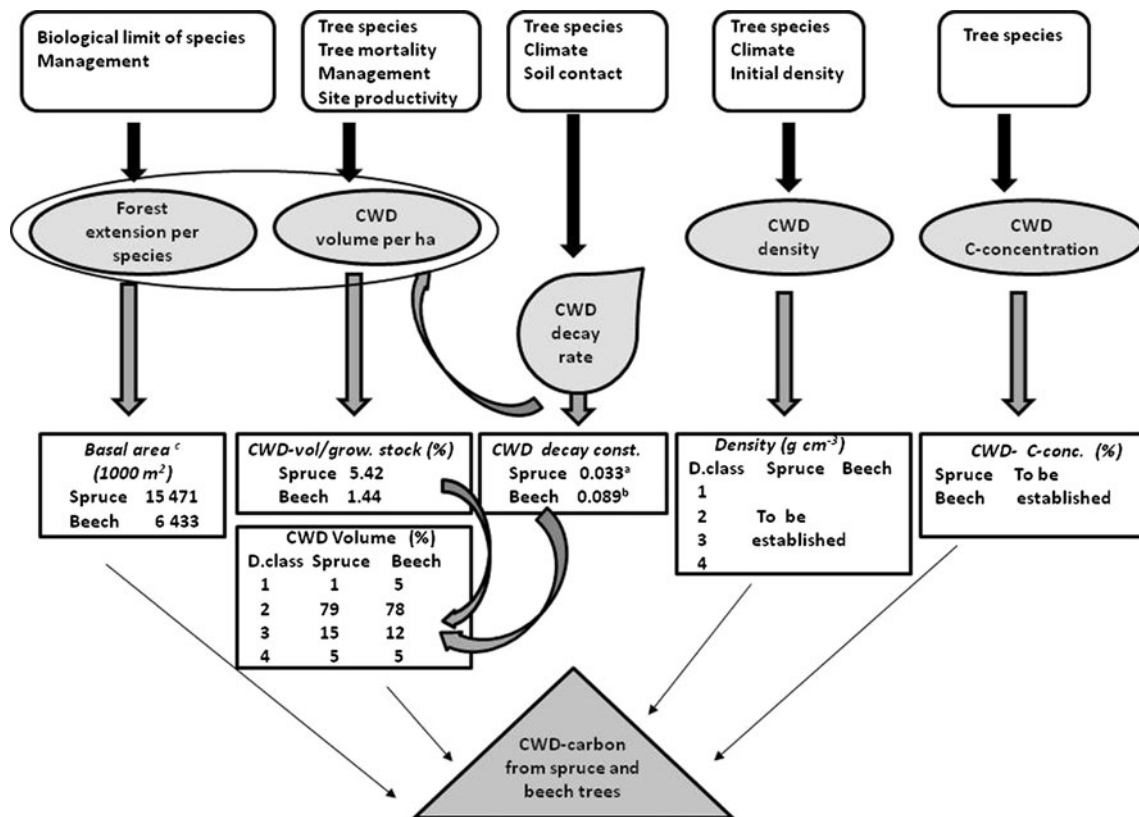


Fig. 1 Factors that can influence the amount of CWD carbon (*Round cornered fields*), ‘values’ necessary to estimate it (*ellipsoid fields*). Current information necessary to quantify ‘values’ are provided if available (*Rectangle fields*). ^a from Rock et al. (2008); ^b from Müller-

Using and Bartsch (2009); ^c Forest extension provided as basal area due to the high amount of mixed forests in Switzerland. Abbreviation for decay class: d. class

(Cioldi et al. 2010). Differences in dead wood volume between species have been reported previously, with 25 m³ ha⁻¹ for managed spruce and 5 m³ ha⁻¹ for managed beech forests (Bretz-Guby and Dobbertin 1996). A generally lower dead wood volume for spruce of 2–10 m³ ha⁻¹ has been reported for Scandinavia (Siitonen 2001). If the dead wood volume differs between species, then knowledge about changes in conversion factors for tree species alone is still a limited indicator to forecast changes to the overall dead wood carbon estimate for Switzerland. Knowledge about species-specific conversion factors and volumes is necessary to judge major carbon pools and forecast potential changes to them.

To improve the accuracy of the estimated amount of dead wood carbon for Switzerland, the current study has four aims. The first aim is to extrapolate the survey based, decay class-specific C concentration and density values for spruce and beech to the Swiss NFI3-database.

The second aim is to further improve the estimates of coarse woody debris density by taking local climate into account. The objective is to predict site-specific coarse woody debris density with the help of climate-based models. The third aim is to assess the impact of changes in

conversion factors on the estimated amount of coarse woody debris carbon. The fourth aim is to apply the improved conversion factors based on spruce and beech to the coarse woody debris in mixed forests of Switzerland. The study will focus on coarse woody debris carbon, but implications for smaller woody debris and dead coarse roots carbon will be discussed.

Materials and methods

Dead wood pools

In the NFI3, three pools of dead wood were measured or estimated at 6,608 sites: bigger size woody debris, smaller size woody debris and dead roots (estimated).

In this publication, the term CWD is used for snags, lying dead trees and stumps with a diameter (above bark) of ≥12 cm at breast height (dbh). To determine CWD, all lying and standing dead wood, including stumps, was measured in a circular area of 200 or 500 m² for bigger size stems (d > 34 cm). The method is described in detail by Keller (2005). The dbh was measured 1.3 m above the original

surface. Soil material on top of the dislocated root stock was used to estimate the original surface. Diameter was measured above bark, if still attached and otherwise around the remaining trunk. Broken stems were estimated as separate units. The top part of dead stems that fell below a diameter of 12 cm was accounted for in the LIS pool (see below). For stumps, the volume was assessed from height and diameter at cut off point. The volume of CWD was estimated according to functions published in Kaufmann (2001).

The volume of generally smaller sized woody debris such as lying stems, pieces of stems, branches and other woody debris with a diameter of $7 < d < 12$ cm, excluding snags, is determined by the line intersect method (Keller 2005) and is termed LIS in this publication. All smaller size woody debris was estimated for a circular area of 200 m^2 by measuring the small woody debris that intersects with three lines, 10 m length each, that star like capture the round sample area (lines in 120° angles).

The mass of dead roots (in the following termed D Roots), in kg, is estimated as a function of diameter of the measured dead trees in the CWD fraction, according to Wirth et al. (2004) and Wutzler et al. (2008).

The CWD, as measured in the NFI3, is classified into five decay classes according to methods outlined in Table 1 (Keller 2005). The origin of CWD in terms of tree species

was recorded in the field if it could be determined. For most CWD samples, about 87% of CWD volume, tree species could be determined. Even for decay class 4, tree species could be determined for about 50% of the CWD volume. The volume of CWD and the distribution of CWD volume between the five decay classes for spruce and beech are given in Table 2.

Switzerland has a high percentage of mixed forests. To be able to compare the volume of CWD per hectare for spruce and beech, the area that each species potentially occupies needed to be estimated. We used basal area (BA) ratios to calculate the area covered by one species. For instance, BA-spruce to BA-coniferous trees was assumed to be similar to area-spruce to area-coniferous trees. The same calculation was conducted for beech. Using the estimated area covered by spruce or beech trees, we calculated the volume of CWD per area for spruce and beech. The basal area of spruce, beech, coniferous and deciduous trees and calculated amount of CWD per hectare is given in Table 3.

Density and C concentration of CWD

The C concentration and density of CWD and of living trees was determined at 34 trial sites of the Swiss national forest health inventory (Sanasilva, subset of the NFI sites)

Table 1 Coarse woody debris classification system, terms and method of determination in the field (Keller 2005)

Decay class	Term	Method of determination
0	Alive tree	–
1	Fresh wood	Stem still contains sap
2	Dead wood	No sap, firm, a knife hardly can penetrate along the fibers
3	Rotten wood	Less firm, knife penetrates along the fibers easily, but not diagonally
4	Moldy wood	Soft, the knife penetrates in each direction easily
5 ^a	Mulm wood	Very soft and powdery, hardly hanging together

^a not analyzed in this study

Table 2 Spruce and beech CWD volume per decay class and for the five NFI regions of Switzerland

Decay class	CWD volume (1,000 m ³)											
	Jura	SEM	Plateau	SEM	Pre-Alps	SEM	Alps	SEM	South. Alps	SEM	Switzerland	SEM
Spruce												
1	11	7	47	21	24	10	30	10	1	1	113	26
2	463	68	821	162	2,997	337	2,931	250	431	86	7,643	463
3	24	9	91	24	303	52	838	100	178	44	1,434	124
4	9	7	32	16	62	18	268	50	80	29	452	63
Sum	507	68	917	171	3,386	349	4,067	302	690	108	9,641	509
Beech												
1	1	1	18	13	3	2	13	12	14	13	50	22
2	186	54	196	52	244	61	136	37	65	18	827	105
3	22	11	61	33	7	4	27	11	10	5	127	37
4	5	3	10	7	7	5	15	11	18	12	55	19
Sum	215	58	284	63	261	61	191	50	108	27	1,058	120

Data from the NFI3 (Speich et al., 2010). Standard error (SEM) is shown

Table 3 Forest area, basal area, growing stock, CWD volume and calculated amount of CWD per hectare, listed for coniferous, deciduous, spruce and beech trees. Data from the NFI3 (Cioldi et al. 2010) unless labelled with an^a

Source	Forest area (ha)	Basal area ^b (1,000 m ²)	Grow. stock ^b (1,000 m ³)	CWD volume ^b (1,000 m ³)	CWD volume ^b (m ³ ha ⁻¹)
Spruce	480,185 ^a	15,471 (3,02)	178,799 (3,253)	9,691 (509)	20.2 (1.0)
Coniferous trees		24,159 (359)	277,924 (3,955)	14,962 (503)	12.8 (0.5)
Coniferous tree dominated forest	749,841				19.9 (1.1)
Beech	223,297 ^a	6,433 (167)	73,346 (1,844)	1,058 (119)	4.7 (0.5)
Deciduous trees		12,168 (246)	127,450 (2,454)	3,709 (160)	3.2 (0.2)
Deciduous tree dominated forest	422,365				8.8 (0.4)
Total forest	1,172,200	36,334 (405)	405,374 (4,393)	18,733 (553)	16.0 (0.5)
Ratio: spruce/beech	2.2	2.4	2.4	9.2	4.3
Ratio: coniferous/deciduous		2.0	2.2	4.0	4.0

^a Calculated using ratio: spruce basal area/coniferous basal area, and beech basal area/deciduous basal area

^b Standard error (SEM) is given in brackets

and the long-term forest ecosystem research network (LWF) (Innes 1995; WSL 2010). The CWD of spruce was sampled at 21 sites and the CWD of beech at 19 sites. These sites represent the five NFI regions of Switzerland and also the major environmental and climatic conditions found in spruce and beech forests in Switzerland (Table 4, Fig. 2).

The CWD was classified according to the CWD classification system adopted in the NFI3 (Keller 2005). The CWD and living wood samples were taken between June and August 2009. Wood cores from living stems (length = 15 mm, d = 5 mm) were taken at the base of the tree using a dendro corer. The CWD samples were taken along dead stems, where the degree of decay appeared uniform. Preferably trunks with known mortality dates were sampled. However, for trunks showing higher decay status, the mortality had occurred prior plot installation. Samples from those trunks were taken when species of origin could be determined. The samples were about a fist full of material (500–1,000 cm³) and were taken using an axe. Samples with higher degree of decay were cut out using a knife. Five replicate samples were taken for decay class 0–4 at each site. No samples were taken for decay class 5 (Mulmholz) since sampling is difficult, and handling (vacuum packing) would have caused erroneous readings for density. Furthermore, only 0.4% of total CWD volume in NFI 3 was in decay class 5.

After taking the fresh weight of samples, the dry weight was determined after drying at 105°C for 48 h. The volume of CWD was measured by the method of water displacement. For this purpose, each sample was vacuum packed and volume was determined. In prior tests, we compared volume estimated using the water displacement and vacuum packing method with volume determined using geometrical volume calculations. We found the estimates to be within ±5%

difference with no systematic error. Density was calculated as the ratio of fresh volume to dry weight. One of the 5 replicate samples per decay class and site was subsampled prior to drying. The subsample was dried at 65°C and analyzed for C and N concentration using an element analyzer (Carlo Erba Instruments NC 2500). The remaining water content of samples dried at 65°C was determined by further drying some of the sample material at 105°C. The C concentration was calculated in two ways (a) as C₆₅, which implies that the C concentration was calculated relative to the mass determined at 65° and (b) as C₁₀₅, the C concentration relative to the mass determined at 105°. Unless stated, the C concentration is provided as C₁₀₅ in the results.

Climate models to predict CWD density

Models to explain variability in CWD density were established separately for spruce and beech. The wood quality of angiosperm and gymnosperm is very different in terms of wood density, C concentration and C/N ratio (Weedon et al. 2009) and thus species were analyzed separately.

The list of climate and environmental attributes, which have been tested in the regression analysis, are given in Table 5. Annual and monthly rainfall and average annual and average monthly temperature data are based on climate data from the Federal Office of Meteorology and Climatology of Switzerland, with surface data calculated according to the method of Thornton et al. (1997). The surface data of potential evapotranspiration were calculated according to the empirical equation by Turc (1963). The attribute drought in this publication is the difference between the sum of monthly rainfall minus the sum of daily potential evapotranspiration for that month (daily values multiplied by 30 or 31).

Table 4 Location, type of inventory site, NFI region, average annual temperature, annual rainfall and altitude of the sampling sites for spruce and beech CWD

Inventory ^a	Location (North/East) ^c	NFI region	Annual temperature (°C)	Annual rainfall (mm)	Altitude (m)	Mean annual evapotranspiration. (mm day ⁻¹)	Summer drought (mm) ^b
Spruce							
1	498000/145000	Jura	5.2	1,762	1,230	1.17	329
1	546000/209000	Jura	5.5	1,557	1,110	1.38	259
1	562000/225000	Jura	6.1	1,469	1,022	1.43	224
2	598335/230470	Jura	5.4	1,642	1,150	1.31	344
1	514000/161000	Plateau	3.2	1,932	1,575	1.17	438
1	562000/193000	Plateau	9.1	976	475	1.84	-55
1	706000/257000	Plateau	7.4	1,377	712	1.50	260
2	540171/159464	Plateau	7.5	1,209	800	1.67	76
2	633909/236004	Plateau	8.7	1,122	480	1.69	62
1	690000/209000	Pre-Alps	7.7	1,751	650	1.34	533
2	696800/211631	Pre-Alps	5.4	2,149	1,150	1.17	759
2	624757/172177	Pre-Alps	3.9	1,630	1,500	1.29	461
1	610000/113000	Alps	3.8	844	1,635	0.71	144
1	690000/177000	Alps	4.3	1,420	1,355	0.88	371
1	642000/161000	Alps	3.0	1,532	1,650	0.94	462
1	658000/145000	Alps	2.3	1,517	1,820	1.00	262
1	754000/161000	Alps	1.1	1,375	1,977	0.92	462
1	802000/177000	Alps	3.1	850	1,580	0.77	224
2	784500/187700	Alps	2.7	1,134	1,600	0.91	314
2	762589/174074	Alps	3.9	1,098	1,450	1.15	263
2	705538/144866	S. Alps	5.0	1,703	1,350	0.88	573
Beech							
1	578000/225000	Jura	5.6	1,552	1,112	1.27	276
1	498000/145000	Jura	5.2	1,762	1,230	1.17	329
1	562000/209000	Jura	6.7	1,228	930	1.29	160
1	578000/257000	Jura	8.8	1,035	450	1.78	-5
1	594000/241000	Jura	7.0	1,370	832	1.37	238
2	598335/230470	Jura	5.4	1,642	1,150	1.31	344
2	682373/282029	Jura	8.1	1,027	580	1.37	82
1	562000/177000	Plateau	7.8	1,171	740	1.70	80
1	562000/193000	Plateau	9.1	976	475	1.84	-55
1	578000/209000	Plateau	8.6	1,096	555	1.78	-1
1	626000/225000	Plateau	8.3	1,188	555	1.68	102
2	540171/159464	Plateau	7.5	1,209	800	1.67	76
2	659495/250156	Plateau	8.7	1,124	480	1.73	57
2	633909/236004	Plateau	8.7	1,122	480	1.69	62
1	658000/209000	Pre-Alps	7.4	1,457	790	1.29	385
1	690000/209000	Pre-Alps	7.7	1,751	650	1.34	533
2	723464/225068	Pre-Alps	7.3	1,891	780	1.26	624
1	578000/113000	Alps	6.1	1,183	1,192	1.23	139
2	721303/109369	S. Alps	6.8	1,993	1200	1.13	757

^a (1) Sanasilva (sites coincide with NFI sites) (2) LWF

^b Summer Drought = precipitation (May–September)—evapotranspiration (May–September)

^c Swiss country coordinate system LV03

Fig. 2 Location of sites, where spruce and beech CWD was sampled for analysis. The five NFI regions are indicated with different background coloring

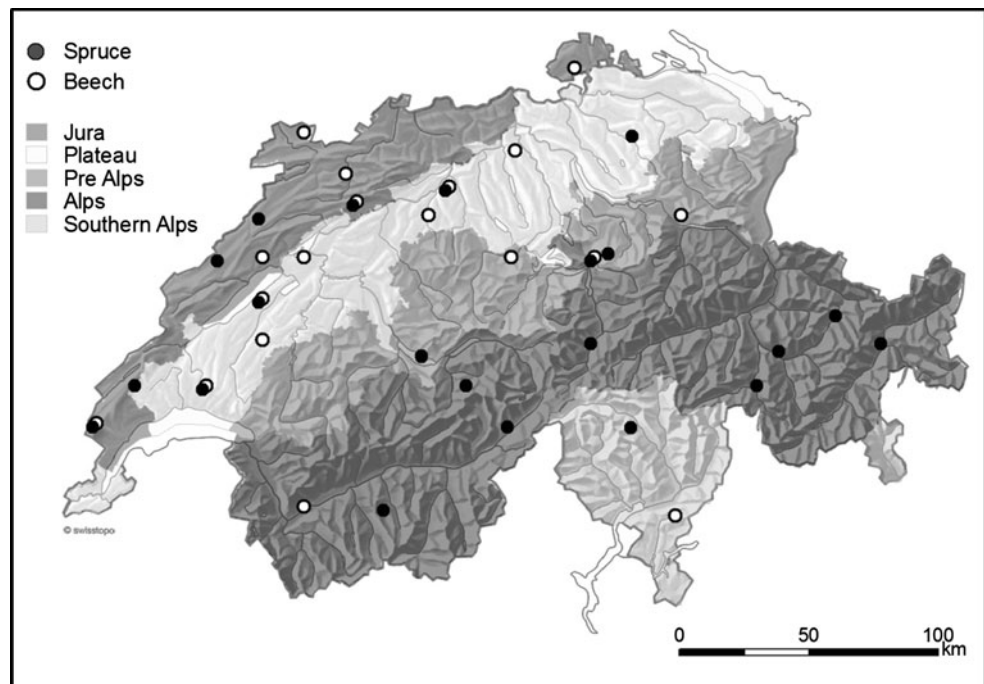


Table 5 Climate and environmental attributes tested in the regression analysis

Attribute	Term	Data	Month ^a	Method
Mean annual temperature	Temp	1961–1990		Thornton et al. (1997)
Mean monthly temperature	TempMonth	1961–1990	1, 6, 7	Thornton et al. (1997)
Mean annual rainfall	Rain	1961–1990		Thornton et al. (1997)
Mean monthly rainfall	Rain Month	1961–1990	1, 6, 7	Thornton et al. (1997)
Mean daily potential evapotranspiration, averaged per month	EvMonth	1966–2006	6, 7, 8, 9	Turc (1963)
Mean monthly drought factor ^b	DroMonth	1961–2006	6, 7	Rain Month-30*EvMonth ^b
Elevation	Height			
NFI region	Region			Brändli et al. (2010)

^a Month given as: January (1), February (2), March (3), April (4), May (5), June (6), July (7), August (8), September (9), October (10), November (11), December (12)

^b EvMonth was multiplied with 30 or 31, depending on the number of days per month

Statistical analysis and regression models

The influence of climate and environmental attributes on CWD density was tested using linear regression analysis (reg, stepwise forward selection, SAS 9.1) or nonlinear-regression analysis (nlin) when linear regression did not fit. Statistical analysis was performed separately for spruce and beech data, due to observed interactions when using the whole data set. Models were established separately for each decay class, due to observed interactions between decay class, density and the influence of temperature. Standard errors (SEM) of the combined estimate of CWD carbon as given in Table 9, 10 and 11 was calculated as follows:

$$\text{Combined estimate} : d = a \times b \times c$$

$$\text{SEM}_d = \text{SQRT} \left[(\text{SEM}_a/\bar{a})^2 + (\text{SEM}_b/\bar{b})^2 + (\text{SEM}_c/\bar{c})^2 \right] \times \bar{d}$$

d, combined estimate of CWD carbon; *a*, C conc.; *b*, CWD density; *c*, CWD volume. The SEM_{attribute} is the respective standard error of each attribute. If standard error of a given attribute was unknown, then double the SEM of the measured attribute of our study was taken. When the SEM for CWD carbon of coniferous and deciduous species was calculated (Table 11), then the SEM for density and C concentration for spruce and beech again was doubled.

Methods of carbon estimation

The amount of CWD carbon depends on (a) CWD C concentration (b) CWD density and (c) CWD volume. In the sensitivity analysis, we estimated the amount of CWD carbon for two species according to Methods 1–4, as outlined in Table 6. Method 1 uses default values, as set out by the IPCC (1997): a general C concentration of 50% and country specific, average wood density of alive trees (values for Switzerland are as follows: spruce: 0.39 g cm^{-3} , beech: 0.56 g cm^{-3} according to Assmann (1961)). Method 2 uses species-specific CWD C concentration and default values for CWD density. Method 3 uses species-specific CWD C concentration and average values of species and decay class-specific CWD density. Method 4 uses species-specific CWD C concentration and species- and site-specific CWD density values as predicted by climate-based regression models. For all methods, the CWD volume as measured in the NFI3 was used (Cioldi et al. 2010).

Coarse woody debris volume scenarios

Changes in growing stock can increase or decrease CWD volume. With a range of scenarios in terms of growing stock and resulting CWD volume, we assessed the impact of changes in CWD volume on the estimated amount of CWD carbon. All scenarios were assessed according to the following assumption: In the NFI3, spruce CWD volume was 5.4% and beech CWD volume was 1.44% of their respective growing stock (Cioldi et al. 2010). Those percentages were assumed to remain stable, and potential regional variations were not taken into account.

The result of changes in CWD volume on the estimated amount of CWD carbon was assessed in scenario 1–4 for spruce and scenario 11–44 for beech. A change in growing stock in the order of 10–20% is realistic, since the growing stock of beech has increased by 6% and that of deciduous trees by 10% between LFI2 and 3 (Cioldi et al. 2010). Growing stock of spruce has decreased by 4% and that of

coniferous trees by 1% during the same time. Although changes in growing stock usually take place gradually, for our estimates, we assumed a forest in steady state with a higher level of growing stock.

In scenario 5 and 55, the impact of a change in Forestry management on the estimated amount of CWD carbon was assessed. Arbitrarily it was assumed that the amount of ‘wood used for energy’ from 1 year, as published by the Swiss Forestry Statistics (Swiss Forestry Statistics 2010) for 2009, is left in the forest. About 482,000 m^3 coniferous and 1,066,000 m^3 of deciduous wood were used for energy production in 2009. This is about 14% of the total amount of traded coniferous wood and 70% of deciduous wood in 2009. The volume of growing stock necessary to produce merchantable wood is about 32% higher than the volume of merchantable wood (Kaufmann and Brassel 1999), because some components and some trees are not usable for trade. The volume of this respective growing stock was converted into carbon by using C concentration and density of fresh wood as conversion factors. This is due to the assumption that wood used for energy wood presumably consists of recently fallen or felled trees.

CWD in mixed forests of Switzerland

The volume of CWD for coniferous and deciduous trees, as measured in the NFI3, is shown in Table 3. The total amount of CWD carbon for the mixed species forests of Switzerland was calculated according to Methods 1–4. The CWD C concentration and density values of spruce were used for all coniferous CWD, and those of beech were used for all deciduous tree CWD. Based on those numbers, we calculated the CWD carbon that exists in conifer dominated forests and in deciduous tree dominated forests.

Dead wood carbon from the LIS and DRoots pool

To simulate the effect of improved conversion factors on the LIS and DRoot pools, we estimated the amount of dead

Table 6 Input values used for CWD C concentration, CWD density and CWD volume to estimate the amount of CWD carbon from spruce and beech trees in forest areas of Switzerland, according to Methods 1–4

Attribute	Description	Method			
		1	2	3	4
CWD C conc.	IPCC default value of 50% C conc. in CWD	X			
	Species-specific C concentration of CWD		X	X	X
CWD density	Species-specific density of fresh wood	X	X		
	Species-specific CWD density for decay class 1–4			X	
	Models based on climate variables to predict site- and species-specific values for CWD density for decay class 1–4				X
CWD volume	NFI3	X	X	X	X

wood carbon for those pools as well according to method 4. To be able to calculate this, we assumed that the volume distribution between decay class 1–4 for LIS and D Roots was the same as for CWD and that density in decay class 1–4 decreased in the same way as for CWD.

Results

Carbon concentration and density of CWD

Spruce and beech CWD differed significantly in C concentration, N concentration and C/N ratio. The C₁₀₅ concentration of spruce CWD was 49.3% and beech CWD 47.6% (Table 7). However, C₁₀₅ concentrations were not significantly different in the four decay classes for both species. The C₆₅ concentrations were lower than the C₁₀₅ concentrations. The absolute difference between C₆₅ and C₁₀₅ determined values is 1% for spruce and 0.8% for beech CWD.

The density of spruce and beech CWD decreased significantly with an increase in decay class (Fig. 3). From decay class 1–4, spruce CWD density decreased by 36% from 0.39 to 0.25 g cm⁻³ and beech CWD density decreased by 56% from 0.52 to 0.23 g cm⁻³. In fresh wood and decay class 1, CWD density was significantly different between species. In decay classes 2, 3 and 4, the density was similar for the two species (Fig. 3).

Climate models to predict CWD density

Significant correlations between local climate attributes and CWD density allowed to establish some predictive

models. Models varied with species and decay class. The models with the best fit are listed in Table 8. Climate models explained up to 22% of the variability in spruce CWD density and up to 7% in beech CWD density. The density of spruce CWD is mainly influenced by annual rainfall. In decay class 1 and 4, temperature and potential evapotranspiration additionally have a significant influence. For beech, models to predict CWD density could only be established for decay classes 2 and 4. The factor drought is correlated with beech CWD density in decay class 2 and 4, but overall correlations were weak. For decay class 1 and 3, the average measured density values could not be improved.

Methods of carbon estimation

In the sensitivity analysis, we estimated carbon for spruce and beech CWD according to Methods 1–4. Results are listed in Table 9. Improving the accuracy for CWD C concentration reduced the estimated amount of CWD carbon for spruce by 1.4% and for beech by 4.7% (Method 2 compared to 1). Improving the accuracy of CWD density values reduced the estimated amount of CWD carbon for spruce by additional 17.8% and for beech by additional 41.6% (Method 3 compared to 1). Including climate models to predict site-specific CWD density reduced the estimated amount of CWD carbon again for spruce by 3.9% and for beech by 1.3% (Method 4 compared to 3).

Although relative changes in CWD carbon due to improved estimation methods appear more pronounced for beech CWD, absolute changes are more pronounced for spruce CWD. For instance, differences in the total amount of spruce CWD carbon estimated according to Method 1

Table 7 Average C₆₅, C₁₀₅, N₆₅ concentration, C₆₅/N₆₅ ratio and water content of spruce- and beech CWD from decay class 1–4

Decay class	C ₆₅ (%)	C ₁₀₅ (%)	N ₆₅ (%)	C ₆₅ /N ₆₅ ratio (%)	Water- cont. _(65°C) (%)	Water- cont. _(65-105°C) (%)
Spruce						
1	47.9 a	48.7 a	0.189 cd	257 b	38 c	1.72 a
2	48.1 a	49.1 a	0.286 c	204 bc	55 bc	1.97 a
3	48.7 a	49.7 a	0.417 b	172 c	98 b	1.99 a
4	48.9 a	49.6 a	0.603 a	83 d	274 a	2.09 ab
Average	48.3	49.3				1.94
Beech						
1	47.0 a	47.7 a	0.309 d	166 b	43 c	1.47 a
2	46.8 a	47.6 a	0.433 c	121 c	92 c	1.57 a
3	46.5 a	47.3 a	0.640 b	82 d	242 b	1.64 a
4	46.9 a	47.9 a	0.860 a	61 d	317 a	2.14 ab
average	46.8	47.6				1.71

a,b,c,d values with the same letter within one species are not different at F-Probability < 0.05

C₆₅, N₆₅ carbon or nitrogen concentration relative to a mass, dried at 65°C

C₁₀₅ carbon concentration relative to a mass, dried at 105°C

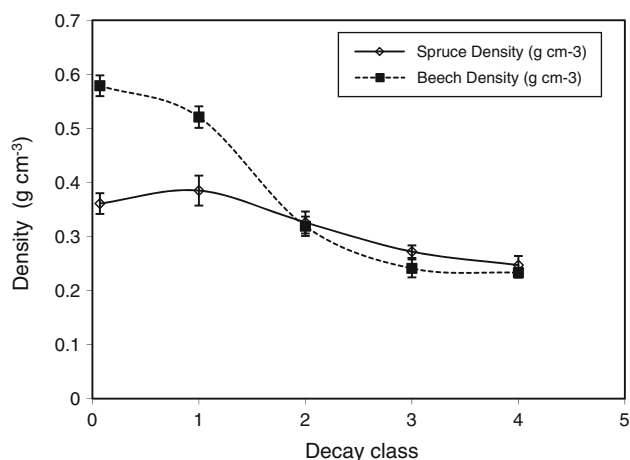


Fig. 3 Average density of CWD (decay class 1 to 4) from spruce (*Picea abies*) and beech (*Fagus sylvatica*). The average density from wood of alive trees is provided as decay class 0. The standard errors are indicated (bars)

compared to Method 4 are 434,000 t C, but only 141,000 t C for beech CWD (Table 9). Higher absolute changes in spruce compared to beech CWD carbon are due to a significantly higher volume of spruce CWD compared to beech CWD. The CWD volume of spruce is about 9 times higher compared to beech, although the area covered by spruce and the basal area of spruce is only about 2.4 times higher compared to beech trees (Table 3). The calculated CWD volume per hectare is 20.2 m³ ha⁻¹ for spruce and 4.7 m³ ha⁻¹ for beech (Table 3). The estimated amount of CWD carbon per calculated spruce or beech area is 3 and 0.69 t C ha⁻¹, respectively (Table 3 and 9).

The distribution of CWD carbon per species and NFI regions, estimated according to Method 3, is shown in Fig. 4. Most CWD volume and CWD carbon is stored in decay class 2 for both species (Fig. 4, Table 2). Significantly more carbon is stored in spruce than in beech CWD. Spruce CWD in the Pre-Alps and Alps stores by far the

Table 8 Best-fitting models established using linear or nonlinear regression analysis (SAS) for each decay class (D. class)

D. class	Model	R ²
Spruce		
1	Density = exp (-0.526-2.590 (EvJune) + 2.293 (EvJuly)-0.00185 (Rain) + 0.0625(Temp))	0.22
2	Density = 0.51211-0.01998 (EvJune) -0.00095158 (Rain)	0.19
3	Density = exp (-0.9409-0.00256 (Rain))	0.10
4	Density = 0.28018 + 0.31860 (EvJune)-0.31326 (EvJuly)	0.12
Beech		
1	Density = 0.52	
2	Density = exp (-1.0975-0.00129 (DroJune))	0.06
3	Density = 0.24	
4	Density = exp (-1.4590-0.00161 (DroJuly))	0.07

The coefficient of determination (R²) is given for each model. Only climatic attributes with an *F*-Probability < 0.15^a are listed
A more stringent significance limit of *F*-Probability < 0.05 would have reduced the predictive value of models

^a Significance level of *F*-Probability < 0.15 is the default limit for significance in this routine, provided by SAS 9.1

Table 9 Estimated amount of CWD carbon, calculated according to Methods 1–4, from spruce or beech

Method	Growing stock (1,000 m ³)	CWD/Grow. stock (%)	CWD volume (1,000 m ³)	CWD density (decay class 1, 2, 3, 4) (g cm ⁻³)	CWD C ₁₀₅ conc. (%)	Total CWD carbon (1,000 t C)	SEM ^b (1,000 t C)
Spruce							
1	178,799	5.42	9,691	0.39 ^a	0.500	1,880	197
2				0.39 ^a	0.493	1,854	192
3				0.39; 0.33; 0.28; 0.25	0.493	1,519	117
4				Models	0.493	1,446	111
Beech							
1	73,346	1.44	1,058	0.56 ^a	0.500	296	40
2				0.56 ^a	0.476	282	38
3				0.52; 0.32; 0.24; 0.23	0.476	159	21
4				Models	0.476	155	20

^a Density of wood from living trees, according to Assman (1961)

^b Combined standard error (SEM) is shown

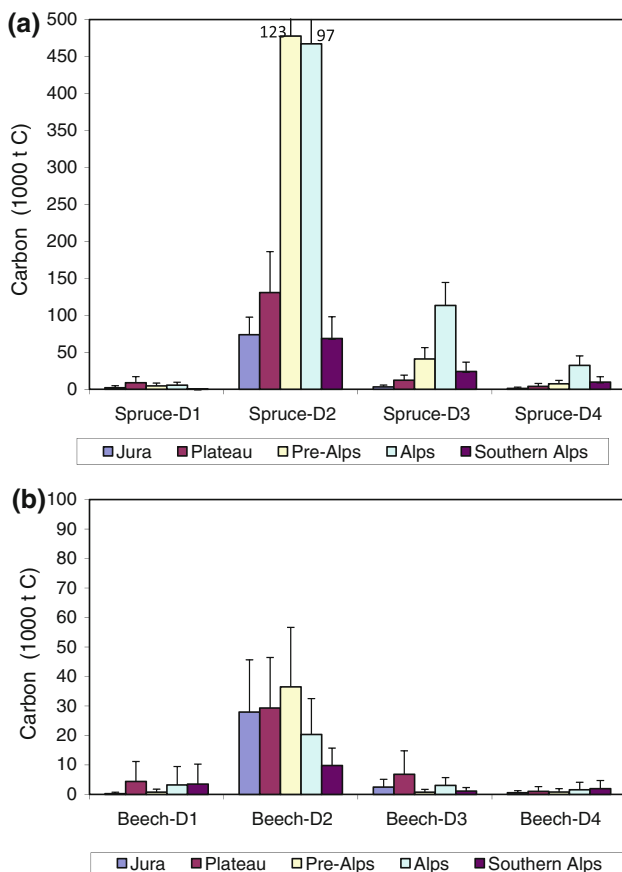


Fig. 4 Amount of CWD carbon in decay classes 1–4 (D1–D4) from **a** spruce (*Picea abies*) and **b** beech (*Fagus sylvatica*) in the five NFI regions of Switzerland, estimated according to Method 3. (Standard error shown)

major amount of CWD volume and CWD carbon. Spruce CWD also stores the major amount of carbon in regions such as the Plateau or the Jura, where beech trees are more abundant than spruce (Fig. 4).

Scenarios for CWD volume

The influence of CWD volume on the estimated amount of CWD carbon was assessed by estimating CWD carbon under five different scenarios. Results are listed in Table 10. Expansion of spruce growing stock by 20% would increase the estimated amount of spruce CWD carbon by 11% or, in absolute terms, by 188,000 t C (Scenario 1 compared to 0, Table 10). The same expansion in beech growing stock would increase the estimated amount of beech CWD carbon by 6% or 9,000 t C (Scenario 11 compared to 00).

Scenario 5 and 55 assessed the impact of leaving the wood used for energy of 1 year in the forest to decay (Table 10). This measure would increase the amount of spruce CWD carbon by 7.3% and of beech CWD carbon by

236%. The total amount of spruce and beech CWD carbon would be increased by 29.5% compared to the current amount of CWD carbon due to this management intervention (Scenario 5 plus 55 compared to 0 plus 00, Table 10).

Coarse woody debris carbon in coniferous and deciduous tree forests

The estimated amount of CWD carbon for all tree species, grouped according to coniferous or deciduous tree dominated forests and calculated with increasing accuracy (Methods 1–4), is shown in Table 11. The estimated amount of CWD carbon for all species has decreased by 31% due to applying improved conversion factors for CWD (Methods 4–1). In comparison, an increased growing stock of only spruce and beech trees by 20% would increase the estimated amount of CWD carbon for the coniferous and deciduous tree forest area by 7.2% (Scenario 1 plus 11 compared to Method 4, Table 11).

The amount of CWD carbon in coniferous dominated forests is 2.6 t C ha⁻¹ compared to 1.9 t C ha⁻¹ in deciduous tree dominated forests (Table 11). This seemingly does not reflect the difference in coniferous and deciduous tree CWD volume per hectare, which differs by a factor of 4 (Table 3). The discrepancy is due to the fact that CWD carbon values in mixed forests do not reflect the source of CWD. When the actual amount of conifer CWD carbon is compared to deciduous tree CWD carbon, then they actually differ by a factor 4 (2,221,000 t C compared to 537,000 t C).

Carbon estimates for all three dead wood fractions, such as CWD, LIS and DRoots, are given in Table 12. Estimates are calculated according to Methods 1 and 4. When estimates for only the CWD fraction are improved, then the total dead wood carbon estimate is reduced by 15%. When all three dead wood pools are estimated according to Method 4, then the total amount of dead wood carbon would be reduced by an additional 16% compared to the original estimate using default values (Method 1). This amounts to a reduction of altogether 31%, provided that the assumptions taken to estimate DRoot and LIS carbon in Method 4 can be verified.

Discussion

The estimated amount of CWD carbon is considerably reduced after improving the two conversion factors to translate CWD volume into carbon.

Including species-specific C concentrations, instead of using default values, reduced the estimated amount of spruce CWD carbon by 1.4% and that of beech by 4.7%.

Table 10 Estimated amount of CWD carbon, calculated according to scenario 1–5 for spruce and 11–55 for beech trees

Scenario	Growing stock. (1,000 m ³)	CWD/Grow. stock (%)	CWD volume (1,000 m ³)	Assumption	CWD carbon (1,000 t C)	SEM (1,000 t)
Spruce						
1	214,558		11,353	+20% grow. stock spruce	1,634	117
2	196,678		10,407	+10% grow. stock spruce	1,539	114
0	178,799	5.42	9,691	Measured NFI3 ^a	1,446	111
3	160,919		8,528	−10% grow. stock spruce	1,352	111
4	143,039		7,581	−20% grow. stock spruce	1,259	110
5	178,799		9,691	CWD		
			604	+wood for energy ^b	1,552	116
Beech						
11	88,015		1,267	+20% grow. stock beech	164	19
22	80,680		1,161	+10% grow. stock beech	160	19
00	73,346	1.44	1,058	Measured NFI3 ^a	155	20
33	66,011		952	−10% grow. stock beech	151	21
44	58,677		846	−20% grow. stock beech	146	23
55	73,346		1,058	CWD		
			1,336	+wood for energy ^c	521	42

^a Species-specific C concentration, CWD density predicted using climate models, Method 4 Table 9

^b Wood for energy' carbon calculated as alive wood, density = 0.36 g cm^{−3}, C concentration = 48.3%

^c Wood for energy' carbon calculated as alive wood, density = 0.58 g cm^{−3}, C concentration = 46.8%

Table 11 Estimated amount of CWD carbon for coniferous or deciduous tree dominated forests and the whole accessible forest area of Switzerland, using Methods 1–4 and scenario 1 and 11

^a An increased volume of CWD was assumed for spruce and beech, but not for other coniferous or deciduous tree species

Method	Conifer dominated forest	SEM	Deciduous tree dominated forest	SEM	Total
CWD carbon (1,000 t C)					
Method 1	2,613	482	1,373	204	3,987
Method 2	2,570	468	1,323	194	3,893
Method 3	1,993	233	835	110	2,828
Method 4	1,941	(333)	817	(110)	2,758
Scenario 1, 11 ^a	2,181	254	864	111	3,045
Method 4					
Area (ha)	749,841		422,365		1,172,206
CWD carbon (t C ha ^{−1})	2.6		1.9		2.4

Table 12 Carbon in the CWD, LIS and DRoof fractions of the dead wood carbon pool, as estimated using Method 1 or 4

Method (1,000 t C)	CWD carbon	LIS carbon	DRoof carbon	CWD, LIS, DRoof carbon
1	3,987	2,030	2,241	8,258
4	–	–	–	–
1	–	2,030	2,241	7,029
4	2,758	–	–	–
1	–	–	–	–
4	2,758	1,404 ^a	1,550 ^a	5,712

^a Calculated under following assumptions: (1) volume ratios between decay class 1–4 were similar as for CWD, (2) density in decay class 1–4 was reduced in a similar way as for CWD

Our implemented C_{105} concentration for *F. sylvatica* CWD of 47.6% is slightly lower than values published for *F. sylvatica* growing in a moderately oceanic climate in North Rhine-Westphalia in Germany of 48.9–50.7% (Joosten et al. 2004). The implemented C_{105} concentration for *Picea abies* CWD of 49.3% is in accordance with values determined in alpine regions (49.7% C) or in Scandinavia (50.3% C) (Bütler et al. 2007; Sandström et al. 2007). The estimate of coniferous and deciduous CWD carbon was reduced by 2.4% due to refining the value for C_{105} concentration (Table 11).

Historically wood was dried at 105°C to determine water content. However, recent studies found that C concentration is lower when wood is dried at 105°C compared to 65°C due to a loss of volatile carbon at higher temperatures. However, when samples are dried at 65°C, then the calculated C concentration, a ratio of C-mass to sample-mass, is slightly lower compared to samples dried at 105°C (Bert and Danjon 2006), due to some water remaining in the sample dried at 65°C. The remaining water content (Bert and Danjon 2006; Lamlon and Savidge 2003) needs to be determined and corrected for.

We have done this in our studies. However, omitting this correction step would have caused a difference of 4% instead of 2.4% in the estimated amount of CWD carbon due to applying species-specific C_{65} concentrations (Table 11). This shows the diligence required in stating methods and also a level of uncertainty, when comparing estimated carbon data from different sources, unless their method is provided in detail. To put this in perspective, uncertainty in measuring CWD volume in the field is about 6% (twice relative standard error, Table 3) (IPCC 2003). Although the error due to applying a standard C concentration appears low compared to the uncertainty of the CWD volume measurement, it is an additional source of error that can be avoided with feasible means.

Implementing decay class-specific CWD density values, the second conversion factor changes the estimated amount of CWD carbon most significantly by 17.8% for spruce and 41.6% for beech. The estimated amount of CWD carbon for the whole forest area in Switzerland is reduced by 27% (Table 11), stressing the importance of this conversion factor. This is due to the fact that CWD density decreases significantly with an increase in decay class, which has been observed previously for spruce and beech (Bütler et al. 2007; Harmon et al. 1987; 2000; Kahl 2008; Krankina and Harmon 1995; Means et al. 1985; Müller-Using and Bartsch 2009; Sandström et al. 2007; Yatskov et al. 2003). A comparison of CWD density values is difficult, since most often CWD classification systems differ between studies. The range of CWD density determined in Scandinavian open forest of 0.41–0.19 g cm⁻³ (Naesset 1999a) was close to our determined range of 0.39–0.24 g cm⁻³,

whereas the values determined by Bütler et al. (2007) were slightly higher (0.43–0.31 g cm⁻³). For beech, our CWD density range of 0.52–0.22 g cm⁻³ was close to the range determined by Kahl (2008) of 0.50–0.25 g cm⁻³. Although ranges are not directly comparable, it is clear that CWD density is reduced significantly with an increased state of decay. Additionally, the average density of alive trees, the previously used conversion factor, is even higher than our maximum CWD density values. The density of *P. abies* trees was found to be between 0.37 and 0.57 g cm⁻³ and that of *F. sylvatica* trees between 0.58 and 0.85 g cm⁻³ (Gryc and Horacek 2007; Skomarkova et al. 2006).

The conversion factor CWD density is further refined by using climate-based models to predict site-specific CWD density. This further improvement reduces the estimated amount of CWD carbon for spruce by 3.9% and for beech by 1.3%. The explanatory, climatic variables in models differed for the four decay stages possibly in line with climatic optima of the dominant decomposing organisms in each phase. Rainfall is a dominant factor that determined spruce CWD density, predominantly in decay class 1 and 3. Temperature and potential evapotranspiration are important in decay class 1, 2 and 4. The importance of rainfall in early decay stages may be due to the fact that the first phase of decomposition is that wood assumes a moisture status suitable for decomposer organisms (Grier 1978; Harmon et al. 2000; Laiho and Prescott 1999; Meentemeyer 1978). However, the amount of variability explained by our climate models decreased with proceeding decay, at least for spruce CWD. Berg and Meentemeyer (2002) have shown that the direct influence of climate on decomposition can vanish during the late stages of decomposition. This might explain the relatively loose correlation between density and climate attributes at later decay stages.

The climate models are of limited use to predict beech CWD density. Parameters for litter quality, such as initial wood density or lignin to N ratio, have been reported to influence decomposition (Berg and Meentemeyer 2002; Mackensen et al. 2003). Including initial wood density actually improved our models, particularly for beech CWD (data not shown). However, widespread data coverage for tree density is not available, and modeling this parameter would create an additional source of variation. Therefore, we did not include those parameters in our models.

The N or lignin concentrations also have been shown to influence decomposition of litter or woody debris and the decomposition rate of angiosperm wood (Berg and Meentemeyer 2002; DeSanto et al. 2009; Taylor et al. 1989; Weedon et al. 2009). Although we appreciate this fact, we did not include N concentration as a variable in the regression analysis, due to the lack of widespread data coverage.

The moderate explanatory value of local climate to predict CWD density may also be partly due to the fact that

our data were already classified into four decay classes. Those decay classes are already the result of past decay processes. However, each of the broad decay classes, determined with coarse field test, includes CWD of a fair time span in the general decay process. Decay processes and climatic influences on those are deemed to take place within each decay class but on a much smaller time scale as in the overall decomposition process. This small scale in time may be the reason that the variation of CWD density within a decay class is too limited to be able to show tight correlations between density and climate influences.

Using improved conversion factors, we calculated the amount of CWD carbon that originated from spruce and beech trees for each region in Switzerland. It is obvious that by far the biggest amount of CWD carbon is stored as spruce CWD in the Pre-Alps and Alps. The difference in CWD carbon is foremost based on a four times difference in CWD volume per hectare between spruce and beech (Table 3). A difference in CWD volume per hectare in the same order of magnitude has been reported previously for managed stands of spruce and deciduous trees (Bretz-Guby and Dobbertin 1996; Gough et al. 2007; Vogt 1991). Differences in CWD carbon between coniferous and deciduous tree dominated forests appear lower in comparison (Table 11). Comparing coniferous and deciduous tree dominated forests disguises the fact that most CWD volume and CWD carbon actually originates from coniferous trees, even in mixed forests of Switzerland (Table 3, Fig. 4). As a consequence, changes in the conversion factors for coniferous CWD affect the estimated CWD carbon pool most profoundly due to the predominant amount of coniferous CWD, although the relative changes in estimated CWD carbon for spruce and beech after improving conversion factors had suggested the reverse (Table 9).

The significant difference in CWD volume between spruce and beech could be based on a difference in tree mortality, CWD decay rate and forest management. Indeed, annual mortality rates of spruce trees were found to be twice as high compared to beech trees (Dobbertin et al. 2002), and the following storm events mortality was found to differ by a factor of 2.5–10 (Dobbertin et al. 2002; NW-FVA 2008). Furthermore, the decay rate constant for spruce wood is almost three times lower than that of beech wood under European conditions (Müller-Using and Bartsch 2009; Naeset 1999b; Rock et al. 2008) (Fig. 1). For example, a 77% difference in decay rate constant, as found between gymnosperm and angiosperm wood, translates into a 44% reduction in the size of the woody debris pool (Weedon et al. 2009). Also forest management differs between species, partly because spruce is more prevalent than beech on mountainous, low accessible area. A survey has shown that 45% of Pre-Alps and Alps forests are not deemed to need urgent management in the next 20 years

compared to 13% of the Plateau and Jura forests (Speich et al. 2010).

The improved conversion factors that translate dead wood volume into carbon are currently applied to the CWD but not to the LIS and DRoot fraction of the dead wood pool. However, the LIS and DRoot fractions are considerable sources of dead wood volume as well, with the two of them being about equal in volume compared to the CWD fraction. Currently carbon for the LIS and DRoot fractions is still estimated according to Method 1 (using default values). Including improved conversion factors reduced the estimated amount of CWD carbon by 30.8% and carbon from the three dead wood fractions by 15% (Table 11, 12). Reductions in estimated carbon of the same magnitude as for the CWD carbon can be expected for the LIS and DRoot fractions, once improved conversion factors are established. This would reduce the estimated amount of dead wood carbon additionally by another 16%, which means a reduction by altogether 31% compared to estimated dead wood carbon using default values (Table 12) can be expected. Hence, uncertainties about conversion factors for the LIS and DRoot fractions should be addressed soon.

The amount of dead wood carbon is calculated on the basis of C concentration, wood density and volume, which in turn can be influenced by a range of factors. Those factors can be broadly grouped into two categories a) factors given by tree physiology and environmental conditions and b) factors that can be influenced by human interventions.

The CWD C concentration and CWD density are mainly influenced by factors from the first category and thus only the measurement of the resulting values can be improved. The CWD volume is mainly influenced by factors of the second category, such as forest management and selection of tree species. The CWD volume in managed forests is usually considerably lower compared to unmanaged forests (Bretz-Guby and Dobbertin 1996; Christensen et al. 2005). In unmanaged forests CWD volumes of 90–120 m³ ha⁻¹ have been reported for spruce forests and 130 m³ ha⁻¹ for beech forests (Christensen et al. 2005; Siitonen 2001) compared to our measured volumes of 20.2 and 4.7 m³ ha⁻¹ in managed spruce and beech areas, respectively. Concluding from those numbers, there is still leeway to increase CWD volume and thus CWD carbon in managed forests of Switzerland. Switzerland has decided to include forest management in their accounting of GHG emissions and removals. The reduced extraction of CWD, particularly in spruce forests, could be a feasible tool to increase the amount of carbon stored in Swiss forests and thus create a management-based carbon sink.

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