Estimates of decay rates of components of coarse woody debris in thinned Sitka spruce forests

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Summary

The requirement for reporting of changes in forest carbon (C) stocks under the United Nations Framework Convention on Climate Change and to the Kyoto Protocol has underlined a need for information on the deadwood pool. As the coarse woody debris (CWD) component of the deadwood pool falls outside the remit of most C-stock change models used in reporting processes, this study set out to develop a methodology to evaluate the C-content of CWD stocks in the main Irish forest type (Sitka spruce plantations). In order to calculate CWD stocks without information on thinning/harvesting dates, the development of a system of classifying CWD into five decay classes (DCs) is presented. DCs were based mainly on visual characteristics linked to the degree of decomposition. Samples were taken from thinned first rotation plantations to establish the basic density loss associated with each DC. Stocks, including logs, stumps and roots, ranged from 5.1 to 13.1 t C ha^{-1} in forests aged 30 and 33 years, respectively. Decay rates for both stump and log material were 0.0592 and 0.0466 g cm^{-3} a^{-1}, respectively.

Introduction

Woody debris is an important and often neglected component of many terrestrial ecosystems (Sollins, 1982; Harmon *et al.*, 1986; Sturtevant *et al.*, 1997; Næsset, 1999; Chen *et al.*, 2001; Rock and Badeck, 2004). It provides an essential nutrient and water store, thus affecting forest soil development (Harmon *et al.*, 2000) and, in combination with litterfall, is the most important source of element flux to the forest floor (Pedersen and Bille-Hansen, 1999). In forest ecosystems, this component encompasses the transformation of biomass to necromass and its subsequent breakdown and release into the soil and air. Coarse woody debris (CWD) is an important component in the carbon (C) cycle as the decomposition rate of deadwood is among the major controls of C-retention in forest ecosystems (Yatskov *et al.*, 2003). The change in C-stock in deadwood is required for reporting to the Kyoto Protocol, as well as to the United Nations Framework Convention on Climate Change, thereby providing a policy-based incentive for robust and reliable estimation methods. Forest managers have begun the move away from a 'blanket' removal of all the woody detritus to leaving and even enhancing the amounts in forests (Harmon, 2001). This

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follows the recognition of the importance of CWD with regard to nutrient recycling and biodiversity in forest ecosystems (Anonymous, 2000).

CWD is often used as an indicator of 'old-growth' status, as well as biodiversity (Marchetti, 2004). The decay process reduces the complex organic structure of the biological material to its mineral form (Mackensen and Bauhus, 1999). CWD is an essential habitat element for bacteria, insects, fungi, plants, birds and animals (Lee *et al.*, 1997; Densmore *et al.*, 2004). Large pieces have been shown to have the greatest habitat value (Lee and Sturgess, 2001). CWD is an essential factor in supporting biodiversity as the needs of different species, and of their dependent food chains, are provided for by the constantly changing environment of the decaying wood. Decaying logs and stumps are often colonized by a significantly different subset of species than the remainder of the forest floor (Lee and Sturgess, 2001). CWD can be separated into decay classes (DCs) largely according to its visual appearance and degree of decay. This system has been widely used in ecological research (Maser *et al.*, 1979) where DCs represent different ecological niches for different species.

Inputs to the CWD pool come from natural mortality and suppression within a forest stand, fallen trees/storm damage and other disturbances. The largest and most common disturbances to natural forest ecosystems are often fires (Harmon *et al.*, 1986; Lee *et al.*, 1997; Sturtevant *et al.*, 1997). However, in intensively managed temperate forests, harvesting is the largest generator of CWD (Lõhmus and Lõhmus, 2005). It provides periodic inputs of debris, e.g. tree tops cut off at timber height (7 cm top diameter), branches, stumps and harvesting residues.

The measurement and quantification of CWD in forest ecosystems is difficult. The addition of logs and stumps to the pool is sporadic in space, time and is highly episodic (Lambert *et al.*, 1980; Sollins, 1982). Thus, the rate of CWD production is difficult to measure, requiring long periods of observation over large areas to quantify the amounts of CWD as well as the changes to this quantity. Furthermore, the estimation of decay rates is made extremely difficult by the slow decay of wood and the variation within and between logs and stumps caused by differences in diameter, position on the ground, whether or not partly embedded in the earth or degree of shading (Lambert *et al.*, 1980; Harmon *et al.*, 1986; Harmon and Sexton, 1996; Mackensen and Bauhus, 1999). Defining the pool requires a minimum diameter to separate fine woody debris (i.e. litter) and CWD. In Ireland, a 7-cm minimum diameter would intuitively seem a good, practical choice as it coincides with the minimum commercial 'timber size'. Volume estimation is normally carried out either in plots or with line transects, where species, length, diameter and decay status are recorded (Harmon *et al*, 1986). To quantify changes in the CWD pool, successive estimates are needed, as well as an estimate of the decomposition rate.

A number of methods to determine decay rate have been used:

(1) Long-term studies provide the most reliable results (Stone *et al.*, 1998) but require foresight and resources at the set-up stage. Resources are needed to ensure that measurements are taken at time intervals and that the data are stored and accessible after a long period of years. There can also be managerial difficulties in ensuring that the management of the site continues as was agreed at the start of the experiment.

(2) Input–biomass ratio is where the decay rate can also be estimated from the ratio of CWD mass inputs to the pool of CWD mass in an ecosystem (Sollins, 1982). This assumes that the CWD pool is in a steady state and thus is not applicable to managed forest, because, although the interventions are usually made at regular intervals, changes are larger in scale than in old-growth forests.

(3) Chronosequences can be used to solve the 'long-term' problem of attempting to follow the decay of individual samples for an extended period, where samples of known CWD-ages (age in relation to stumps or logs should be taken to refer to the time since their creation (separate from tree age) i.e. the number of years since the harvesting operation or other event, which caused it to be termed a stump or log or CWD, and will hereafter be termed 'CWD-age') or DCs (Harmon *et al.*, 1986) are collected and analysed. The method relies on the ability to

accurately determine the CWD-age of CWD and to identify sites and stands of comparable conditions. The decomposition rate is derived from the change in wood density or mass over time (Sturtevant *et al.*, 1997; Laiho and Prescott, 1999; Chen *et al.*, 2001).

The objectives of this work were:

- To identify DC indicators for use in C-stock and stock change calculations in Irish Sitka spruce (*Picea sitchensis* (Bong.) Carr.) forests—the main forest type in Ireland.
- To determine the density loss associated with each DC.
- To investigate whether the C-fraction of deadwood material is affected by the degree of decomposition and whether the fraction differs from the Intergovernmental Panel on Climate Change (IPCC) default of 50 per cent.
- To use the resulting information to carry out an initial evaluation of the CWD in post-thinning chronosequence sites and to calculate the CWD C-stocks and changes. This was to test the feasibility and usefulness of the developed DC-based decay estimation method.

Methodologies for the description of woody decay

Decay rate is conventionally expressed as a constant, *k* (Harmon *et al.*, 1986), and encompasses losses due to leaching, respiration and mineralization as well as losses due to fragmentation (Lambert *et al.*, 1980). Different functions are used to describe the course of decomposition, including linear, quadratic, exponential or sigmoidal, with models occasionally using an additional constant to allow for a lag time to adjust the rate according to the time between tissue death and onset of decay. These equations are often applied to the input of CWD to decay matter according to the number of years it is present in the forest as CWD.

Although decay is often defined in terms of time, there can be difficulties in linking specific CWD with specific harvesting operations. An alternative approach is to make an assessment of the current stock of CWD at a site and to assign a DC to the material. Once DC–density relationships are established, it is then possible to work out a stock as well as mass loss for C-reporting purposes.

Materials and methods

Sites

The research was carried out on forests growing on surface water mineral gleys in the Irish midlands, and the sites used for the development of the DCs and in the inventory of CWD are listed in Tables 1 and 2. The 30-year mean annual temperature was 9.3°C with a mean rainfall of 850 m.

Thinning operations began in 1985 in Ahenny, 1991 in Dooary and 1998 in Glenbarrow, where the CWD ranged in age from 4 to 20 years, 2 to 14 years and 7 years, respectively. The latter two sites have been core CARBiFOR sites (Black *et al.*, 2004; Black and Farrell, 2006) and have a 3-year data collection and observation history, which greatly aided the development of suitable DC indicators. Original stocking at all sites was *c.*2500 stems ha^{-1}. First thinnings were systematic and carried out with mechanical harvesters which typically removed every fourth row, thereafter harvesting operations became increasingly selective.

CWD DCs

The IPCC definition (2003) of the deadwood pool includes all non-living woody biomass not contained in the litter pool, either standing, lying on the ground or in the soil. It thus includes wood lying on the ground surface, dead roots and stumps (larger than or equal to a diameter decided by the reporting country). In this study CWD was divided into two groups, stumps (including the associated roots) and lying logs, for two main reasons. Positioning and aspect may have given rise to different decay rates and appearances, and second, based on previous work, different initial densities were expected from samples originating from the very base and roots of a tree compared with those taken from upper levels in the stem (Gardiner, 2005). Standing deadwood was not included in the CWD C-pool; it accounted for a maximum of 5.6 per cent of total stems (in the stand immediately after canopy closure in the chronosequence). This had declined to 2.5 and 2.3 per cent of the total stem number at the G28 and D30 stands, respectively (see Tables 1 and 2). There was no standing deadwood in the A39 stand.

CWD was categorized into DCs based on visual and mechanical characteristics linked to the degree of decomposition. Examples of DCs were taken from Crites and Dale's (1995) modification of McCullough's (1948) seven-class system and also from Sollins (1982) and Harmon and Sexton (1996). These were assessed in light of Irish conditions and our personal experience and observations of the chronosequence sites, and sets of new DCs for stumps and logs were then developed (Tables 3 and 4).

The five-class system used to assign logs and stumps to DCs was consistent in most aspects with those used in many other studies (Sollins, 1982; Yatskov *et al.*, 2003). The presence of moss (and other similar biological indicators), though frequently cited in literature (particularly North-American and Canadian) as good indicators of a decay stage, was not found to be a good indicator of decay in Sitka spruce forests. The presence of moss was recorded in all classes. The presence or absence of invading roots, used in other studies, was not consistent and was found to be a poor indicator of DC in logs and stumps.

An attempt was made to use a penetrometer to produce an indication of the advancement of decay (similar to Lambert *et al.* (1980) and Lee and Sturgess (2001)). However, because of the variability of decay within logs and stumps (depending particularly on their dimensions), this method was unpredictable and was not further developed because too many measurements would be needed to produce a reliable index rating. However, the use of a knife blade (8 cm in length) was found to be a practical aid in judging the degree of decay in sapwood *vs* heartwood and was particularly useful in distinguishing between DCs 2, 3 and 4.

DC density ranges

A decay series of CWD samples was established in order to observe the decline in density with decomposition. Samples representing each DC, for both stumps and logs, were identified in Dooary forest (D30), which contained CWD samples of ages 2, 6, 10 and 14 years (Tables 1 and 2). The CWD-age (i.e. number of years since felling) of samples was determined from management records and position within the stand. This task proved difficult and limited the number of samples taken. Thirty-one samples were taken from stumps and 51 samples from logs. Disks, 3 to 5 cm, were cut and collected from stumps and logs. Use of a chainsaw was found to reduce the damage to and disturbance of the more decayed pieces. Disk diameters ranged from 4.2 to 30.5 cm for stumps and from 5 to 28.5 cm for logs. Although logs were defined as CWD above a minimum diameter of 7 cm, some logs were smaller. Samples were representative of the complete range of DCs for stumps and logs and were all of known CWD-age.

Samples were sealed in plastic bags and were weighed on the same day as sampled. Fresh (swollen) volume of the samples was obtained using the water displacement method, described and used by Olesen (1971), O'Sullivan (1976) and Woodcock and Shrier (2003). Samples were then oven dried at 70°C until constant weight, cooled in a desiccator and weighed. Density was calculated as dry mass divided by fresh volume, i.e. bulk density or basic density. These samples provided data to establish mean densities for the CWD DCs.

Based on work previously carried out over the chronosequence, it was known that wood basic density varied between tree stems and large roots/stumps (Gardiner, 2005). To provide a benchmark for the DC density ranges obtained in this work, initial (live wood) basic densities were taken as 0.377 and 0.479 g cm^{-3}, respectively, for logs and stumps (Black and Farrell, 2006). These were the means of the site averages for the post-thinning sites (G28, D30 and C45).

Deadwood C-fraction

Five samples representing each DC for both logs and stumps were collected randomly. In order to test whether there was a decline in the C-fraction with increased decomposition, the C-fraction of these samples was determined using a LECO SC-144DR elemental analyser. The methodology described by Tobin (2006) for the preparation of samples was followed.

Decomposition rate

Decomposition rate was estimated using two different approaches.

- First, in line with the majority of CWD studies, and thus allowing a direct comparison, the decomposition constant k was estimated.
- Second, decomposition was described according to the DC classification, thereby allowing the resulting k_{DC} values to be applied in cases where exact dates of thinning and other events were not known.

As stated, decomposition can be expressed as either density or mass loss. In this study, density loss was used.

Decomposition in terms of time
The most frequently used function for describing the course of woody decomposition in forests is a negative single exponential of time (Grier, 1978; Sollins *et al.*, 1987; Næsset, 1999):

$$D_t = D_0 e^{-kt}, \tag{1}$$

where D_t is density at time t, D_0 the initial density and k the decomposition rate constant.

Equation (1) was transformed to make it linear and expressed in terms of k:

$$k = \frac{(\ln D_0 - \ln D_t)}{t}. \tag{2}$$

In the separate calculations of k for log and stump samples, ln D_0 was constant, −0.976 and −0.736, respectively.

Decomposition in terms of DC
Although the decomposition rates calculated from equation (2) are most easily comparable with those obtained in other studies, they are difficult to use in practice where forest management records are not available to calculate the CWD-age. Therefore, a DC-based decomposition rate was calculated, according to the change in DC, k_{DC}:

$$k_{DC} = \frac{(\ln D_0 - \ln D_t)}{t}. \tag{3}$$

CWD inventory

In order to measure the CWD C-stock in the three post-thinning stands (Tables 1 and 2), four plots were randomly located at each of the three sites. Plot sizes varied from 0.02 to 0.03 ha, depending on the age and management of the site

Table 1: Description of CWD survey sites

Property	Planting date	Compartment ID	Geo-reference position	Previous land management	Cultivation and management	Thinning history (dates)	Survey plot size (ha)
Glenbarrow	1975	77166 O-1	53° 8′ N, 7° 27′ W	Rough grassland	Mouldboard ploughed. Poor establishment (80%).	First in 1998	0.02
Dooary	1972	77971 A-8	52° 57′ N, 7° 16′ W	Grass pasture	Mole drained, shallow ploughed, no fertilizer	1991, 1995, 1999, 2003	0.02
Ahenny	1966	23134 E-3	52° 24′ N, 7° 26′ W	Rough grassland	Ripped, no fertilizer	Mid-1980s, 1992, 1996, 2001 and due to be felled in 2006	0.03

(see Table 1). In the four plots, an inventory was taken of the CWD; measurements included the length, end diameters and DC classification (according to Table 4) of logs and the surface diameter, height of the cut stump surface above ground level and DC classification (Table 3) of stumps. The methodology used in the determination of CWD C-stock was divided into two parts, i.e. (1) logs and (2) stumps and is illustrated in Figure 1.

Logs

Lying deadwood was classified into DCs and the two end diameters and the length were recorded for each log. Logs physically within the boundaries of the sample plots were measured; however,

Table 2: Current crop statistics (2005)

Forest	Code	Age (years)	Yield class (m^3 ha^{-1} a^{-1})	Stem (# ha^{-1})	Mean d.b.h (cm)	Mean height (m)	C-stock* t C ha^{-1}
Glenbarrow	G28	30	20	1133	23	14.9	183.8
Dooary	D30	33	22	1083	25	17.6	197.9
Ahenny	A39	39	20	579	31	22.0	n.d.

n.d. = not determined.
* Source: Tobin, 2006.

Table 3: Stump DCs adapted for Sitka spruce forests in Ireland

Class	Description
1	Inner wood hard, bark intact, not decayed or weathered at all.
2	Sapwood beginning to be soft in places with pitting. Signs of decay showing, but knife blade cannot be inserted far. Bark more or less intact.
3	Sapwood very soft, pieces breaking off. Knife goes easily into sapwood. Decay beginning in heartwood. Some bark missing, other areas hollow. In some cases invading roots in sapwood.
4	Large pieces missing, stump reduced in size. Heartwood soft but with a hard core (when probed with a knife blade). In some cases invading roots in heartwood periphery.
5	Stump largely diminished/obliterated, and just a hump in ground. No longer resistance in heartwood to knife blade. Not really a stump anymore (from decay and break-up reducing the stump towards the ground, and a build-up of debris material and roots bringing surrounding soil level upwards).

Table 4: Log DCs adapted for Sitka spruce forests in Ireland

Class	Description
1	Log whole and hard, with some showing signs of decay in places (often starting from harvester head injuries). Bark ± 100% intact.
2	Sapwood soft in patches, with small pieces missing. All branch knots flush with log surface. <50% bark.
3	Sapwood generally soft with small blocky pieces missing and crevices appearing. Branch knots beginning to appear (i.e. where sapwood surrounding harvester-trimmed branch knots is weathered away, leaving the knot to protrude). Little or no bark remaining (bark between log and soil does not count).
4	Large blocky pieces missing. Deformed outline. Sapwood ± half-missing. Branch knots more prominent. No bark.
5	Well decayed and badly deformed. Humification ± 100%. Colonized with vascular plants and moss. Collapses when moved. Inside a red colour.

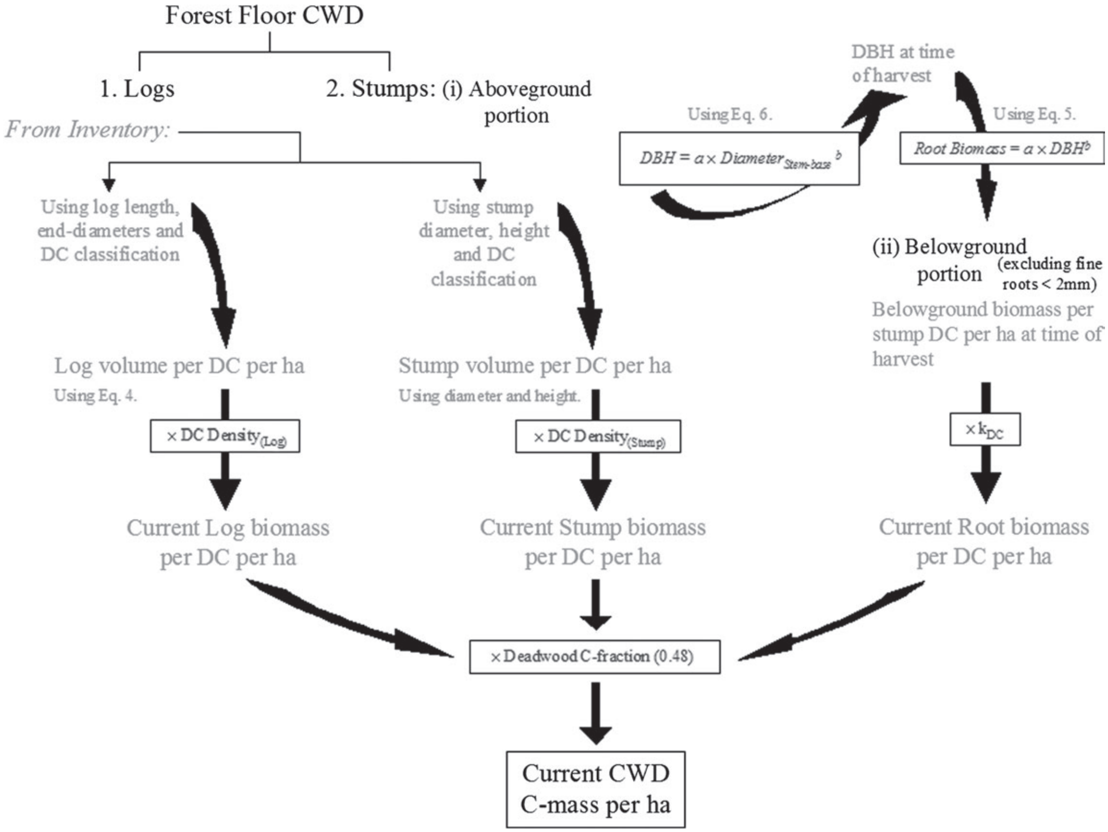

Figure 1. Diagram illustrating the methodology of CWD C-stock calculation.

logs where the majority of volume occurred within the plot were also included in their entirety. Log volumes were calculated using the formula for a frustum of a paraboloid (Hamilton, 1975):

$$V_{\log} = [(\pi \times L)/8] \times (D_1^2 + D_2^2) \qquad (4)$$

where $V_{\log}$ is the volume (m^3), L the length (m), and D_1 and D_2 the large and small end diameters (m) of the log. The volume of logs per DC in each plot was scaled up to 1 ha according to the size of the plot, and the mean of the four plot values was taken as the stand volume estimate for the DC. The volume of logs in each DC was multiplied by the corresponding mean DC stem density and summed to give the current mass of logs present. Current CWD C-mass was obtained by multiplying this value of current deadwood by the deadwood C-fraction.

Stumps

For the purposes of C-stock calculations, stumps were divided into two sections, i.e. above- and belowground portions.

Aboveground portion Stump diameters (D_S) and heights were recorded in the survey, and each stump was assigned a DC. It was also noted whether there was live sapwood under the bark. The volume of the aboveground stump was calculated as for a cylinder. The aboveground volume of stumps for each DC in each plot was estimated and scaled up to the hectare level and the stand volume estimate was calculated as the mean of the four plot values. The aboveground volume of stumps per DC was multiplied by the mean stump density of the appropriate DC and summed over all DCs to give the current mass of aboveground stumps, which was in turn converted to stand C-mass through multiplication by the deadwood C-fraction.

Belowground portion The belowground component of stump CWD was taken to include the entire root system to a root diameter of 2 mm. The following equation was derived for the estimation of belowground biomass in a previous study using d.b.h. as a predictor (Tobin, 2006):

$$\mathrm{Biomass_{Root}} = 0.5359 \times \mathrm{d.b.h.}^{0.6198} \quad (R^2 = 0.94). \tag{5}$$

From the same study (described in Tobin and Nieuwenhuis (2007)), data collected from a chronosequence of Sitka spruce plantations allowed the following relationship between d.b.h. and stem-base diameter to be developed (Figure 2). This was used to predict d.b.h. from stump diameter measurements:

$$\mathrm{d.b.h} = 0.6246 \times \mathrm{diameter_{stem\text{-}base}}^{1.04} \quad (R^2 = 0.95). \tag{6}$$

To apply this relationship to stumps, we assumed that diameter at stump height was equal to that at stem-base/ground level. This was imperative because there was no definitive stump height data available (and only diameter data from ground level were available to develop the relationship). While this assumption is appropriate for spruce stems of small diameters, it should also hold for stems of larger diameter because the buttresses and areas of greatest non-symmetric butt swell had been removed from the larger stems from which the data arose.

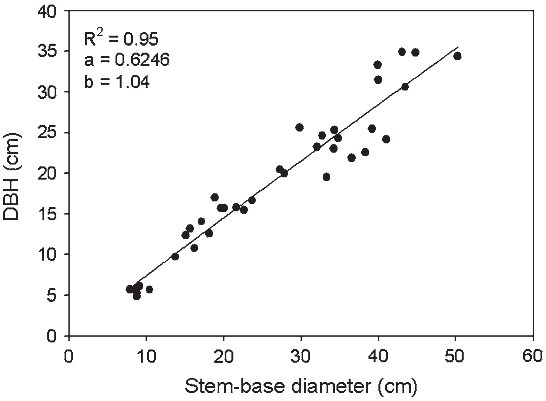

Figure 2. Scatter plots of the measured tree d.b.h. against tree stem-base diameter. The line shows the relationship resulting from the regression using the following power equation: Tree d.b.h. = a × (Diameter$_{\text{stem-base}}$) B. Data were gathered from a study looking at Irish forest C-stocks (Tobin and Nieuwenhuis, 2007).

Equation (6) was applied to the stump diameter measurements from the inventory, producing the d.b.h. which when combined with Equation (5) resulted in the calculation of belowground biomass of the individual stumps per DC per plot at the time of harvest. Similarly to the log volume calculations, stand-level root biomass estimates were the means of the four plot estimates for each site. Because of a lack of information on belowground decomposition, two assumptions had to be made: first, that roots decay at the same rate as the attached aboveground stump portion and second, that the decline in density due to decay is proportional to the decline in mass. Therefore, a decay rate in terms of DC (k_{DC}), rather than time, was used to decay estimated root biomass from the time of harvest to the present time, according to the stump's DC classification.

Equation (1) was rearranged, with root mass (M) replacing density (D):

$$M_{\mathrm{DC}} = M_0 \mathrm{e}^{-k_{\mathrm{DC}} \times \mathrm{DC}}, \tag{7}$$

where M_{DC} is the current root biomass of a particular DC and M_0 the original calculated undecayed root biomass.

Use of equation (7) resulted in the current root biomass per DC, which, when summed and multiplied by the deadwood C-fraction gave the belowground C-mass.

The CWD C-stock per hectare was calculated as the sum of the C-mass of the logs and above- and belowground portions of the stumps. Losses were calculated by comparison of current with starting C-stock values.

Results

Decomposition rates

The decomposition rate constants, describing the rate of decomposition according to time, calculated using equation (2) and based on loss of initial density for both stumps and logs, were 0.0592 and 0.0466 g cm^{-3} a^{-1}, respectively (Table 5). The coefficient of determination of the model fitted to the stump data was low, however, this possibly reflected a smaller sample size ($n = 31$) or perhaps other factors.

DC classification

Similar patterns in density change were observed for log and stump samples (Figure 3 and Table 6). The extent of initial density loss (between DC1 and 2) was greater for logs than for stumps. This difference was maintained, though becoming smaller, throughout the rest of the decay curve.

Changes in DC mean density are shown in Table 6. Density values all decreased with increasing DC, with the exception of DC5 for logs, where the value was slightly higher than for DC4. Differences between DC4 and 5 for both stumps and logs were not significant. The difference between DC3 and 4 for stumps was also not significant, though by a small margin. Differences between the remainder of the DCs were all significant.

In order to be able to describe decay according to the DC system, separate density decay constants were determined for changes in DC (k_{DC}) using equation (3). This allowed a decomposition calculation in terms of DC rather than time (Table 7). Unlike the decay rate constant k (expressed in terms of time), and with the exception of the DC2 constant, k_{DC} was higher for logs than for stumps.

Table 5: Density decay constants (g cm^{-3} a^{-1}) for stumps and logs calculated using the model: $k = (\ln D_0 - \ln D_t)/t$

	k	n	R^2	SE	F ratio
Stumps	0.0592	31	0.39	0.25	19.63*
Logs	0.0466	51	0.54	0.22	60.51*

The number of observations (n), coefficient of determination (R^2), F ratio and SE of the regressions are also given.
SE = standard error.
* $P \leq 0.05$.

The k_{DC} constants for stumps were used in the calculation of root C-stocks through the use of equation (7); an initial root mass of 500 kg (at time of cutting) classified as DC 3 becomes a current decayed mass of 369 kg.

Deadwood C-fraction

The C-fraction of stumps ranged from 47.54 to 49.07 per cent (Table 8). For logs the range was 47.39–48.38 per cent. There were no significant interactions between either stump or log and DC. There was no significant difference between the C-fractions of stumps and logs. Therefore, the data were pooled to give an overall mean C-fraction for both stumps and logs for all DCs of 47.98 per cent.

Plot inventory and C-stock

CWD stocks were divided between three pools, stumps, logs and roots. Log volume per DC per plot was highly variable and stand mean log volume ranged from 2 to 6 m^3 ha^{-1}.

The greatest C-stock was that of roots, ranging from 4 t C ha^{-1} at the G28 site to 11 t C ha^{-1} at D30 (Table 9). Stocks of stumps and logs were of less significance relative to belowground stocks. From the difference between the stocks of undecayed CWD (i.e. CWD stocks before the decay rates were applied) and the current decayed stocks, it was possible to calculate stock

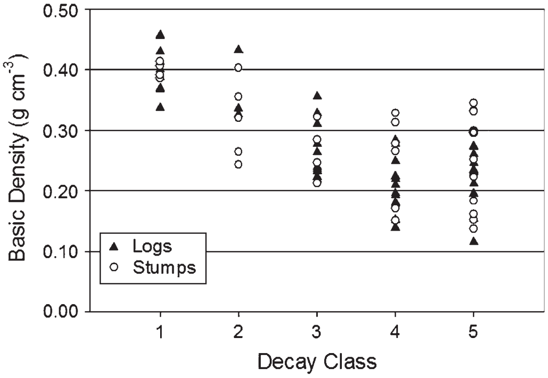

Figure 3. Density per DC, for stump and log samples.

Table 6: Mean densities (g cm^{-3}), associated SE and sample sizes for stump and log samples by DC

CWD type	DC	1	2	3	4	5
Stumps	Density	0.399^{a}	0.317^{b}	0.266^{c}	0.251^{c}	0.244^{c}
	SE	0.007	0.029	0.024	0.03	0.022
	n	4	5	4	6	12
Logs	Density	0.402^{a}	0.365^{b}	0.263^{c}	0.201^{d}	0.22^{d}
	SE	0.014	0.034	0.013	0.011	0.015
	n	9	3	12	16	11

The superscript letters present the results of an analysis of variance (at the 95 per cent level). Observations with a different letter (for the same CWD type, i.e. stumps or logs) were significantly different.

Table 7: Decay constants (k_{DC}; g cm^{-3} a^{-1}) for individual DCs for stumps and logs using the model: $k_{DC} = (\ln D_0 - \ln D_{DC})/DC$

		K_{DC}	*n*	R^2	SE	*F* ratio
Stumps	k_{DC2}	0.0714	9	0.43	0.16	5.37*
	k_{DC3}	0.1012	13	0.56	0.16	13.78*
	k_{DC4}	0.1083	19	0.44	0.22	13.23*
	k_{DC5}	0.1007	31	0.31	0.27	13.20*
Logs	k_{DC2}	0.0111	12	0.14	0.11	1.69*
	k_{DC3}	0.1034	24	0.68	0.14	47.08*
	k_{DC4}	0.1434	40	0.73	0.18	102.57*
	k_{DC5}	0.1311	51	0.56	0.22	63.42*

The number of observations (*n*), coefficient of determination (R^2), *F* ratio and SE of the regressions are also given.
* $P \leq 0.05$.

Table 8: Mean deadwood C-fractions (per cent) for stump and log samples by DC

CWD type	DC	1	2	3	4	5
Stumps	C-fraction	48.04	49.07	47.54	48.01	47.92
	SE	0.34	0.63	0.33	0.69	0.33
Logs	C-fraction	47.39	47.68	48.29	47.66	48.24
	SE	0.22	0.15	0.62	0.47	0.22

losses due to decay at each forest stand. These losses, expressed on an annual basis, ranged from 0.11 t C ha^{-1} a^{-1} at the A39 stand (over 20 years) to 0.08 t C ha^{-1} a^{-1} at the G28 stand (over 7 years). This calculation is rather simplistic as it does not take into account that the G28 stand has only been thinned once whereas the other stands have had more than one thinning.

The numbers of live stumps observed at the three forest stands ranged from 11 per cent of total stump numbers at G28, 6 per cent at D30 to 2 per cent at A39 (percentages are means of stand plot values). Stumps were living in so far as there was live sapwood present, allowing different amounts of callusing across the cut stump surface. When the CWD-age of the stumps (years since removal of the tree) was determined, it became apparent that these callusing stumps ranged in CWD-age from 2 to 14 years, with varying amounts of decomposition taking place across the centre of the stump. The varying density and stages of decomposition within these stumps defied classification using the DC system, and these stumps were left out of the decay ranges.

Table 9: Current CWD stocks (m^3 ha^{-1}, t d.wt. ha^{-1}, t C ha^{-1}) and losses (t C ha^{-1}) in thinned stands for 2005

	Forest (date of first thinning)		
CWD pools	G28 (1998)	D30 (1991)	A39 (1985)
Stocks			
Stumps (m^3 ha^{-1})	4.35	9.25	9.02
Logs (m^3 ha^{-1})	2.16	6.13	3.15
Roots (t biomass ha^{-1})	8.93	22.86	21.93
Stumps (t C ha^{-1})	0.600	1.384	1.209
Logs (t C ha^{-1})	0.252	0.707	0.366
Roots (t C ha^{-1})	4.286	11.062	10.529
Total (t C ha^{-1})	5.140	13.154	12.103
Losses			
Total loss (t C ha^{-1})	0.591	1.313	2.188
Years since first thinning	7	14	20
Annual loss (t C ha^{-1} a^{-1})	0.084	0.094	0.109

Total loss of C was converted to an annual loss by dividing by the number of years since the first thinning operation.

Discussion

CWD stocks

CWD stocks ranged between 2.8 and 6.6 per cent of the total biomass C-stocks at the G28 and D30 stands, representing a significant C-pool, although the stocks calculated did not include standing dead trees or snags. This level of stock is similar to findings of Kolari *et al.* (2004) who report CWD as 5 per cent of biomass C-stocks in a 40-year-old Scots pine dominated stand in southern Finland.

The importance of the belowground component of CWD is demonstrated clearly in Table 9. Roots accounted for 83, 84 and 87 per cent of total CWD C ha^{-1} (at the G28, D30 and A39 sites, respectively). It is commonly accepted that aboveground CWD stocks decrease markedly with the intensity of forest management (Kolari *et al.*, 2004; Debeljak, 2005; Ekbom *et al.*, 2006), largely because of the reduction in snags and deadwood that are allowed to remain in the forest. However, the reverse is true for belowground CWD according to Debeljak (2005), who similarly estimated the amounts of belowground deadwood (in a mixed silver fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) managed forest in Slovenia) using stump diameter measurements. This importance of belowground CWD has not been reflected in the quality of estimation methods in the past, which have been imprecise. Further work on the determination of belowground decomposition rates will be needed to test the common assumption that stumps and roots decay at the same rate. This will be needed in assessing the residence time of dead roots and thus in understanding the extent of its contribution to the total C-balance, particularly towards the end of the rotation. CWD stocks are more significant in the earlier stages of forest development because of the great mass of stumps and dead coarse roots following thinnings (Kolari *et al.*, 2004). The extent of their contribution towards the end of a rotation will depend greatly on the rate of decomposition, which currently is most likely to be overestimated.

Ireland's new National Forest Inventory (NFI) will provide stump data (numbers and dimensions), however, only for stumps above a minimum diameter of 20 cm. Because of the significant afforestation programme in the Irish forest estate, this omission will underestimate the belowground CWD stock. In this study, 64, 70 and 54 per cent of the total belowground CWD stock at each site (data not shown) was derived from stumps with diameters of less than 20 cm. Once the inventory is repeated, stock changes will be easier to estimate.

Decomposition

The decomposition constants derived coincide with the initial rapid phases of decomposition found by Yatskov *et al.* (2003) for *Picea* species. The values of *k* produced in this study (0.0592 and 0.0466 g cm^{-3} a^{-1}, for stumps and logs, respectively) are comparable with the combined decomposition rate for branch, stem and woody roots of 0.06 g cm^{-3} a^{-1} as used by Dewar and Cannell (1992) in their forest C-flow model.

Despite the harvester injuries to the logs, the *k* value for stumps was higher than for logs (Table 5). When k_{DC} values were calculated for individual DCs, the largest difference in values was observed while moving from DC2 to 3 for both stumps and logs. As DC increased, these differences decreased for both categories. This is most likely explained by a relatively rapid physical breakdown and weathering of the wood tissue, followed by a slowing of decay due to the higher lignin content of the inner heartwood. In future work it may be possible to define a DC according to lignin content. Differences may also heavily depend on the definitions which, thus, must be carefully defined not only in terms of their practical identifiability but also in terms of their dependence on the decay processes.

One difficulty experienced in this work has been the inability to account for mass/density losses due to fragmentation over time. For 20-year-old samples, Krankina and Harmon (1995) estimated a mass loss due to fragmentation of 10–12 per cent. Thus, the decay constants will tend towards underestimates of the true decomposition rate because it was not possible to take into account the loss from the samples' original volume. While without a more long-term experiment where repeated measurements of the same sample could be taken, it is extremely difficult to account for fragmentation losses in *k*, the DC system can provide a useful alternative for assessing current forest stock levels.

Although case hardening (this condition occurs when outer tissues dry out while inner tissues continue to decompose, thus resulting in soft and friable material at the centre surrounded by a hard shell) has featured in other surveys of *Picea* logs (Yatskov *et al.*, 2003), introducing extra variation to the data, no instances were encountered in this study, probably because this feature occurs most often in snags and suspended timber. No standing snags or fallen trees were found in any of the surveys.

DC identification

In common with other studies, the greatest difficulty faced in the field was in separating logs and stumps in DCs 4 and 5. This difficulty is demonstrated by the non-significant differences between the mean densities of samples in those two classes (Table 6). Though our classification system has defined a DC5, it is likely that if older logs had been sampled it might enable a further refining of the classification and so delineate more clearly between DC4 and 5. Another possibility might be to decrease the number of DCs. Combining DC 2 with 3 and DC 4 with 5 (thereby only having three DCs) would resolve the difficulties of differentiation. The adoption of such a system may well depend on the type of data available from the NFI.

Similarly to findings by Yatskov *et al.* (2003), as DC increased, the differences between class densities decreased, though the pattern was more apparent for the stump data than for logs. This may indicate that a more homogenous sample of stumps was taken. In contrast, logs were more heterogeneous representing a range of different sizes (diameter ranged from 5 to 28 cm), which originated from different positions in the stem as well as from different CWD-aged material. These factors contribute to the varying of density of logs in a DC. Because basic density varies according to age, with height in the stem, as well as among individual trees (Dinwoodie and Desch, 1981; Treacy *et al.*, 2000), the DC1 category for logs must accept material for decay from all sources and will inherently have a higher variation than for stumps.

Logs were found singly or in groups left uncollected after thinning operations. Hence, all branches had been removed by the harvesting head, which, in most cases, left grip mark injuries in the log's bark and sapwood. It was generally from here and from the ends that decay appeared to begin in logs. It was because of the abundance of these injuries that the description of DC1 for logs had to include small damage and signs of slight decay. For both stumps and logs, DC1 encompassed fresh material as inputted directly from harvesting operations, as well as more seasoned material of much lower moisture content which had yet to show serious signs of decay. Therefore, variation in the material classed as DC1 was quite high, as seen in the range of density in Figure 3.

Deadwood C-fraction

There was no relationship between DC and C-fraction in this study. Lambert *et al.* (1980) also reported a steady C-concentration, of 48.4 to 52.1 per cent, in Balsam Fir (*Abies balsamea* (L.) Mill.) boles of varying stages of decay. Laiho and Prescott (1999) report a C-fraction of 50.84 per cent in Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) logs after 14 years of decomposition. In this study, the deadwood C-fraction is 2 per cent lower than the fresh stem wood or total tree C-fractions and 3 per cent lower than the dead branch wood C-fraction (Tobin, 2006). The latter was not statistically different to that of live branches.

Callusing stumps

It was found that callused stumps had to be omitted from the DC system. Though not growing vigorously, the various stages of decay observed appeared to follow no pattern and obscured patterns followed by 'dead' stumps. The 'live' stumps' visual appearance did not aid their classification into a DC representative of their state of decay. However, their occurrence decreased with the age of the stand, from 11 per cent at the youngest stand to 2 per cent at the oldest. Since these callusing stumps appear primarily to be the result of root grafts with neighbouring trees, the decline in their proportion of total stumps might be associated with lower numbers of stems per hectare with increasing stand age.

It was surprising to find such significant numbers of stumps '*in vivo*' and thus, in some cases, delaying or inhibiting to some degree the onset of decay and entry into the DC classification. Chen *et al.* (2001) noted their presence in a stand with western hemlock (*Tsuga heterophyla* (Raf.) Sarg.) but ignored them because their occurrence was low. Fraser *et al.* (2007), in a study of the persistence of live roots on stumps of lodgepole pine (*Pinus contorta* var. *latifolia* Dougl. ex Loud.) in Canada, demonstrated that numbers of live roots grafted to live trees were related to the size of the phloem connection across the graft, and noted that roots of species which form callus tissue over the exposed stump surface survive longer. Further research at a greater range of stands will be needed to assess the relative importance of these stumps in Ireland.

Conclusions

The decomposition rates and DC density ranges reported here are related to logs and stumps in the early part of a first rotation forest in closed canopy conditions in Ireland. Care should be taken in comparing these values with those generated in more open forest, in further rotations and under different climatic conditions.

When detailed information on inputs to the CWD pool from thinning events is not readily available, the DC system appears a useful alternative. By providing a picture of current stocks and states of decay, it automatically takes into account any delay experienced in the onset of decay (DC1) or any slow down/acceleration due to localized stand conditions (all DCs). It also eliminates the need to age pieces of CWD, thereby avoiding a potential source of error.

This study points to the need for more extensive work to further test and refine the developed DCs, particularly in older stands, and to extend sampling to older material to address difficulties of differentiating between DCs 4 and 5. Very little is understood about belowground decay processes and rates, and this will remain an important source of error in C-stock and stock change interactions until further research sheds light on it. Because numbers of live stumps are greatest in the stands immediately following first thinning, for countries with a significant afforestation rate since 1990, they will contribute to uncertainty in Article 3.3 reporting to the Kyoto reporting (Penman *et al.*, 2003). The significance of such stumps may well increase if forest management moves further towards the use of continuous cover practices and away from clear-cuts.

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Conflict of Interest Statement

None declared.

References

Anonymous, 2000 *Code of Best Forest Practice-Ireland*. Forest Service, Department of the Marine and Natural Resources, Leeson Lane, Dublin, Ireland.

Black, K. and E.P. Farrell (eds). 2006 Carbon sequestration and Irish forest ecosystems. COFORD, Dublin, Ireland.

Black, K., Tobin, B., Siaz, G., Byrne, K.A. and Osborne, B. 2004 Allometric regressions for an improved estimate of biomass expansion factors for Ireland based on a Sitka spruce chronosequence. *Irish For.* **61**, 50–65.

Chen, H., Harmon, M.E. and Griffiths, R.P. 2001 Decomposition and nitrogen release from decomposing woody roots in coniferous forests of the Pacific Northwest: a chronosequence approach. *Can. J. For. Res.* **31**, 246–260.

Crites, S. and Dale, M. 1998 Diversity and abundance of bryophytes, lichens, and fungi in relation to woody substrate and successional stage in aspen mixedwood boreal forests. *Can. J. For. Res.* **76**, 641–651.

Debeljak, M. 2006 Coarse woody debris in virgin and managed forest. *Ecol. Indicators* **6**, 733–742.

Densmore, N., Parminter, J. and Stevens, V. 2004 Coarse woody debris: inventory, decay modelling, and management implications in three biogeoclimatic zones. *B C J. Ecosys. Manage.* **5**, 14–29.

Dewar, R.C. and Cannell, M.G.R. 1992 Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. *Tree Physiol.* **11**, 49–71.

Dinwoodie, J.M. and Desch, H.E. 1981 *Timber: Its Structure, Properties and Utilisation*. 6thdn.. Mackmillan Press, London.

Ekbom, B., Schroeder, M. and Larsson, S. 2006 Stand specific occurrence of coarse woody debris in a managed boreal forest landscape in central Sweden. *For. Ecol. Manage.* **221**, 2–12.

Fraser, E.C., Lieffers, V.J. and Landhäusser, S.M. 2007 The persistence and function of living roots on lodgepole pine snags and stumps grafted to living trees. *Ann. For. Sci.* **64**, 31–36.

Gardiner, P. 2005 Variation in basic density of Picea sitchensis (Bong.) Carr. B.Agr.Sc. Thesis (unpublished), Department of Crop Science, Horticulture and Forestry. University College Dublin, Dublin.

Grier, C.C. 1978 A *Tsuga heterophylla—Picea sitchensis* ecosystem of coastal Oregon: decomposition and nutrient balance of fallen logs. *Can. J. For. Res.* **8**, 198–206.

Hamilton, G. 1975 Forest Mensuration. *Forestry Commission Booklet*. HMSO, London. No. 39.

Harmon, M.E. 2001 Moving towards a new paradigm for woody detritus management. *Ecol. Bull.* **49**, 269–278.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V. and Lattin, J.D. 1986 Ecology of coarse woody debris in temperate ecosystems. *Adv. Ecol. Res.* **15**, 133–302.

Harmon, M.E., Krankina, O.N. and Sexton, J. 2000 Decomposition vectors: a new approach to estimation woody detritus decomposition dynamics. *Can. J. For. Res.* **30**, 76–84.

Harmon, M.E. and Sexton, J. 1996 Guidelines for Measurements of Woody Detritus in Forest Ecosystems. *U.S. LTER Publication* No. 20. College of Forest Resources University of Washington, Seattle.

IPCC 2003 *Good Practice Guidance for Land use, Land-use Change and Forestry*. IPCC National Greenhouse Gas Inventories Programme, Hayama, Japan.

Kolari, P., Pumpanen, J., Rannik, U., Ilvesniemi, H., Hari, P. and Berninger, F. 2004 Carbon balance of different aged Scots pine forests in southern Finland. *Glob. Change Biol.* **10**, 1106–1119.

Krankina, O.N. and Harmon, M.E. 1995 Dynamics of the dead wood carbon pool in northwestern Russian boreal forests. *Water Air Soil Pollut.* **82**, 237–238.

Laiho, R. and Prescott, C.E. 1999 The contribution of coarse woody debris to carbon, nitrogen, and phosphorous cycles in three Rock Mountain coniferous forests. *Can. J. For. Res.* **29**, 1592–1603.

Lambert, R.L., Lang, G.E. and Reiners, W.A. 1980 Loss of mass and chemical change in decaying boles of a subalpine Balsam fir forest. *Ecology*. **61**, 1460–1473.

Lee, P., Crites, S., Nietfeld, M., Van Nguyen, H. and Stelfox, J. 1997 Characteristics and origins of deadwood material in aspen-dominated boreal forests. *Ecol. Appl.* **7**, 691–701.

Lee, P. and Sturgess, K. 2001 The effects of logs, stumps, and root throws on understory communities within 28-year-old aspen dominated boreal forests. *Can. J. For. Res.* **79**, 905–916.

Lõhmus, A. and Lõhmus, P. 2005 Coarse woody debris in mid-aged stands: abandoned agricultural versus long-term forest land. *Can. J. For. Res.* **35**, 1502–1506.

Mackensen, J. and Bauhus, J. 1999 The decay of coarse woody debris Australian Greenhouse Office, National Carbon Accounting System, Technical Report No. 6. Canberra.

Marchetti, M. 2004 Monitoring and indicators of forest biodiversity in Europe -From ideas to operationality, Conference in Florence, Italy, 2003 European Forest Institute, Joensuu, Finland.

Maser, C., Anderson, R.G., Cromack, K., Williams, J. T. and Martin, R.E. 1979 Dead and down woody material. In *Wildlife Habitats in Managed Forests—the Blue Mountains of Oregon and Washington*. J.W. Thomas (ed.). U.S. Department of Agriculture, Forest Service, General Technical Report PNW-118, pp. 78–95.

McCullough, H.A. 1948 Plant succession on fallen logs in a virgin spruce-fir forest. *Ecology*. **29**, 508–513.

Næsset, E. 1999 Decomposition rate constants of *Picea abies* logs in southeastern Norway. *Can. J. For. Res.* **29**, 372–381.

Olesen, P.O. 1971 The water displacement method—a fast and accurate method of determining the green volume of wood samples. *Forest Tree Improvement 3*. Akademisk Forlag, Copenhagen, pp. 5–16.

O'Sullivan, P. 1976 The influence of initial espacement and thinning regime upon wood density in Sitka spruce (Picea sitchensis (Bong.) Carr.). M.Agr.Sc. thesis unpublished, Department of Crop Science, Horticulture and Forestry. University College Dublin, Dublin.

Pedersen, L.B. and Bille-Hansen, J. 1999 A comparison of litterfall and element fluxes in even aged Norway spruce, Sitka spruce and beech stands in Denmark. *For. Ecol. Manage.* **114**, 55–70.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D. and Pipatti, R. 2003 IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry. Institute for Global Environmental Strategies, Kanagawa, Japan.

Rock, J. and Badeck, F-W 2004 Decay constants for European tree species. In COST E21: Contribution of Forests and Forestry to the Mitigation of the Greenhouse Effect. UCD, Dublin.

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.

Sollins, P., Cline, S.P., Verhoeven, T., Sachs, D. and Spycher, G. 1987 Patterns of log decay in old-growth Douglas-fir forests. *Can. J. For. Res.* **17**, 1585–1595.

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

Sturtevant, B.R., Bissonette, J.A., Long, J.N. and Roberts, D.W. 1997 Coarse woody debris as a function of age, stand structure, and disturbance in boreal Newfoundland. *Ecol. Appl.* **7**, 702–712.

Tobin, B. 2006 *Carbon sequestration in Sitka spruce in Ireland*. School of Biology and Environmental Science University College Dublin, Dublin. Ph.D. thesis unpublished.

Tobin, B. and Nieuwenhuis, M. 2007 Biomass expansion factors for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. *Eur. J. For. Res.* **126**, 189–196.

Treacy, M., Evertsen, J.A. and Ní Dhubháin, Á 2000 *A comparison of mechanical and physical wood properties of a range of Sitka spruce provenances*. COFORD, Dublin.

Woodcock, D.W. and Shrier, A.D. 2003 Does canopy position affect wood specific gravity in temperate forest trees?. *Ann. Bot.* **91**, 529–537.

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

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