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Stocks and decay dynamics of above- and belowground coarse woody debris in managed Sitka spruce forests in Ireland

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ABSTRACT

Coarse woody debris (CWD) has become recognised as an important component of the carbon (C) pool in forest ecosystems. In Ireland, managed Sitka spruce (*Picea sitchensis* (Bong) Carr.) forests account for 52.3% of the total forest estate. To determine the stock and decay dynamics of above and belowground CWD, field surveys using fixed area sample plots, were conducted in six even-aged Sitka spruce stands, representing the young, intermediate and mature stages of a typical commercial rotation. The volume, mass, density loss and C:N ratio of all CWD types (logs, stumps, and coarse roots) were determined using a five-decay class (DC) system. The decay rates and half life of CWD was also determined. To estimate CWD coarse root mass; roots associated with stumps classified in different decay classes were excavated. The coarse roots were categorised into small (2–10 mm), medium (10–50 mm) and large (>50 mm) diameter classes.

CWD C-mass ranged from 6.98 to 18.62 Mg ha^{-1} and was highest in an intermediate forest (D35), while the aboveground volume varied from 6.31 to 42.27 m^3 ha^{-1}. Coarse roots accounted for 21% to 85% of the total CWD C-pool in the surveyed stands. The total CWD C-mass was poorly correlated with the number of thinning events ($R^2 = 0.29$), when data from D35 was excluded. The density loss was significant in logs (45%), stumps (58%), and small- (38%), medium- (50%) and large roots (38%) as decay progress from DC 0 to 4. There was a 46%, 41%, 51%, 72% and 57% decline in C:N ratio of logs, stumps, small-, medium- and large roots, respectively, as decay progressed from DC 0 to 4. The density decay rates were 0.059, 0.048 and 0.036 kg m^{-3} year^{-1} for logs, stumps and coarse roots, respectively. The size classification of roots did not significantly affect their decay rate. The half life (50% decomposition) of CWD was estimated has 12-, 14- and 19 years for logs, stumps and roots of Sitka spruce. Regression curves showed a strong correlation between the density and C:N ratio ($R^2 = 0.69$, 0.74 and 0.93 for logs, stumps and coarse roots, respectively). The long term storage of C and its slow rate of decomposition make CWD a vital structural and functional component of the CWD C-pool and a major controller of forest ecosystem C-retention.

1. Introduction

Coarse woody debris (CWD) is a significant component of forest ecosystems, often accounting for 7% to 20% of the total forest carbon (C) in mature forests (Harmon et al., 1990; Delaney et al., 1998; Alberti et al., 2008). CWD or deadwood includes all non-living woody biomass (or necromass) not contained in the litter pool; either standing, lying on the ground or within the soil as dead roots and stumps. It provides an important structural and functional component of managed and natural forests, creating within-stand heterogeneity, providing a favourable environment for many plant species and encouraging seedling establishment (Harmon et al., 1986; Mackensen and Bauhus, 2003; Garrett et al., 2007; Yan et al., 2007). Since the 1990s, the protection of CWD habitats has become an environmental priority in European forest policy (Butler et al., 2002). Consequently, forestry practices have shifted to management that reconciles cost-effective wood production with biodiversity maintenance and long-term ecosystem productivity (Bergeron and Harvey, 1997). The main sources of CWD in managed forests are thinning and harvesting operations or severe climatic events, which generate both above- and belowground fine and coarse woody debris.

Changes in CWD C-stocks are required for reporting to the Kyoto Protocol, as well as to the United Nations Framework Convention on Climate Change (UNFCCC), thereby providing a policy-based incentive for robust and reliable estimation methods (IPCC, 2006). Accurate estimates of CWD quantity and quality is crucial for the assessment of the multiple functions of CWD in forest ecosystems. Such characteristics (i.e. logs, snags, stumps and roots), as well as an evaluation of size classes, decay state and C to other nutrient ratios, are often used to reflect stand structure, ecosystem function and forest management history (Siitonen et al., 2000;

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Table 1
Site information and thinning history of surveyed forests.

Sample site	Forest age (years)	Yield class (m^3 ha^{-1} $year^{-1}$)	Plot size (ha)	Current tree density (trees ha^{-1})	No. of plots	Thinning history (date)
Cullenagh (C25)	25	30	0.01	800	4	2005, 2008
Dooary (D22)	22	24	0.05	1768	3	2006, 2008
Cullenagh (C32)	32	22	0.01	775	4	2000, 2003, 2006, 2009
Dooary (D35)	35	20	0.01	1225	4	1991, 1995, 1999, 2003
Baunreagh (B45)	45	24	0.01	371	4	1982, 1985, 1988, 1991, 1994, 1997, 2000, 2003
Cullenagh (C45)	45	16	0.01	575	4	1993, 1997, 2002, 2006, 2009

Pedlar et al., 2002; Jonsson et al., 2005; Ekbom et al., 2006). The decomposition of CWD is a major factor influencing C retention in forest ecosystems. Identifying CWD decay rates can significantly improve our understanding of C dynamics (especially sequestration) in forest biomes (Harmon, 2001; Fraver et al., 2002; Pregitzer and Euskirchen, 2004; Vanderwel et al., 2006; Van Miegroet et al., 2007).

CWD is an important long-term C sink and nitrogen (N) source due to its slow decay rate. It affects soil cycling through the dissolution of organic C which leads to N immobilization (Spears et al., 2003; Hafner and Groffman, 2005). Many studies have observed increases in the nutrient content of wood during decay (Stevens et al., 1995; Laiho and Prescott, 2004; Yang et al., 2010). Some research suggests that CWD provides active sites of non-symbiotic N fixation in N-limited forests. The increase of N content results in a declining C:N ratio as decay progresses; the C:N ratio could, therefore, be a potential indicator of the state of decay (Griffiths et al., 1993; Crawford et al., 1997; Yang et al., 2010).

In Ireland, CWD data used for C-reporting are obtained from the first National Forest Inventory (NFI), which was published in 2007 which estimated the total aboveground volume of CWD in Irish forests as 5.6 million m^3 (Forest Service, 2007). Approximately 10% of the land area is forested, 90% of which is coniferous plantation. Sitka spruce (*Picea sitchensis* (Bong) Carr.) is the most widely planted commercial tree species and accounts for 52.3% of the total forest estate (Forest Service, 2008). Information on the decomposition of coniferous CWD (specifically that of Sitka spruce) and its contribution to managed-forest C stocks is therefore essential for C-reporting. Tobin et al. (2007) developed a methodology for evaluating the C-content of CWD stocks in Irish Sitka spruce plantations and conducted an initial evaluation of the CWD decay rates. Following that work, this study determined the CWD stocks, but compared the decay dynamics of above and belowground components of CWD as well as investigated the C and N interactions in decomposing CWD and its relationship with density loss.

The objectives of this study were: (1) to quantify aboveground volume, estimate C stocks and decay status of above- and belowground CWD in thinned Sitka spruce stands; (2) to determine the change in C:N ratio across different decay classes (DCs); (3) to compare DCs used in this study with those used in the NFI; (4) to estimate CWD density decay rates (k) and half lives (50% decomposition or $t_{0.5}$) from decay curves; and (5) to determine the relationship between density and C:N ratio using regression models.

2. Materials and methods

2.1. Site description

The study was conducted in six even-aged, mono-species Sitka spruce stands, representing young, intermediate and mature stages of a typical commercial rotation of Sitka spruce in Ireland. This chronosequence was identified for investigating C sequestration in Irish forests (CARBiFOR research project; Black and Farrell, 2006). These stands were grown on surface water mineral gley soils in the Irish midlands (52°57′N, 7°15′W, and ~260 m elevation). The 30-year mean annual temperature was 9.3 °C with a mean annual rainfall of 850 mm (Tobin et al., 2007). The sites include stands that were thinned between 2 and 8 times. The first thinnings were mostly systematic and removed every seventh row (with some selective thinning in the rows between the racks), thereafter thinning operations were selective (see Table 1).

2.2. CWD field surveys

The need to decide on practical diameter thresholds for distinguishing between litter (i.e. twigs, leaves and needles), fine, and coarse woody debris in C accounting has been recognised previously (Gifford, 1999). The need for a consistent definition is important, not only to prevent double accounting, but also to enable comparisons of CWD amounts between different studies and ecosystems (Meggs, 1996; Woldendorp et al., 2002). It has been recommended that the size threshold between fine and coarse woody debris be made at 10 cm at the larger diameter end of logs for most forests (Harmon and Sexton, 1996). For this study however, a 7 cm minimum diameter for logs is a good, practical choice as it coincides with the minimum commercial 'timber size' used in Irish forest management. Coarse roots were categorised as roots >2 mm in diameter (Green et al., 2007).

The fixed-area sampling method was used for the quantification of volume of aboveground CWD. Four 0.01 ha plots were randomly laid down in each site (except for D22, where three permanent sample plots (0.05 ha each) were surveyed) (Table 1). Logs and stumps physically within the boundaries of the sample plots were measured; however, logs and stumps whose majority of volume occurred within the plots were also included in their entirety (after Harmon and Sexton, 1996). Lying deadwood and stumps were classified into five-DCs modified from Tobin et al. (2007), and the classification of coarse roots was according to the visible stump, they were associated with (Table 2a).

The methods used in the NFI excludes stumps <20 cm top diameter and logs <1 m in length, it also uses a general four DC system (Table 2b). This study estimated C stock excluded when using the NFI system and the limitations of the DC system used in the NFI. This resulted in the combination of DC 0 and 1, DC 2 and 3, to represent the first and second decay categories in the NFI system, while DC 4 represented the fourth category. Rotten heartwood, solid sapwood (NFI category 3) was not encountered during this study. Two end diameters and length were recorded for each log; while, two perpendicular surface diameters and heights (from soil surface in up- and down-slope directions) were measured for stumps.

Log volume (V_{logs}) was calculated using the method of Garrett et al. (2007):

$$V_{logs}\ (m^3) = \frac{\pi \times L \times (d_1^2 + \{d_1 \times d_2\} + d_2^2)}{12} \qquad (1)$$

where L is length of the log (m), d_1 and d_2 are diameters of the frustum ends (m).

Table 2a
Five decay class system for stumps and logs of Sitka spruce.

	Description
Stumps DC	
0	Freshly created or live sapwood (from root grafts to adjoining live trees)
1	Stump is dead, inner wood intact and hard, decay barely commenced, bark is soft or peeling off, sapwood is hard, knife cannot be inserted
2	Sapwood is very soft, fragmentation is evident and knife penetrates sapwood, bark missing in places, other areas hollow, decay commencing in the heartwood. In some cases invading roots in the sapwood
3	Decay in advanced stage, stump reduced in size with large pieces missing. Heartwood is soft. In some cases invading roots found growing in the heartwood
4	Stump largely diminished. Top surface merging into the ground, heartwood disintegrating. Little force breaks up the stump
Logs DC	
0	Freshly felled logs
1	Log whole and hard, with bark intact (±100%), some signs of decay in places
2	Sapwood soft in patches, fragmentation evident, bark $\geqslant$50%, all branch knots flush with log surface or can be seen
3	Large blocky pieces missing. Log frame is deformed. Portions of sapwood missing. Branch knots prominent. Little bark present
4	Well decayed and deformed. Humification is advanced. Collapses when moved

Table 2b
Irish National Forest Inventory (NFI) decay class system for stumps and logs.

DC	Description
1	Solid wood: wood is intact, no signs of decomposition
2	Rotten sapwood, solid heartwood: outer part of wood is rotten, inner core is solid
3	Rotten heartwood, solid sapwood: outer part of wood is solid, inner core is rotten
4	Rotten wood: timber is rotten throughout, but maintains its original shape

Stump volume (V_{stumps}) was determined as:

$$V_{\text{stumps}}\ (\text{m}^3) = \frac{\pi h \times (R^2 + Rr + r^2)}{3} \tag{2}$$

where h is mean height of stump (m), R and r are maximum and minimum radii (m).

2.3. Belowground biomass sampling

Twenty-five stumps (five per DC) of known age (time since trees were felled) were selected for excavation to determine belowground necromass. The sampling was done within a 2 m by 2 m square centred at the stump and all coarse roots (>2 mm diameter), originating from the stump, were collected. The roots were separated into size categories based on diameter: small (2–10 mm), medium (10–50 mm) and large (>50 mm). The excavated roots were weighed in the field and three sub-samples collected for each root size category from each excavated stump system to determine their dry weight and density. The influence of stump diameter, height and volume on excavated root necromass was tested statistically and found to have no consistent effect across all DCs. Therefore, coarse root necromass in each plot was determined by multiplying the mean excavated root necromass per DC with the number of stumps in that DC, then summing all root necromass for each DC in the plot. The plot estimates in each stand were averaged and scaled up to estimate belowground CWD per hectare.

2.4. Basic density determination

As part of the CARBiFOR project CWD logs, stumps and roots of different ages have been sampled since 2003 for density. For density determination, three sub-samples were taken from each CWD type (logs, stumps and roots). Discs (2–4 cm thick) were cut (using a chainsaw) from both ends and the middle of each log and from three cross sections of each excavated stump (samples of roots were collected as stated in Section 2.3). All sub-samples were sealed in plastic bags and were later stored cool (2–4 °C) until further processing. They were cleaned of moss and soil prior to density determination. The wet weight of each log disc, stump cross section, small, medium and large root sub-sample was measured, and the volume determined gravimetrically by water displacement as described by Tobin et al. (2007). Highly decomposed (DC 3 and 4) sub-samples were wrapped in cling film to prevent disintegration and reduce water absorption. Sub-samples were then oven-dried at 80 °C. The basic density (oven-dry mass divided by displacement volume) was calculated for each sample to produce mean densities for the DCs.

The volume of logs and stumps in each DC was multiplied by the corresponding mean DC density and summed to give the current necromass of logs and stumps present in each sample plot. The volume and necromass of logs and stumps in all plots were averaged and scaled up to per hectare values, thus resulting in the stand volume and necromass estimates.

2.5. C-fraction and C:N ratio

Individual sub-samples of logs, stumps and coarse roots (small, medium and large) in different DCs were oven-dried (at 80 °C), mixed and homogenised by passing each through a motorised flail shredder and then three further sub-samples were taken randomly from the mixed material. The resulting sub-samples were ground using a hammer flail mill fitted with a 1 mm gauge. The C and N content were determined using a Vario Max CN element analyser following the method described by Tobin et al. (2007). The C:N ratio was subsequently calculated for each sample. The C-fraction for each CWD type was used to multiply the necromass of above- and belowground CWD types to determine the carbon stock in each stand.

2.6. Decay rate (k)

The single-exponential model was used to determine k, and is based on the assumption that the decomposition rate is proportional to the amount of matter remaining. This is the most commonly used model for describing decomposition patterns (Olson, 1963; Harmon et al., 1986; Mackensen and Bauhus, 2003; Tobin et al., 2007). The single negative exponential decay function is described as shown in Eq. (3):

$$D_t = D_o e^{-kt} \tag{3}$$

where D_t (kg m^{-3}) is the wood density at time t, D_o (kg m^{-3}) is the initial density (determined as the intercept on the decay curve), k (year^{-1}) is the decay rate constant and t (years) the time since the piece of CWD was created. This is the number of years since the harvesting operation which created the CWD occurred (Harmon et al., 1986), which was determined from personal knowledge (research operations at the beginning of the project) and management records).

The half life (50% decomposition or $t_{0.5}$) was estimated using the method of Olson (1963) (see Eq. (4))

$$t_{0.5} = \frac{-\ln(0.5)}{k} = \frac{0.693}{k} \tag{4}$$

2.7. Statistical analysis

Data were analysed using Sigmaplot 11 for Windows. Differences between CWD types, DC densities and C:N ratios were compared using analysis of variance (ANOVA) and post hoc analysis based on Holm–Sidak multiple range tests. The Pearson product moment correlation (r) was used to measure the relationship between variables. All tests were performed at $p < 0.05$. Single negative exponential decay and regression curves were used to assess the relationships between variables.

3. Results

3.1. C-fraction

There were no significant differences in the C-fraction of each CWD type when data from the DCs were compared. Therefore, all DC C-fractions for each CWD type were pooled together to determine a mean C-fraction for each CWD type (Table 3).

3.2. Belowground necromass

As indicated in Section 2.3, the total root necromass across DCs had no significant relationship with the stump volume ($r = -0.16$, $p = 0.45$), stump diameter ($r = 0.03$, $p = 0.9$), or stump necromass ($r = 0.31$, $p = 0.13$). However, root necromass had a significant inverse relationship with the stump DC ($r = -0.87$, $p < 0.0001$). There were differences in the root mass excavated for each stump DC, but the post hoc test revealed no significant differences between stumps in DC 2, 3 and 4 (Fig. 1).

3.3. Aboveground volume and carbon stocks

The aboveground CWD volume was highest among the mature stands (B45: 42.27 $m^3\ ha^{-1}$) and lowest in the younger stands (D22: 6.31 $m^3\ ha^{-1}$). However, a higher volume was found at the second young stand (C25: 41.59 $m^3\ ha^{-1}$) when compared with the older stands (Table 4). The highest total CWD C mass was observed in an intermediate stand reflecting a high volume of logs (D35: 18.62 $Mg\ ha^{-1}$) while the lowest occurred in a young stand (D22: 6.98 $Mg\ ha^{-1}$). Belowground CWD C mass was highest in the younger stands, but with similar amounts found in the intermediate and mature stands. The C mass was poorly predicted by the number of thinnings (Fig. 2a). However, carbon mass from D35 was deemed to be an outlier; its removal slightly improved the regression equation (Fig. 2b).

3.4. DC Density

The density of each CWD type was dependent on its DC ($p = 0.001$). The DC density of logs differed from those of stumps and roots; however the DC densities of stumps and roots were not different. The change in density of stumps followed a similar pattern as that of all root diameter categories (Table 5). There was a progressive loss in density from DC0 to DC4 in all CWD types. The small and medium roots had higher DC densities in the early stages of decay.

Table 3
The C-fraction of CWD logs, stumps and coarse roots of Sitka spruce (mean, standard error (SE) and number of samples).

CWD	% C-fraction	SE	n
Logs	46.61	0.07	24
Stumps	47.47	0.09	21
Small roots	46.98	0.46	21
Medium roots	47.49	0.49	21
Large roots	47.89	0.37	21
All CWD	47.26	0.15	108

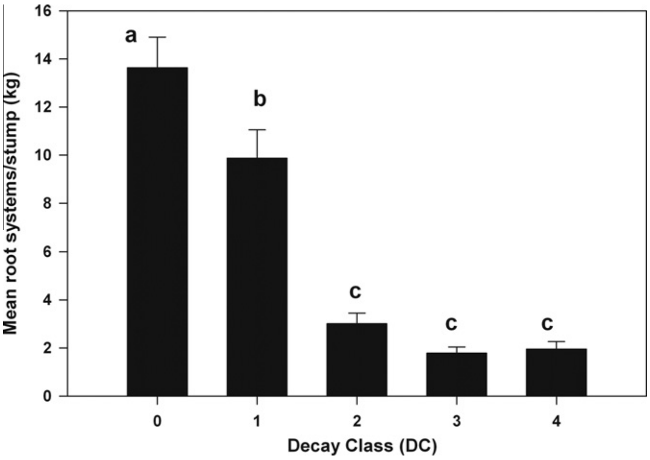

Fig. 1. Belowground necromass excavated from root system of stumps in different DCs (mean with SE bars, same letters indicate no significant differences at $p < 0.05$).

3.5. N ratio of CWD in different DCs

The C:N ratio of each CWD type was dependent on its DC ($p = 0.011$). The post hoc test showed there was no difference between the C:N ratio of stumps and large roots ($p = 0.747$). Generally, there was a reduction in the C:N ratio as decay progressed (Table 6). The small, medium and large roots followed similar patterns of variation in their C:N ratio between DCs.

3.6. NFI DC systems for logs and stumps

There was a significant difference in the combined DC densities for logs across all decay categories ($p = 0.001$); however stump DC densities were not different in the second and third stages of decay (Fig. 3a and b). No clear pattern was observed for C:N ratio of logs and stumps in the second and third stages of decay (Fig. 4a and b). The mean C:N ratio for stumps in the NFI stage 2 was lower than for the stage 3 stumps. Generally, density loss and C:N ratio change was more pronounced in logs than stumps, based on the NFI classification.

3.7. Density decay curves

The decay curves depict decay rates by describing changes in density as a function of time (Fig. 5a–f). Logs had the highest decay rate ($k = 0.059\ kg\ m^{-3}\ year^{-1}$) and small roots the lowest ($k = 0.030\ kg\ m^{-3}\ year^{-1}$). Based on the estimates, aboveground material decayed faster than belowground material (Table 7). The whole root system decay curve (which is the mean density for all root size categories) produced the best fit ($R^2 = 0.72$ and SE = 0.003) for the exponential relationship between density and time. However, density values of 6 year old coarse roots did not follow the same trend as the rest of the data.

3.8. C:N ratio and Density of CWD

There was a direct correlation ($r = 0.57$, $p < 0.0001$) between C:N ratio and density loss of all CWD types. Therefore, quadratic regression curves were used to generate predictive equations relating the two variables (Fig. 6a–f). The whole root system quadratic curve had the highest R^2 value (0.93), while large roots recorded the lowest (0.60). A decrease in density resulted in a corresponding decrease in the C:N ratio, except for some fresh stumps which showed a slight increase in the C:N ratio associated with decreasing density levels.

Table 4
Aboveground volume and carbon mass of CWD in Sitka spruce forests at different stages of development.

Variable	Young		Intermediate		Mature	
	C25	D22	C32	D35	B45	C45
Logs						
Volume ($m^3\ ha^{-1}$)	20.37	4.54	14.93	26.62	23.42	11.75
Mass ($Mg\ C\ ha^{-1}$)	2.77	0.71	2.89	12.87	3.32	1.75
Stumps						
Volume ($m^3\ ha^{-1}$)	21.23	1.77	14.93	12.40	18.85	26.23
Mass ($Mg\ C\ ha^{-1}$)	2.63	0.33	1.94	1.74	2.83	3.21
Coarse roots						
Mass ($Mg\ C\ ha^{-1}$)	4.69	5.94	4.22	4.00	4.00	4.86
Total aboveground volume ($m^3\ ha^{-1}$)	41.59	6.31	29.86	39.02	42.27	37.98
Total forest CWD mass ($Mg\ C\ ha^{-1}$)	10.10	6.98	8.83	18.62	10.15	9.83

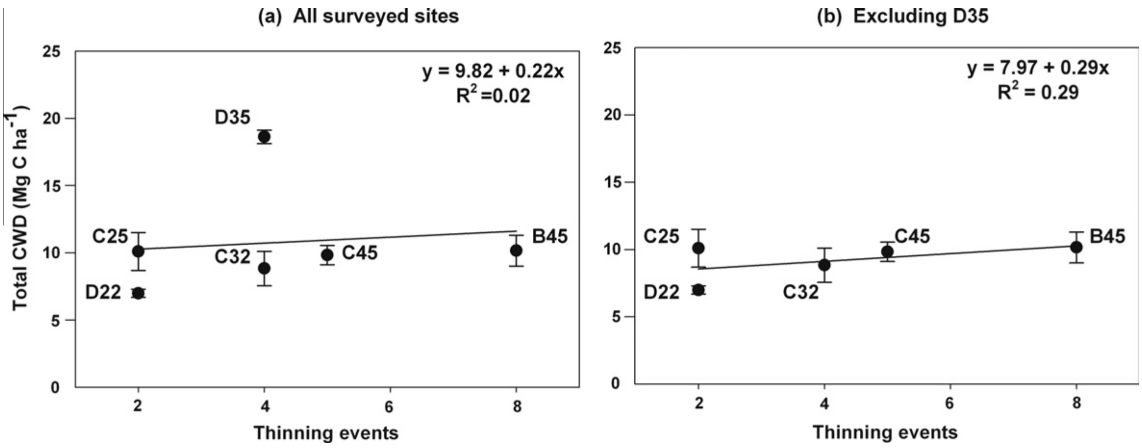

Fig. 2. (a) and (b) Linear regressions relating the number of thinnings to the total CWD C-mass (mean with SE bars, surveyed sites and regression equations indicated on the graphs).

Table 5
Decay class (DC) densities of Sitka spruce CWD (mean in kg m^{-3}, SE (*in italics*), *n* value in parenthesis, $p < 0.05$).

DC	Logs		Stumps		Small Roots		Medium Roots		Large roots	
0	359.35^{a} *9.80*	(8)	398.72^{a} *31.67*	(5)	447.82^{a} *6.81*	(5)	431.60^{a} *14.78*	(5)	385.96^{a} *10.44*	(5)
1	356.53^{a} *15.84*	(9)	391.94^{a} *14.46*	(5)	436.08^{a} *22.70*	(5)	433.02^{a} *13.16*	(5)	393.44^{a} *11.11*	(5)
2	302.89^{b} *9.02*	(8)	208.84^{b} *24.51*	(5)	279.70^{b} *21.86*	(5)	275.48^{b} *32.74*	(5)	275.98^{b} *17.36*	(5)
3	272.92^{b} *20.55*	(9)	167.38^{b} *19.01*	(5)	282.64^{b} *24.69*	(5)	223.26^{b} *18.32*	(5)	242.70^{b} *20.50*	(5)
4	198.80^{c} *10.64*	(10)	172.60^{b} *9.78*	(5)	278.50^{b} *36.17*	(3)	215.13^{b} *27.01*	(3)	238.55^{b} *26.50*	(4)

Mean values in each column with same letters are not significantly different.

Table 6
C:N ratio of CWD in different DCs (mean, SE (*in italics*), *n* value in parenthesis, $p > 0.05$).

DC	Logs		Stumps		Small Roots		Medium Roots		Large roots	
0	276.81^{a} *32.76*	(5)	241.53^{a,c} *23.15*	(5)	136.85^{a} *6.63*	(5)	237.15^{a} *28.81*	(5)	242.60^{a} *22.73*	(5)
1	269.25^{a} *32.95*	(5)	315.63^{a} *24.66*	(5)	146.31^{a} *11.23*	(5)	251.69^{a} *19.45*	(5)	309.48^{a} *19.52*	(5)
2	196.4^{a,b} *13.9*	(5)	110.69^{b} *9.53*	(4)	63.37^{b} *3.25*	(4)	73.19^{b} *8.35*	(4)	139.22^{b} *23.34*	(4)
3	191.26^{a,b} *8.68*	(4)	95.76^{b} *16.92*	(4)	77.30^{b} *3.59*	(4)	87.50^{b} *7.38*	(4)	104.62^{b} *8.24*	(4)
4	148.95^{b} *9.55*	(5)	141.78^{b,c} *51.55*	(3)	67.38^{b} *15.25*	(3)	64.32^{b} *12.40*	(3)	131.84^{b} *17.21*	(3)

Mean values in each column with same letters are not significantly different.

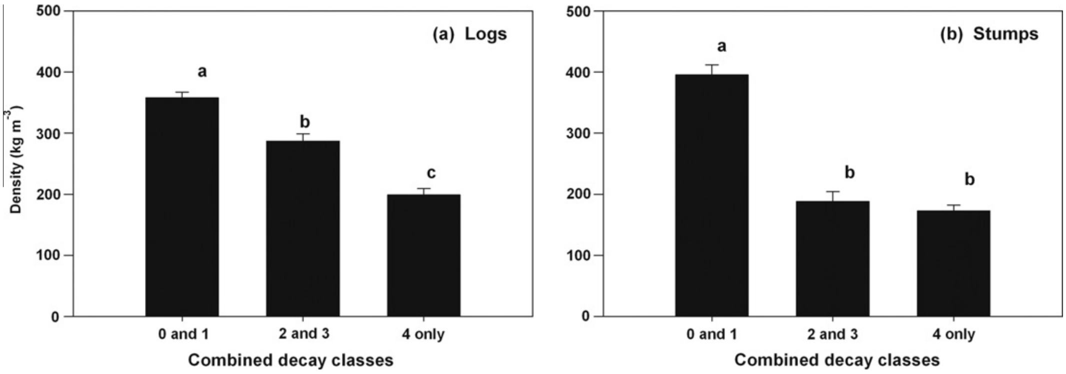

Fig. 3. (a) and (b) Density loss of aboveground CWD using the NFI classification criteria (mean with SE bars, same letters are not significantly different at $p < 0.05$).

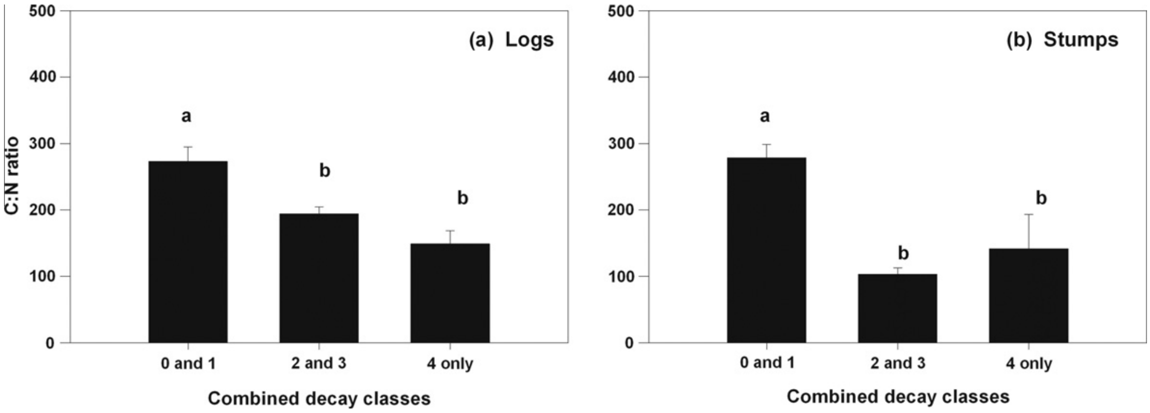

Fig. 4. (a) and (b) Change in C:N ratio of aboveground CWD using the NFI classification criteria (mean with SE bars, same letters are not significantly different at $p < 0.05$).

4. Discussion

4.1. Belowground carbon stocks

A considerable amount of research has been done to determine the contribution of fine roots to the forest C-pool; however, the contribution of dead and decomposing coarse roots to the CWD-pool is typically ignored because of the tremendous effort and time required for measuring this changing belowground component (Soethe et al., 2007; Black et al., 2009). Coarse roots contribute a large proportion of C to the CWD-pool (e.g. 94% in D22), making it a significant component when estimating CWD stocks (Debeljak, 2006; Tobin et al., 2007). The inclusion of accurate belowground CWD stock and stock change estimates in forest C-pools will improve the actual sequestration potential of forests by increasing the stock estimates. Allometric equations which relate live root biomass to tree dbh, stump diameter or volume, have been used to estimate belowground C-stocks in the past (Brown, 2002; Laclau, 2003; Lavigne and Krasowski, 2007; Park et al., 2007). Park et al. (2007) cautioned that allometric equations can under- or over-predict root biomass depending on stand age and development. In this study, stump diameter, stump volume and stump necromass did not correlate with the excavated root necromass. The only variable with a strong correlation was stump DC ($r = -0.87$, $p \leqslant 0.0001$). The mean mass loss as a result of root decay progressing from DC 0 to 4 was estimated at ~86%. This loss in mass limits the use of allometric equations for estimating dead root mass. It is therefore essential that parameters, such as DC, be included when modelling belowground CWD stock estimates, thus reducing the uncertainties that lead to under- or overestimation.

4.2. Aboveground CWD volume and C stocks

The stand volumes of logs and stumps were higher than those observed by some authors (Siitonen, 2001; Humphrey et al., 2003), but were similar to those found by Debeljak (2006) in managed coniferous forests. Sweeney et al. (2010) estimated aboveground volume in second rotation plantations in Ireland to be 38.95 m^3 ha^{-1}; this is consistent with the volume observed during this study (Table 4). The NFI national average value (20.1 m^3 ha^{-1}) is lower than the volumes observed in all sites; except for D22. This is probably due to the fact that stumps with top diameter <20 cm and logs with lengths <1 m were not included in the national survey (Forest Service, 2007). It was observed that 23% (D22), 11% (D35) and 10% (C35) of the stump volume was obtained from stumps with top diameter <20 cm in the surveyed stands. Similarly, 19% (B45), 36% (C45) and 30% (C25) of the log volume was obtained from logs with lengths <1 m. This implies that national figures, based on NFI estimation methods, significantly underestimate the CWD stocks, particularly in first rotation "Kyoto" forests.

The importance of stumps will increasingly become evident as Irish forests mature and move from first to second rotations (Tobin et al., 2007; Sweeney et al., 2010). Stumps contributed up to 69% (C45) and 45% (B45) of the aboveground volume in the mature stands and this would increase greatly after final harvesting. Although stands of different productivity were used in this study, this did not influence the occurrence of CWD C mass (Fig. 2a and b) but clearly impacted on the frequency of thinning events. This is because CWD input is dependent on management decisions, thinning intensity, site and stand quality, operational factors and environmental conditions. These factors greatly influence the amounts

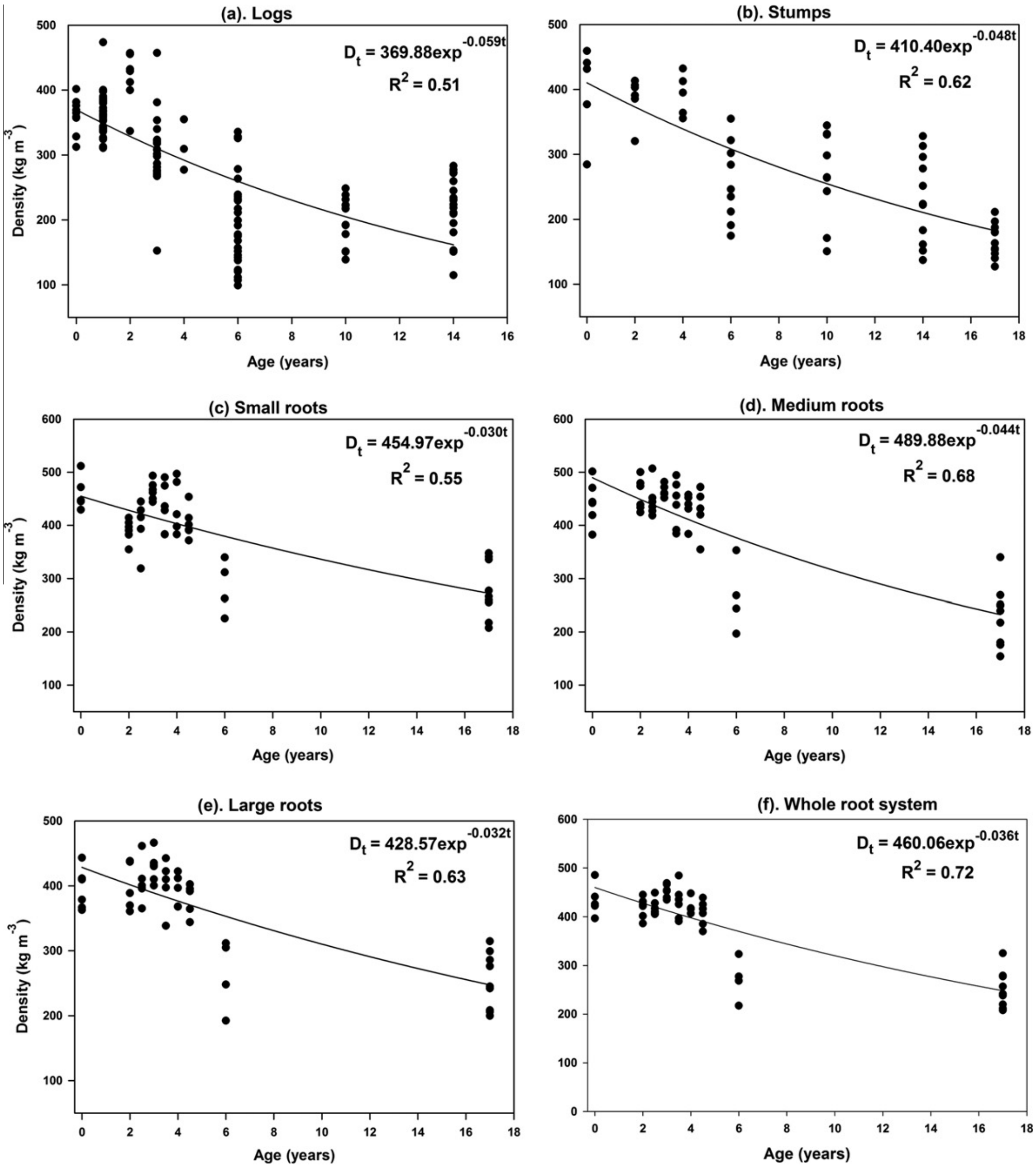

Fig. 5. (a)–(f) Exponential decay curves predicting the *k* values of Sitka spruce CWD from the relationship between density and time of decay (all equations are significant at $p < 0.0001$, parameters are as described in Eq. (3)).

Table 7
Estimated decay rates and half lives (50% decomposition) of CWD logs, stumps and roots of Sitka spruce.

CWD	Decay rate k (kg m^{-3} year^{-1})	Standard error (SE)	Samples (n)	Half life (years)
Logs	0.059	*0.005*	143	12
Stumps	0.048	*0.005*	56	14
Small roots	0.030	*0.004*	54	23
Medium roots	0.044	*0.005*	54	16
Large roots	0.032	*0.004*	52	22
All roots	0.036	0.003	54	19

added during each thinning operation. Thinning operations have a direct influence on stump and root quantities but an indirect and subjective effect on log amounts as product specification and operator efficiency can impact on the production of log debris. The C stock of logs at D35 appeared high and its removal improved the regression presented in Fig. 2b. This supports the possibility of it being an outlier due to the variable and subjective nature of log accumulation. According to the NFI, 87% of the total forest estate was in the juvenile stage (i.e. had not reached the developmental stage for thinning) in 2007 (Forest Service, 2007), thus the CWD-pool will play an important role in future C-stocks of these forests with significant CWD inputs from thinning operations. For instance, CWD contributed 5% of the total forest biomass C-stocks in the D22 stand (unpublished data), after two thinning events.

4.3. DC density of CWD

The relationship between decay classification and density of logs, stumps and coarse roots was consistent with other studies.

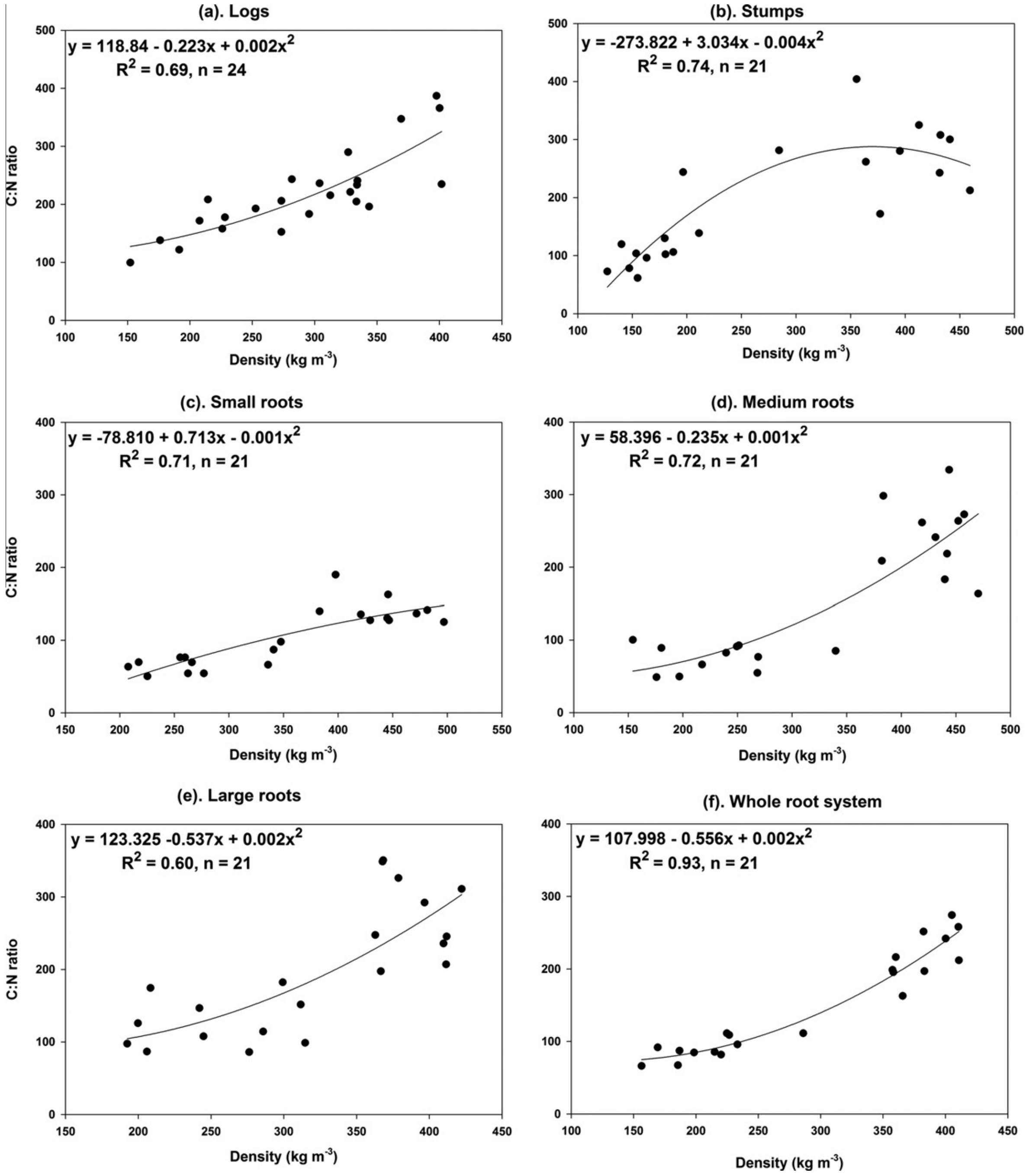

Fig. 6. (a)–(f) Quadratic regression curves relating the C:N ratio of Sitka spruce CWD to their density (all regressions equations are significant at $p < 0.0001$).

Various sources have reported a gradual decrease in density of coniferous and deciduous tree components with decay class, (Hale and Pastor, 1998; Adams and Owens, 2001; Yatskov et al., 2003; Creed et al., 2004; Tobin et al., 2007). There was a decrease in density as decay progressed from DC 0 to 4 in logs (45%), stumps (58%), and small- (38%), medium- (50%) and large roots (38%). The linking of density to DC is useful when undertaking an inventory of CWD C-stocks, but also has a number of shortcomings as noted by Creed et al. (2004). CWD DCs are subjectively assessed and result in categorical data that are based on surface rather than intrinsic characteristics. These shortcomings may result in biased C-stock change estimates, where the objective is to estimate changes over annual or decadal timescales. Density is difficult and time consuming to measure, and decay classification reduces the logistical problems and speeds up the estimation. Consequently, this system requires standardization, combined with a flexible approach to improve its adaptability to local conditions. For example, the combination of DCs to mimic the NFI classification systems did not clearly allow a separation of the density loss in stumps as compared to logs in the later stages of decay (Fig. 3a and b). A more detailed classification system (such as the 5-DC system used in this study), that tries to capture all the stages of decay, would be beneficial to national inventories.

4.4. Decay rates

The development and use of density-time decay functions for predicting decay rates (k) has been widely used (Chen et al., 2001; Mackensen and Bauhus, 2003; Beets et al., 2008). The rates for all CWD types in this study are comparable with the k for the rapid phase of decomposition suggested by Yatskov et al. (2003) for *Picea* species (0.045 year^{-1}). It was observed that roots in different size categories had different rates of decay. Root k values are similar to those mentioned by Chen et al. (2001) for decomposing woody roots of Sitka spruce in coniferous forests of the US Pacific Northwest. The differences in the k values for stumps and roots (Table 7) reveal that, contrary to suggestions, stumps tend to decay faster than roots. The differences in k values for root diameter categories confirm the findings of earlier studies (Chen et al., 2001; Silver and Miya, 2001), however, the small and large roots had similar rates of decay corroborating an earlier suggestion that diameter size may not be the main factor influencing decomposition of woody roots (Fahey and Arthur, 1994; Chen et al., 2001; Guo et al., 2006). As shown in Fig. 5, age may not be the ideal indicator of the stage of decay. Decay rate might not be continuous, but rather better described as a combination of an initial colonisation, followed by more rapid decomposition, in turn, followed by a slower phase of humification (Harmon et al., 2000; Yatskov et al., 2003). Data presented in Fig. 5 may follow this trend; however, there was not sufficient data between years 5 and 15 to test this theory. The key factors influencing slow rates of decay are the substrate quality and the environment (temperature, precipitation, aeration, decomposer organisms). In Ireland, high precipitation and low temperatures result in highly moist soil conditions and this greatly influences the leaching, fragmentation and microbial colonisation of CWD. The time for 50% decomposition predicted in this study are comparable to those of previous authors (Tarasov and Birdsey, 2001; Mackensen and Bauhus, 2003; Beets et al., 2008) for a range of forest tree species. Tarasov and Birdsey (2001) estimated that the time for 85% of initial mass loss to occur was 60 years for logs (20–40 cm diameter) and 71 years for coarse roots of *Picea abies* in Russia. However, caution should be exercised with the accuracy of the belowground decay curves, as they were weakened by the poor fit of the 6 year old samples which displayed low density values for this age. The application of the CWD decay curves is limited by the sampled age range. Age determination of stumps was possible up to the age of 17 years based on management records and the location of stumps within the stand. As older stumps could not be accurately linked with past management, no samples older than 17 years were included in this study.

The 10-year decay period (IPCC default) used for estimating CWD-decomposition for carbon accounting is a considerable underestimation. The time it takes for most CWD to completely decompose exceeds 25–30 years in the majority of cases (Mackensen and Bauhus, 2003). This study lends weight to the case for reviewing the default decay period of CWD for C-stock change estimation.

4.5. C:N ratio, density loss and decomposition

The C:N ratio is an indicator of the state of decay as there was a reduction in C:N ratio with increasing decay, as also observed in earlier studies (Krankina et al., 1999; Creed et al., 2004; Yang et al., 2010; Palviainen et al., 2010). The C:N ratios of roots were lower than those of logs and stumps, due to higher N concentrations. Krankina et al. (1999) showed an increase in N-concentration of CWD logs with decay class, with C:N ratio decreasing by 68% in logs of *P. abies*, and a similar trend was observed in this study with a declining C:N ratio of 46%, 41%, 51%, 72% and 57% for logs, stumps, small-, medium- and large roots, respectively, as decay progressed from DC 0 to 4. However, an increase in C:N ratio was observed in some highly decayed CWD, and this may be due to the concept of the 'critical C:N ratio'. This refers to the point of maximum N accumulation, after which decaying CWD starts to release N (McClaugherty et al., 1985). Palviainen et al. (2010) reported that N release from decomposing stumps of *P. abies* commenced after 80% of C loss. The strong correlation between change in C:N ratio and density loss as decay progressed revealed an important interaction between the chemical and physical properties of CWD. The density of CWD integrates both external and internal properties and is a valuable diagnostic tool for assessing its C:N ratio (Brown et al., 1998; Mackensen and Bauhus, 2003; Creed et al., 2004; Yang et al., 2010).

5. Conclusion

The CWD-pool is a vital C sink and reservoir, which, through sustainable forest management could increase the C storage potential of Irish forests. The stocks reported are from first rotation, thinned forests and may increasingly become significant as the forests mature and move from first to subsequent rotations. The belowground component is an essential stock that contributes significant amounts to the pool and therefore, requires accurate estimation methods. It is imperative that the scope and methods used for CWD stock estimation in Ireland be revised to accommodate smaller logs and stumps. The density change and C:N ratio are good indicators of the decay status of CWD. They provide measurable parameters that can be used to estimate the longevity of CWD and, with standardised decay classification, can improve stock and stock change estimates.

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