

The measurement of woody root decomposition using two methodologies in a Sitka spruce forest ecosystem

Samuel Olajuyigbe · Brian Tobin ·
Michael Hawkins · Maarten Nieuwenhuis

Received: 1 September 2011 / Accepted: 12 March 2012
© Springer Science+Business Media B.V. 2012

Abstract

Background and aims The decomposition of roots is an important process in the loss of carbon (C) and the mineralization of nitrogen (N) in forest ecosystems. The early stage decomposition rate of Sitka spruce (*Picea sitchensis* (Bong.) Carr.) roots was determined using trenched plots and decomposition bags.

Methods Stumps of known age were trenched and quadrants (50 cm by 50 cm) excavated from randomly selected stumps every 6 months over 4 years, while the mass loss from buried roots in decomposition bags, divided among four diameter categories (ranging from fine roots <2 mm to large roots >50 mm), was monitored for 27 months. The C and N concentrations of excavated samples at different time points were analysed.

Results The change in total root necromass per quadrant showed a higher decomposition rate-constant (k) of $0.24 \pm 0.068 \text{ year}^{-1}$ than the k -value of roots in decomposition bags ($0.07 \pm 0.005 \text{ year}^{-1}$). The C concentration

($47.24 \pm 0.609 \%$) did not significantly change with decomposition. There was a significant increase in the C:N ratio of roots in all diameter categories (fine: 48.92 %, small: 38.53 %, medium 11.71 %, large: 76.25 %) after 4 years of decomposition, driven by N loss. Root diameter accounted for 78 % of the variation in the N concentration of roots as decomposition progressed.

Conclusion Though the trenched plot approach offered an alternative to the more common decomposition bag method for estimating root decomposition, high spatial variation and sampling difficulties may lead to an over-estimation of the mass loss from trenched roots, thus, the decomposition bag method gives a more reliable decomposition rate-constant.

Keywords Trenched plots · Root diameter · Root decomposition · Decomposition bags · C:N ratio · Decomposition rate-constant

Introduction

The long-term storage of carbon (C) in forest ecosystems depends greatly on the allocation of biomass into long-lived forest C stocks. These stocks include above- and belowground biomass, deadwood (fine and coarse woody debris; CWD), litter and soil organic matter (Laclau 2003; Petersson and Melin 2010). There are many studies devoted to estimating the C stocks and decomposition rates of litter and CWD created by natural succession (e.g. snags, fallen trees) and disturbance

Responsible Editor: Alfonso Escudero.

Electronic supplementary material The online version of this article (doi:10.1007/s11104-012-1222-7) contains supplementary material, which is available to authorized users.

S. Olajuyigbe (✉) · B. Tobin · M. Hawkins ·
M. Nieuwenhuis
UCD Forestry, School of Agriculture and Food Science,
University College Dublin,
Dublin, Ireland
e-mail: lekito2001@yahoo.com

dynamics (e.g. harvest residues, stumps) (Beets et al. 2008; Jonsson and Jonsson 2007; Shorohova et al. 2008; Tobin et al. 2007a). These processes also produce large pools of C belowground (i.e. dead root systems) which decompose at varying rates and are gradually incorporated into the soil organic matter pool (Chen et al. 2001; Fahey and Arthur 1994).

The contribution of decomposing roots to the forest debris C pool is typically ignored because of the tremendous effort and time required for measuring this component (Resh et al. 2003; Soethe et al. 2007). However, the root system below a stump can represent up to 20 % of the total biomass of a tree, thus underlining the need for quantifying the C stored in dead roots (fine and coarse), their nutrient dynamics and decomposition rates. These are essential for the accurate estimation of the CWD C pool and its role in forest C cycling (Laiho and Finér 1996; Melin et al. 2009).

Estimating rates of root decomposition is challenging because roots are hidden from view and occur in an environment that must be disturbed as part of any analysis. Studies on belowground decomposition have focused mostly on fine roots (generally defined as <2 mm) due to their faster turnover rates (Hobbie et al. 2010; Silver and Miya 2001), with very little attention paid to coarse roots (>2 mm) (Ludovici et al. 2002; Melin et al. 2009), which account for the majority of root biomass (except in very young stands) (Misra et al. 1998). Coarse roots act as conduits for nutrients and water, a storage site for C and nutrients, and also provide physical anchorage (Keplin and Hüttl 2001; Knorr et al. 2005; Tobin et al. 2007b). In addition, the decomposition of coarse roots provide a slow delivery of C and nutrients to the soil and soil biota and so influences the long-term ecosystem productivity and CO₂ emissions from forests (Johnsen et al. 2005; Mao et al. 2011).

The common methods used for studying root decomposition include: buried decomposition bags, buried pots, trenched plots, tethered roots, sequential coring, intact-core methods, laboratory incubation and excavation of stump chronosequences (Aulen et al. 2011; Chen et al. 2000; Ludovici et al. 2002; Silver and Miya 2001). The buried decomposition bag method is the most common and widely-used technique, where the rate of root decomposition is determined from the fraction of original mass remaining over time. However, this method has been criticized for providing unreliable results because it causes a disruption of the root-rhizosphere, hastens the root-death process (without allowing a phase

of e.g. fungal inoculation), could prevent translocation and decreases the accessibility for larger decomposer organisms such as soil invertebrates (Aulen et al. 2011; Fahey and Arthur 1994; Mao et al. 2011).

An alternative approach, which aims to circumvent some of the limitations of the decomposition bag method, is the trenched plot method (Manlay et al. 2004). A trench is dug around a block of soil containing stumps, to a depth deeper than the main rooting zone to ensure all roots within the trench are dead by severing root grafts and mycorrhizal hyphae connections with adjoining trees (Sayer and Tanner 2010; Subke et al. 2006). The decomposition rate is determined from the change in root mass excavated or cored from the trenched plots over time and the experimental design could be stratified based on depth and direction (Silver and Vogt 1993). A somewhat similar approach is the excavation of whole stump and root systems from a chronosequence of sites and estimating the decomposition rate from the mass of root remaining at different time points after harvest (Ludovici et al. 2002; Melin et al. 2009).

Root decomposition depends on both biotic and abiotic factors; the most important being root quality (or chemistry) (Lin et al. 2010; Silver et al. 2000). Root tissue quality generally varies with soil nutrient conditions, tree species and root diameter (Mao et al. 2011). It is a primary controller of belowground decomposition, because the chemical properties of root tissue, such as the varying concentrations of calcium (Ca), lignin, phosphorus (P), nitrogen (N) and water soluble phenols, strongly influence the variation in the rate of root decomposition, especially during the early and late phases (Creed et al. 2004; Olajuyigbe et al. 2011; Palviainen et al. 2010; Yang et al. 2010). Of the chemical properties that have been investigated, Ca concentration and C:N ratio have been shown to explain the largest amount of variability in root decomposition on a global scale (Aulen et al. 2011; Chen et al. 2001; Silver and Miya 2001).

The C, N, lignin and polyphenol concentrations are the most common chemical criteria used to define detrital substrate quality and ratios of e.g. C:N have been used to predict stages of decomposition and nutrient release (Creed et al. 2004; Goebel et al. 2011). Decomposing forest debris do not release N in concordance with loss of mass and changes in N concentration have been confirmed to limit decomposition. Therefore, the changes in C:N ratio as mass is lost can be used as an indicator of the stage of root decomposition (Teklay 2007; Zeng et al. 2010).

Apart from root chemical quality and various environmental factors, root diameter (which often indicates functionality) is another key factor that governs the decomposition and nutrient cycling of roots (Nambiar 1987), because it integrates both chemical and physical properties associated with root development (Fahey and Arthur 1994). For instance, N and P concentrations generally decrease with increasing root diameter (John et al. 2002; Vogt et al. 1991).

Sitka spruce (*Picea sitchensis* (Bong.) Carr.) is the most important commercial tree species in Ireland; accounting for 52 % of the total forest estate (Forest Service 2008). In Irish forest plantations, the main sources of CWD are thinning and harvesting operations, generating both above- and belowground woody debris. The stock change and decomposition of CWD (especially roots) is a major factor influencing C storage in managed forests.

Root growth patterns and the generally shallow rooting depth and architectural distribution of Sitka spruce planted on wet mineral soils in Ireland have been reported (Nieuwenhuis et al. 2003; Nieuwenhuis and Wills 2002), as well as belowground C pools (Black et al. 2009; Green et al. 2007). However, little information exists to date on the belowground decomposition dynamics of this species. In a related study (Olajuyigbe et al. 2011), coarse roots (>2 mm) were estimated to compose 85 % of the CWD C pool in the study site. Thus, the inclusion of belowground CWD in reporting estimates of forest C pools is important, and identifying decomposition rates and N dynamics will enhance our understanding of the role of dead roots in forest ecosystems.

The aims of this study were (1) to determine the early stage decomposition rate of roots using both quadrants from trenched in situ root systems and buried decomposition bags in a Sitka spruce forest; (2) to determine the effect of root diameter categories and depth on root mass loss; and (3) to determine the changes in C and N concentrations and the C:N ratio of the excavated roots as decomposition progressed with time.

Materials and methods

Site description

The study was carried out in a 23-year-old Sitka spruce (*P. sitchensis*) forest stand growing on wet mineral gley

soil located in Co. Laois in the Irish midlands (52° 57'N, 7° 15' W, elevation of 260 m). This wet mineral gley soil was formed under naturally wet or waterlogged conditions and has a greyish colour as a result of the reduction (under anaerobic conditions) of ferric iron to the ferrous state. The soil litter-humus horizon (O) and the mineral horizons (A, B and E) occur within 30 cm of the soil depth in this forest stand (Saiz et al. 2007).

The stand forms part of a long-term experimental field station used for the measurement of climatic data, greenhouse gas flux and biomass accumulation, as part of the Carbon Sequestration in Irish Forests project (CARBiFOR; Black and Farrell (2006)). The 30-year mean annual temperature and rainfall were 9.3 °C and 850 mm, respectively. The 42 ha stand which was previously unmanaged grassland with a slope of 3 %, was afforested in 1988 at a density of 2,300 stems ha⁻¹ (using 2 m by 2 m spacing). It was thinned in the winters of 2006 and 2008, and approximately 22 % and 23 % of the total forest biomass was removed, respectively. The first thinning was largely systematic, in which every seventh row was removed (with selective thinning in the remaining rows), while the second thinning was purely selective. The seventh rows which were removed became the extraction racks (thinning lines) and represented ~14 % of the total stand area.

Root sampling in trenched plots

Stumps in 6 thinning lines were trenched in the spring of 2007, to ensure root death and no grafting with adjoining trees, by digging a channel approximately 1 m on either side of the row of stumps to a depth of 60 to 70 cm (well below the observed major rooting zone). These trenches were then backfilled after carefully severing all root connections with live trees. Six stumps (one per thinning line) of known age (time since harvest and trenching) were randomly selected for excavation to determine belowground necromass, and this was repeated every 6 months. At each sampling time, new trenched stumps (previously undisturbed) were selected for excavation.

For practical reasons, a quadrant of 50 cm by 50 cm located against a stump in one of the cardinal directions was manually excavated from each selected stump. Quadrants were used to reduce the amount of excavation work from each individual stump, while preserving the degree of root diameter variation and allowing a greater number of replicates to be excavated. The top surface

diameters of stumps were measured after the trenching and before each excavation.

The quadrant direction was randomly selected and the excavation was stratified by two depth classes (A: 0–10 cm and B: >10 cm to maximum rooting depth). The maximum rooting depth in each excavated quadrant was recorded and all roots within the quadrant were carefully separated from the soil and collected in sample bags. Roots were transported to the laboratory for cleaning and sorting into four diameter categories; fine (<2 mm), small (2–10 mm), medium (>10–50 mm) and large (>50 mm). The large roots were identified as the large lateral roots radiating from the base of each stump. The samples were oven-dried until constant weight at 80 °C and their dry weight recorded. The excavations commenced in the spring of 2007 and were carried out 0, 2, 2.5, 3, 3.5 and 4 years after trees were felled.

Decomposition bag experiment

Known weights of oven-dried roots from the four diameter categories, previously excavated from the same stand at time 0, were placed in 1 mm nylon mesh bags (bag dimensions: 10 cm by 15 cm for fine and small roots and 25 cm by 50 cm for medium and large roots). Six replicates were prepared for each root diameter category and were buried at two depths (A: 0–10 cm and B: 10–20 cm), apart from large roots which were only buried at depth A, because roots of this diameter category were only found to occur at this depth. Each set of samples were inserted into the soil in 6 plots adjacent to the thinning lines where the trenched roots were excavated. A total of 246 mesh bags (72 each for fine, small and medium roots, and 30 bags for large roots) were inserted into the soil.

To bury the mesh bags, a spade was used to create a slit in the soil at a ~45° angle and the bags were inserted into the incision to depths of 10 and 20 cm. This ensured that soil disturbance was minimized as much as possible and that bags had good contact with the soil. At each point, seven bags (two of fine, small and medium roots (i.e. two depths) and one of large roots) were buried ~50 cm apart and arranged in a wheel pattern. All the bags to be collected at each sampling time were connected with a string and this was anchored at the centre to enable easy recovery of bags and to prevent accidental loss.

The fine, small and medium root bags were collected after 3, 6, 12, 18, 24 and 27 months, while large root

bags were collected after 6, 12, 18, 24, and 27 months. Once returned to the laboratory, the bags were cleaned, dried at 80 °C, and the fraction of initial necromass remaining was determined.

C, N and C:N ratio analysis of excavated root samples

For each diameter category, samples of roots from individual stumps excavated at different time periods were re-dried (at 80 °C), mixed and homogenised by passing each through a motorised flail shredder, and three sub-samples were taken randomly from each batch of mixed material. These sub-samples were ground using a hammer flail mill fitted with a 1 mm gauge. The C and N concentrations were determined using a Vario Max CN element analyser (Elementar Analysensysteme GmbH), using direct combustion at 850 to 1150 °C. Then, the change in C and N concentrations as well as C:N ratios, over the period of decomposition, was determined for each diameter category (with C and N concentrations at time 0 representing the initial concentrations).

Statistical analysis

The data were processed using one-, two-, and three-way ANOVA (fixed effect models) and post-hoc analysis using Holm Sidak and multiple comparison tests in Sigma-Stat 11 for Windows and XLSTAT 11 for Microsoft Office. Differences between main and interaction effects of root diameter categories, time since harvest, direction of excavation and depth of excavation (A and B) on root necromass per quadrant, C and N concentrations, and C:N ratios were assessed. The effects of burying depth (A and B) and decomposition time on the mass loss of roots in decomposition bags were also determined. The Pearson product moment correlation (r) and regression analysis were used to measure the relationship between variables. All significant differences are reported at $P < 0.05$.

Exponential decomposition functions

A single negative exponential decomposition function (Olson 1963) was used to estimate the decomposition rate of root necromass per quadrant based on (Eq. 1):

$$W_t = W_o \exp^{-k_o T} \quad (1)$$

where W_t (kg quadrant⁻¹) is the total root necromass excavated from each quadrant at time since harvest T

(years), W_o , (kg quadrant^{-1}) is the initial necromass determined as the intercept of the decomposition curve, and k_o is the decomposition rate-constant (year^{-1}). This model assumes that the rate of decomposition is proportional to the amount of necromass remaining in the trenched plots.

It has been shown that the predictability of root necromass remaining could be increased if stump diameter was included as an independent variable in a modified exponential decomposition function (Ludovici et al. 2002; Melin et al. 2009). Therefore, the exponential function (Eq. 1) was modified to relate root necromass per quadrant to a combination of stump diameter and time since harvest as shown in Eq. 2:

$$W_t = [a + b(\text{dia})] \exp\{-(c+d(\text{dia}))T\} \quad (2)$$

where (dia) is the stump diameter (m) and a, b, c, and d are equation parameters.

To determine the decomposition rate-constant k_b for each root diameter category placed in mesh bags, we fitted a negative exponential decomposition model (Eq. 3) to the fraction of root mass remaining as shown in Eq. 3:

$$\frac{W_t}{W_o} = \exp^{-k_b T_b} \quad (3)$$

where W_o (kg) is initial mass, W_t (kg) is mass remaining at time T_b (in years after the roots were buried) and k_b is the individual diameter category decomposition rate-constant determined using nonlinear least-squares fitting.

Results

Change in trenched root necromass

A 60 % reduction in the total root necromass per quadrant was observed after 4 years. Generally, the total amount as well as the root necromass for individual diameter categories excavated from all directions decreased as decomposition progressed (Fig. 1a and b). The post-hoc tests showed that the total necromass per quadrant from the western quadrants were only significantly greater than the necromass from the southern quadrants.

There was a positive correlation between total root necromass per quadrant and stump diameter ($r=0.691$, $P<0.0001$). The stump diameter did not differ

significantly ($P=0.069$) between the different sampling times (mean stump diameter ranged from 18.15 to 25.29 cm).

The maximum rooting depth was significantly different ($P=0.025$) for the different sampling times (mean maximum depth ranged from 42.66 to 63.50 cm). However, only maximum depth after 2 years differed from that after 2.5 years. All large root samples occurred only at depth A, while varying amounts of fine, small and medium diameter categories were found at depths A and B.

The interaction between direction of excavation and depth was not significant for fine ($P=0.326$), small ($P=0.690$) and medium ($P=0.128$) roots, while only the three-way interaction effect of time since harvest, direction and depth of excavation on total necromass per quadrant was significant ($P=0.020$) (Table 1).

Decomposition function for root necromass

The single negative exponential decomposition curve (Eq. 1) for change in total root necromass per quadrant (Fig. 1a) produced a poor fit ($R^2=0.26$, $P=0.001$) with a k_o -value of $0.24 \pm 0.068 \text{ year}^{-1}$; while the bivariate model (Eq. 2), relating stump diameter and time since harvest to root necromass per quadrant, gave a better fit ($R^2=0.62$, $P<0.0001$) (Table 2). The plot of residuals for the bivariate model showed the uniform spread of the data around the mean of stump diameter and time since harvest (Online resource 1).

Effect of diameter categories on excavated root necromass

The root necromass excavated for each diameter category depended on the time since harvest and the direction of excavation, as significant main and interaction effects of the time since harvest ($P<0.001$), direction of excavation ($P=0.003$) and the root diameter categories ($P<0.001$) were observed (Table 3). The interaction between time since harvest and direction of excavation had a strong influence on the amount of fine ($P<0.001$) and small roots ($P=0.001$) excavated, but had no effect on the amount of medium ($P=0.949$) and large roots ($P=0.921$) excavated. Only root necromass from the western quadrants of stumps was higher than those from quadrants in the other directions, for all diameter categories (Fig. 2a to d).

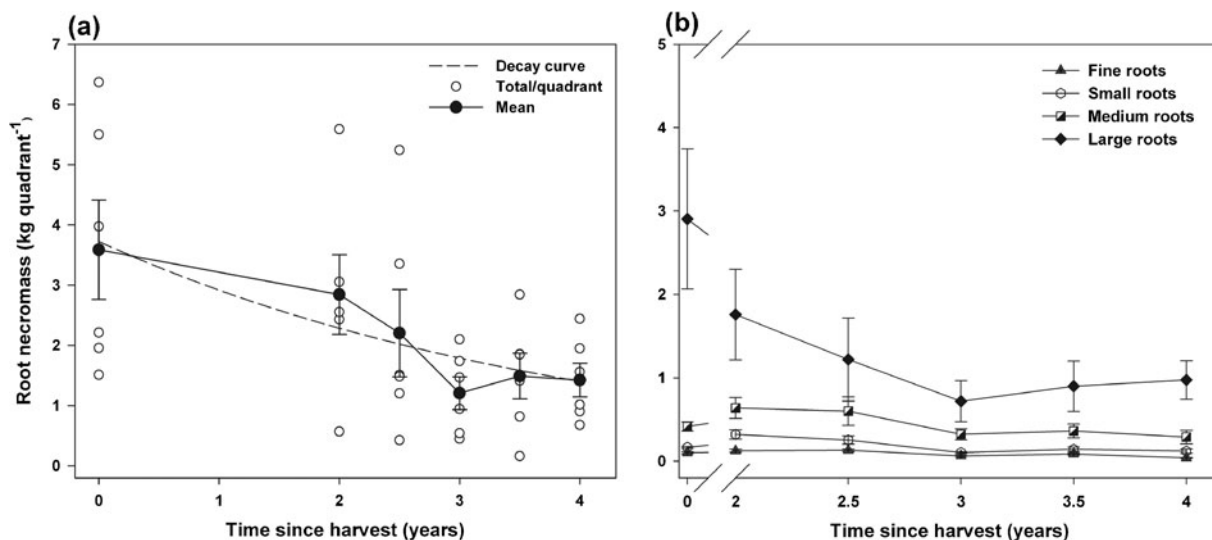


Fig. 1 **a** Single negative exponential decay curve for total root necromass per trenced quadrant (*open circles*) and the mean (with S.E. bars) of total root necromass excavated for each time

point (*filled circles*); **b** change in necromass of decomposing roots of fine, small, medium, and large roots excavated from stumps (mean with S.E. bars)

N and C concentration

The change in N concentrations depended on time since harvest ($P < 0.001$) and the magnitude of this change was influenced by root diameter category ($P < 0.001$) (Table 4). However, pair-wise comparisons within each root diameter category revealed that N concentrations only differed significantly for some time points (Table 5).

There were significant fluctuations (increases and decreases) in fine root C concentrations as decomposition progressed, while no significant changes were observed in the C concentrations of the other diameter categories over time. The C concentration increased with diameter category, with the concentration in fine roots (mean:

45.15 ± 0.706 %) significantly lower than in the other diameter categories (mean: 47.74 ± 0.685 %).

The C:N ratios differed between root diameter categories (Table 4) and generally increased (fine: 48.92 %, small: 38.53 %, medium 11.71 %, large: 76.25 %) after 4 years of decomposition (Table 5). The pair-wise comparisons showed significant variations within each root diameter category, over the decomposition period.

Root decomposition in buried mesh bags

For the root decomposition bag experiment, the mass loss from fine and small roots significantly increased with decomposition time, while the depth of burial had

Table 1 Results (P -values) of three-way ANOVAs on the effects of time since harvest (T), direction of excavation (DIR), depth (DE) and their interactions on root necromass per quadrant (50 cm by 50 cm) during the early stages of decomposition

Source of Variation	Fine roots (<2 mm)	Small roots (2–10 mm)	Medium roots (>10–50 mm)	Large roots (>50 mm)	Total root mass
T	<0.001	<0.001	0.002	0.002	<0.001
DIR	0.069	0.393	0.029	0.052	0.004
DE	<0.001	0.001	<0.001	–	<0.001
T x DIR	0.103	0.556	0.049	0.105	0.011
T x DE	0.003	0.060	0.004	–	<0.001
DI x DE	0.326	0.690	0.128	–	0.014
T x DIR x DE	0.306	0.424	0.073	–	0.020

(columns represent separate analyses for 4 root diameter categories, $n=6$ quadrants per time point and there were 6 time points during the 4 years of study)

Table 2 Regression coefficients for the single exponential decay curve (Eq. 1) and the bivariate model (Eq. 2) relating total root necromass per quadrant to time since harvest and stump diameter

Exponential decay curve $W_t = W_o \exp^{-k_o T}$					Bivariate model $W_t = [a + b(\text{dia})] \exp\{-(c+d(\text{dia}))T\}$				
Coefficient	Value	S.E.	R ²	P-value	Coefficient	Value	S.E.	R ²	P-value
W_o	3.72	0.534	0.26	0.0014	a	2.35	2.508	0.62	<0.0001
k_o	0.24	0.068			b	5.11	9.892		
					c	1.06	0.331		
					d	-4.02	1.349		

no effect. On the other hand, there was a significant difference between the mass loss of medium roots placed at depths A and B ($P < 0.001$).

The respective mass losses from depths A and B were 28 and 29 % for fine roots, 18 and 22 % for small; 16 and 11 % for medium and 8 % for large roots (only at depth A) after 27 months of decomposition (Fig. 3a to d). Data from both depths were pooled for fine and small root diameter categories and negative exponential decomposition curves were fitted for each diameter category (Fig. 4a to d). The decomposition models fitted fine root data best, while the weakest fit was with medium root data (at depth B). The k_b -values were 0.17 ± 0.008 , 0.11 ± 0.005 , 0.08 ± 0.006 , 0.04 ± 0.004 and $0.05 \pm 0.004 \text{ year}^{-1}$ for the fine, small, medium at depth A, medium at depth B and large roots, respectively.

Discussion

Belowground C necromass

Many studies have been conducted to determine the amounts of C and nutrients returned to the soil as a

Table 3 Three-way ANOVA for the main and interaction effects of the time since harvest (T), direction of excavation (DIR) and diameter category (DC) on root necromass per quadrant

Source of variation	P-value
T	<0.001
DIR	0.003
DC	<0.001
T x DIR	0.005
T x DC	<0.001
DIR x DC	0.010
T x DIR x DC	0.017

result of fine root turnover, with less attention paid to coarse roots (Lin et al. 2010; Melin et al. 2009; Soethe et al. 2007). The C and N pools of dead coarse roots on the study site were estimated at $5.94 \text{ Mg C ha}^{-1}$ and $0.08 \text{ Mg N ha}^{-1}$ (calculated from necromass estimates in Olajuyigbe et al. (2011) and C and N concentrations in Table 5). The C pool falls within the range (2.9 to 34 Mg C ha^{-1}) estimated by Black et al. (2009) for a chronosequence (9 to 45-years-old) of Sitka spruce stands in Ireland. Coutts et al. (1999) reported that a large proportion of resources in trees are allocated to coarse roots which represent 80 % of the root systems in 18-year-old Sitka spruce forests in Britain. On average, the fine, small, medium and large root diameter categories contributed 4.52 %, 9.00 %, 22.08 % and 64.41 % respectively, to the total necromass per quadrant during this 4-year study. Coarse roots (i.e. all except the fine root diameter category) represented 94 to 97 % of the total root necromass (based on excavations from all time points). These coarse roots represent significant pools of belowground C and N, even during a first rotation of approximately 40 to 50 years.

Trenched plot excavations

The excavation of 50 cm by 50 cm quadrants for this study was an attempt to capture a representative proportion of roots within a small area around the stump. Nieuwenhuis and Wills (2002) reported that the majority of the vertical and horizontal spread of roots were within a 60 cm radius from the rootstock in 7 to 8-year-old Sitka spruce forests growing on mineral gley soils in Ireland. They suggested that the majority of root volume would still be concentrated within a 1 m radius from the root-stock as the trees matured and these roots would form the structural (coarse) roots

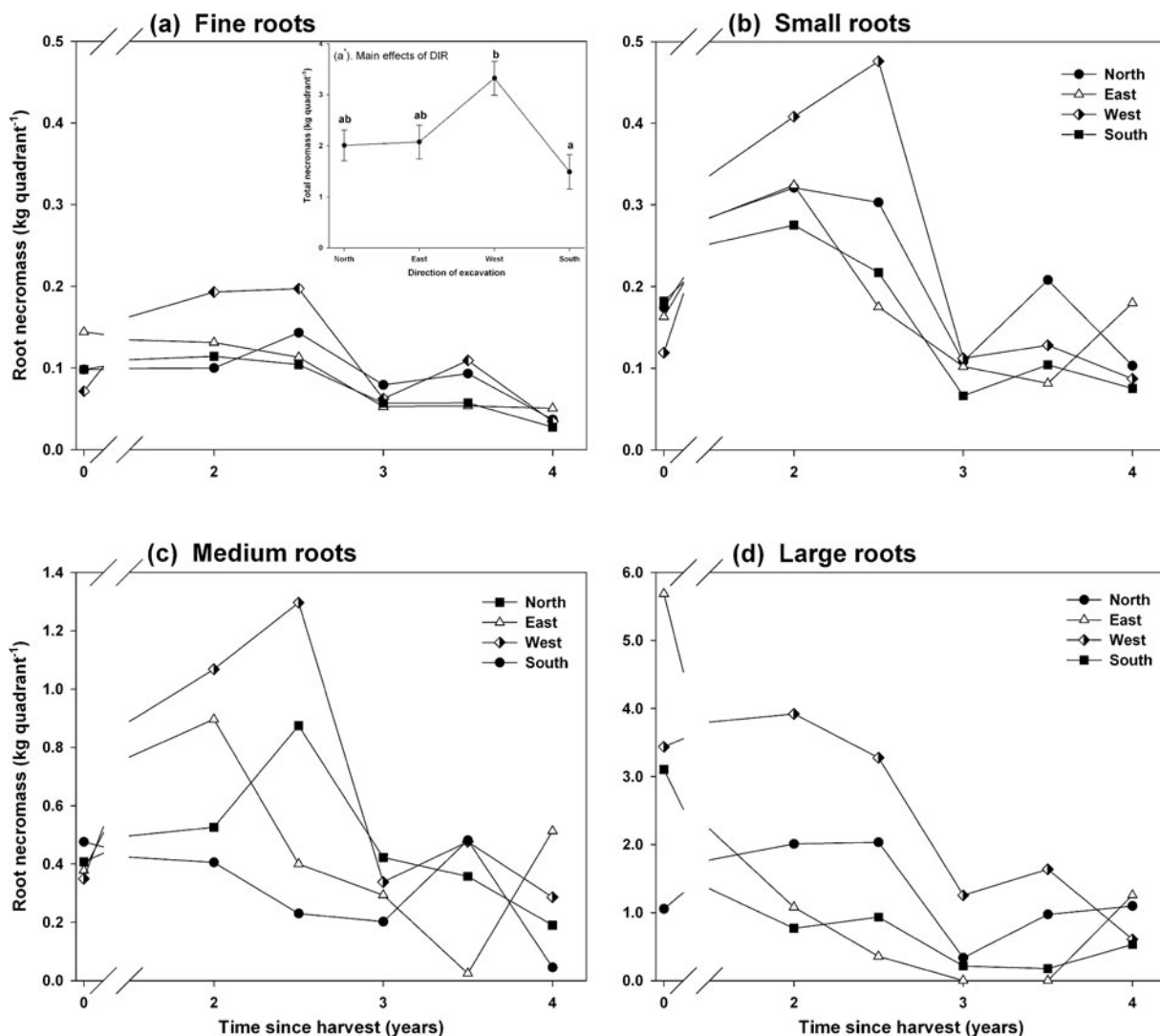


Fig. 2 a to d Profile plots of the least square means of the interaction effects of time since harvest (T) and direction of excavation on the necromass for each diameter category (each data point

represents a 50 cm by 50 cm quadrant); Inset: (a*) represents the main effects of the direction of excavation (least square mean (with S.E. bars), same letter indicate no significant difference at $P < 0.05$)

corroborating earlier work by Coutts (1983). They further observed that the root distribution patterns of

Sitka spruce trees were symmetrical with a slight variation due to the orientation of slopes within the forest.

Table 4 Two-way ANOVA for the main and interaction effects of time since harvest (T) and diameter category (DC) on the N and C concentrations and on the C:N ratios of decomposing roots

Source of Variation	N (%)	C (%)	C:N ratio
T	<0.001	<0.001	<0.001
DC	<0.001	<0.001	<0.001
T x DC	<0.001	0.006	0.044

In this study only the root quantities excavated from western oriented quadrants (wind ward side) were significantly higher than those from other directions. This was probably due to the predominance of wind from the southwesterly direction of the study site. This agrees with findings by other authors, that a larger mass of roots is allocated on the windward side of shallow rooted trees, to increase anchorage and strength (Coutts et al. 1999; Nicoll and Ray 1996). The western quadrant

Table 5 Concentrations of N and C, and the C:N ratio of individual diameter categories during the early stages of root decomposition (mean in % and S.E. in italics)

Time (years)	N concentration*				C concentration*				C:N ratio*			
	Fine	Small	Medium	Large	Fine	Small	Medium	Large	Fine	Small	Medium	Large
0	0.91 ^a 0.030	0.43 ^{ab} 0.019	0.21 ^a 0.025	0.21 ^a 0.017	46.58 ^{ac} 0.309	47.88 ^a 0.587	47.72 ^a 0.757	48.08 ^a 0.838	51.59 ^{ac} 1.643	114.50 ^{ab} 5.884	248.21 ^a 23.348	242.60 ^b 22.729
2	0.88 ^a 0.020	0.56 ^a 0.021	0.16 ^c 0.005	0.17 ^b 0.017	40.36 ^b 1.040	48.50 ^a 1.310	47.00 ^a 0.062	46.82 ^a 0.137	45.89 ^a 2.054	86.99 ^a 3.066	290.29 ^b 9.776	300.89 ^a 31.401
2.5	0.66 ^b 0.020	0.38 ^b 0.042	0.18 ^a 0.008	0.16 ^c 0.013	45.24 ^a 0.612	46.48 ^a 0.377	46.66 ^a 0.088	47.17 ^a 0.005	69.46 ^{bd} 2.669	129.38 ^{ab} 12.936	261.54 ^a 10.868	297.92 ^{ab} 22.556
3	0.68 ^b 0.021	0.33 ^b 0.012	0.16 ^c 0.008	0.14 ^d 0.010	46.03 ^{ac} 0.399	48.20 ^a 1.052	46.92 ^a 0.117	48.50 ^a 1.540	68.01 ^{bd} 2.524	149.65 ^b 6.393	292.32 ^a 14.160	344.97 ^{ab} 22.373
3.5	0.72 ^b 0.031	0.42 ^b 0.055	0.19 ^a 0.020	0.16 ^c 0.011	43.81 ^a 1.005	47.14 ^a 0.882	47.87 ^a 0.989	47.71 ^a 0.900	62.08 ^{bc} 3.082	125.70 ^{ab} 12.285	260.88 ^b 20.650	309.48 ^{ab} 19.522
4	0.66 ^b 0.052	0.34 ^b 0.038	0.21 ^a 0.028	0.13 ^b 0.010	48.89 ^a 0.871	48.69 ^a 0.835	48.88 ^a 1.381	49.12 ^a 0.484	76.82 ^d 5.681	158.62 ^b 22.695	277.30 ^b 55.461	427.59 ^b 41.197

*Mean with same letters in the same columns were not significantly different at $P < 0.05$

necromass was observed to only differ significantly from that in the southern sections in the overall analysis of total necromass per quadrant (Fig. 2a* inset), probably due to the relatively level terrain (site slope was 3 %). The majority of the coarse roots occurred at a shallow rooting depth in the 0–10 cm layer, echoing the findings of other studies on Sitka spruce growing on wet mineral soils in Ireland and Britain (Nieuwenhuis et al. 2003; Nicoll et al. 2006; Ray and Nicoll 1998). The deepest rooting depth observed during the study was 86 cm, while the mean maximum rooting depth for all time points ranged from 42.66 to 63.50 cm. This shallow root development has been attributed to high water tables in Sitka spruce forests growing on mineral gley soils (Tobin et al. 2007b; Wills et al. 2001). Measurements of soil moisture content in another study on the same site showed high soil moisture content in the thinning lines where the trenches were located. The volumetric moisture content (0 to 6 cm depth) ranged from 57 to 77 % between June 2010 and February 2011 (Olajuyigbe et al. 2012).

Ray and Nicoll (1998) reported a maximum rooting depth of 63 cm for a 46-year-old Sitka spruce forest growing on similarly wet soils in Scotland, while Wills et al. (2001) found that the water table of mineral soils of Irish Sitka spruce plantations did not fall below 50 cm, leaving only the top soil layers sufficiently oxygenated to accommodate root growth. This resulted in a high concentration of roots in the upper soil layer, as was found in the current study. Over the sampling period, 51–73 % of fine roots, 54–77 % of small roots and 43–88 % of medium roots were present in the upper soil layer (depth A), and no large roots occurred at depth B. This shallow rooting pattern could facilitate the use of trenched plots for studying root decomposition in wet soils, as an increased accessibility of roots reduces the amount of time required for excavation and processing.

Change in root necromass and rate of decomposition

The total root necromass per quadrant had decreased by 60 % after 4 years. Silver and Vogt (1993) found that 48 to 65 % of the fine root necromass was left in trenched plots after one year using the same method. However, comparison of rates is difficult because that study was limited to fine roots and conducted in a different ecosystem. In this study, only the large roots showed a clear pattern with a reduction in mass of 66.46 % when the first and last excavations were compared.

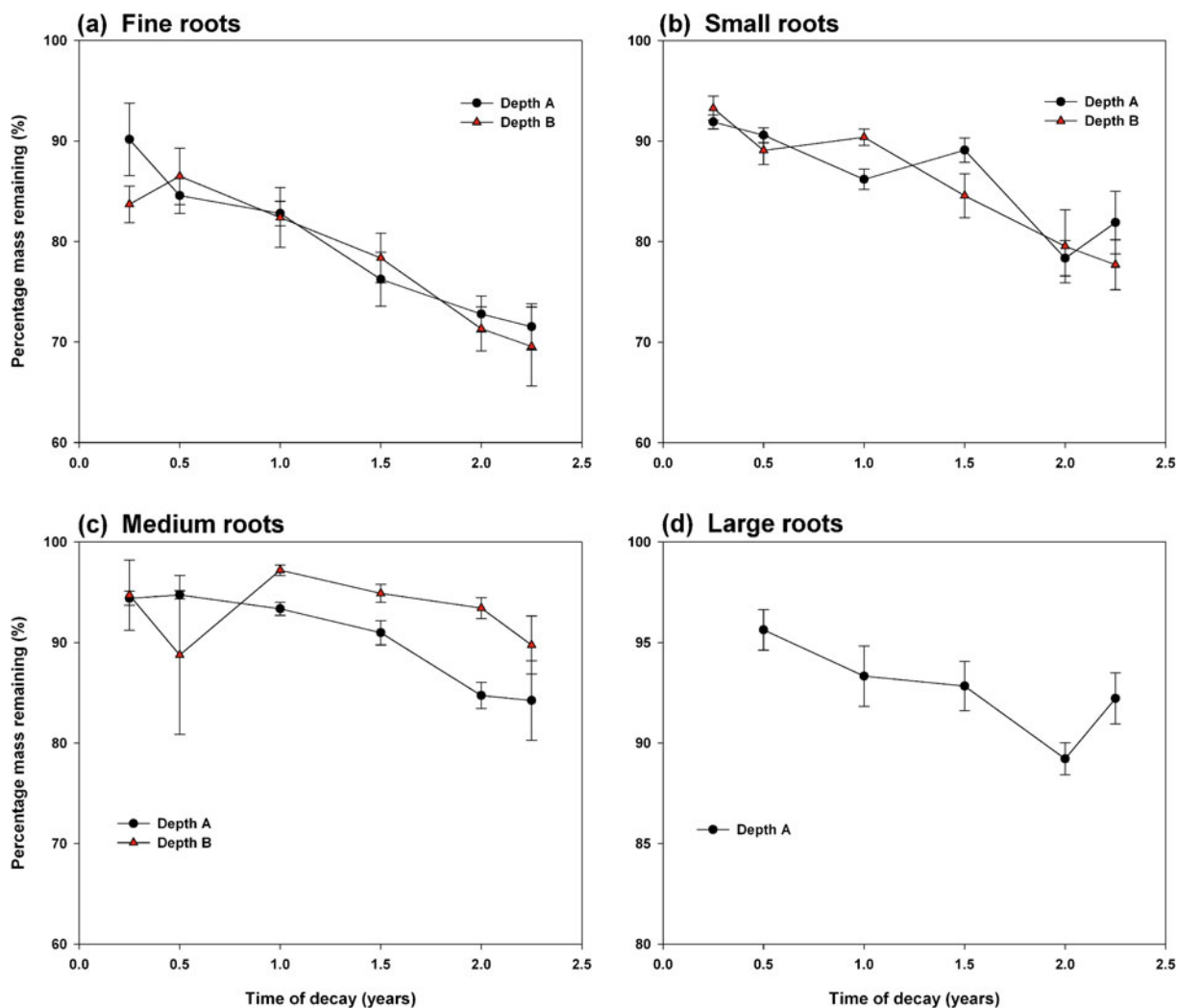


Fig. 3 Percentage of mass remaining for roots in decomposition bags placed at depths A (0–10 cm) and B (10–20 cm) after 27 months of decomposition (mean with S.E. bars), for **a** fine roots, **b** small roots, **c** medium roots and **d** large roots (only buried at depth A)

Though the period of decomposition in this study was short, the change in necromass per quadrant over time (Fig. 1a and b) demonstrated the potential of using the trenched plot technique for estimating the rate of decomposition. Melin et al. (2009) suggested that the direct measurement of root necromass using dry weights of excavated samples from decomposing root systems was a more accurate method than the use of combined estimates of volume and bulk density. Trenched plots are desirable because they do not require the removal or treatment of roots prior to sampling, but the unknown initial starting mass is the main problem with this technique. Manlay et al. (2004) stated that tethering roots or trenching soil to allow roots to decompose in situ would

lead to faster decomposition rates than those decomposing in mesh bags. In a trenched plot experiment, conducted in Puerto Rico (Silver and Vogt 1993), a high decomposition rate-constant ($k_o=0.70\pm 0.15$) was obtained for fine roots, which was similar to that of a decomposition bag study ($k_b=0.72\pm 0.12$) conducted simultaneously in the same forest and using the same diameter class of roots (Bloomfield et al. 1993). In contrast, the k_o (0.24 year^{-1}) estimated for the trenched experiment in the current study was higher than the weighted mean k_b for mesh bags (0.07 year^{-1} across all diameter categories). The act of trenching, i.e. the inclusion of severed live roots in the decomposing substrate, fragmentation of the root substrate (especially

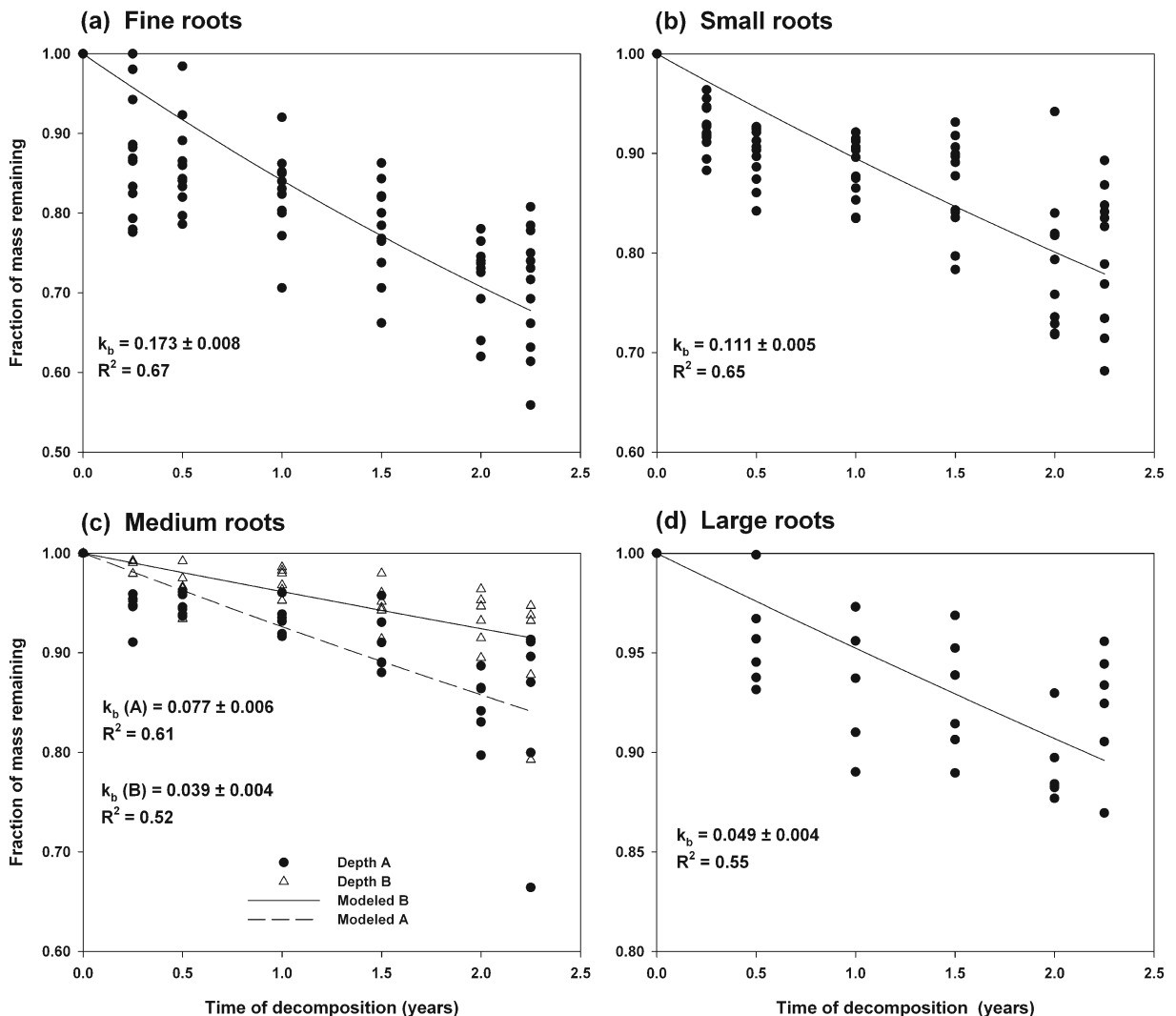


Fig. 4 a to d Negative exponential decomposition curves for buried roots of different diameter categories (k_b -value with S.E. and R^2 indicated on the individual graphs, decomposition curves

for medium roots buried at depths A and B were plotted separately because there was a significant difference between mass loss from the two depths)

fine roots), human error during root sampling and a high natural variation in root distribution may further have reduced the precision of this technique for estimating decomposition rates and nutrient release from roots (Silver et al. 2000; Silver and Vogt 1993). Another potential treatment artifact that could limit the accuracy of this technique is the presence or absence of ectomycorrhizal (EM) sheaths on decomposing roots in the trenched plots. It has been suggested that the presence of EM associations with roots slows down decomposition (Langley et al. 2006) and the finer the EM roots, the slower the rate of decomposition (Aulen et al. 2011). The trenching method, by excluding live roots and their

associated EM hyphae, may have resulted in an unrealistic decomposition environment, in which demand for nutrients is reduced due to the lack of root uptake, and the absence of extracellular enzymes (e.g. proteases) released by EM fungi.

Despite its weaknesses, the trenched plot approach is a less intrusive method than using mesh bags, as root systems are relatively undisturbed and remain in their natural environment, without the effects of root removal, oven-drying, reintroduction and re-acclimatization to the soil environment, all of which result in changes to both the physical and chemical characteristics of root samples used in

decomposition bag experiments (Aulen et al. 2011). Because of this it was felt that the trenched plot derived decomposition rate-constant should have been more accurate, despite the greater cost of excavation in terms of effort and time. However, the results from this methodology proved less reliable than those from the decomposition bags, in that there was a higher variability associated with the k_0 rate-constant.

A check was carried out to test whether mean stump diameter was found to vary significantly between any of the excavation times. This was not the case, so it was concluded that there was no sampling bias introduced as a result of the random choice of stumps sampled at each time point. However, as the decomposition period was short in this study, relationships based on stump diameter largely reflect live-tree allometric relationships between stumps and roots (Tobin and Nieuwenhuis 2007), as stump surfaces were observed not to have deteriorated over the 4 years of the study.

C:N ratio and decomposition

The nutrient concentrations of roots are strongly related to their diameter (Vogt et al. 1991). In this study, N concentrations were root diameter (i.e. function) dependent with the highest levels in fine roots and the lowest in large roots. Nambiar (1987) reported a similar relationship between nutrient concentration and root diameter in *Pinus radiata*, while John et al. (2001) reported a decrease in N and P concentrations in *P. kesiya* roots with increasing diameter. The root diameter in this study accounted for 78 % of the variation in N concentration of the decomposing roots.

The N concentration decreased with time during the study, with a 28 %, 43 %, 21 % and 38 % reduction after 4 years in fine, small, medium and large roots, respectively. Chen et al. (2001) suggested three phases for N dynamics in decomposing roots: a decrease in the early stages, followed by an increase during the middle stages (a phase in which N immobilization is tightly coupled with the rate of microbial degradation (Benner et al. 1991)), and then a final extensive decline during the final stages of decomposition. The findings in the current study confirm the downward trend of N concentration during the early stages of decomposition, but the period of study was too short to test the second and third stages of this hypothesis. Some possible N loss pathways during the early stages of decomposition include fragmentation, absorption by mycorrhizae, leaching,

insect activity, and the growth of fungal sporocarps (Harmon et al. 1994).

The mean C concentration of the roots in this study was 47.24 ± 0.609 % and was not significantly different between the coarse root categories (small, medium and large), but there was a significant difference between the C concentration of coarse and fine roots. The mean C concentration in fine roots varied with time since harvest, but without a distinct pattern, and this was not observed in other diameter categories.

There was an increase in the C:N ratio of all root diameter categories as decomposition proceeded, especially in the large root category. It has been suggested that decomposition is faster at higher N concentrations, and slower at higher C:N ratios (Goebel et al. 2011). For instance, Mao et al. (2011) opined that a high N concentration and a low C:N ratio in poplar roots stimulated microbial growth and hence root decomposition, whereas pine roots with high C:N ratios had slow decomposition, due to the high amounts of structural woody materials, as well as low amounts of N available for decomposer organisms. The change in C:N ratio further supports the idea that the decomposition of organic materials may be limited by the availability of macronutrients, especially N, which is an important controller of the rate of decomposition (Ostertag and Hobbie 1999; Silver and Miya 2001; Weedon et al. 2009).

The findings of an earlier study (Olajuyigbe et al. 2011) showed that the C:N ratio eventually decreases in the later stages of decomposition due to N accumulation in roots and that the ratio is a good indicator of the state of decomposition. Furthermore, it highlighted an important correlation between change in chemical (C:N ratio) and physical (density) properties of roots as decomposition progressed. However, the scope of this study was too short to categorically demonstrate this point and link it to loss in root density and prove this conclusion using belowground material.

Mass loss from decomposition bags

The fraction of original mass remaining in the decomposition bags showed that the smaller the root, the faster the mass loss. Fine roots lost 29 % of their mass as compared to an 8 % mass loss in large roots. The mass loss from all root diameter categories (especially fine roots) was very low when compared to results from other studies (probably due to microclimatic conditions) (Teklay 2007). For example, in subtropical wet forest

ecosystems, Bloomfield et al. (1993) found 24 to 36 % mass loss from fine roots of *Dacryodes excelsa* Vahl. and *Prestoea montana* (R. Graham) Nichols. after six months, while Berg et al. (1998) reported first year mass losses ranging from 17 to 41 % for fine roots of three species (*P. abies*, *Pinus sylvestris* and *P. contorta*) across a climatic transect of coniferous forests in Northern Europe.

On a global scale, the combination of substrate quality, climate and environmental factors have the strongest influence on root decomposition (Silver and Miya 2001). In Ireland, high precipitation and low temperatures result in very wet, anaerobic soil conditions and this greatly influences the leaching, fragmentation and microbial colonisation of dead roots. These wet, cold conditions slow down the metabolic activities of decomposer organisms, especially during winter. The findings of a related study (Olajuyigbe et al. submitted) showed a significant drop in the CO₂ respired from decomposing logs resident on the same site during winter, when soil temperature was low and soil moisture was high.

The increase in decomposition rates with decreasing root diameter observed in the decomposition bag data corroborates the findings of similar studies (Chen et al. 2000; Silver and Miya 2001). The higher surface: volume ratios and the chemical composition of finer roots favour their exposure to macro- and microorganisms (Manlay et al. 2002). Some investigators have suggested that reduced mass loss from larger diameter roots in decomposition bags may be due to slower leaching rates of water-soluble compounds (Fahey and Arthur 1994), a longer time required for fungal hyphae penetration (Berg 1984), or higher proportions of resistant organic substances and structural mass (Fitter 1985). Large-diameter roots in decomposition bags are less susceptible to herbivory, mechanical damage and desiccation, compared to fine roots, and this is consistent with the general observation that root longevity increases with root diameter.

The roots were buried at two depths, but this had no significant influence on the decomposition rates, except for medium roots, resulting in two decomposition rate-constants for this category. The absence of a significant effect in the other diameter categories suggest that results are inconclusive regarding this effect and a further study would be required, perhaps involving roots buried at deeper depths than investigated here, though the depths investigated in this study were representative of this forest type.

Conclusion

Obtaining accurate estimates of belowground decomposition is constrained by the need to disturb the root system at some stage during sampling and this study was motivated by the idea that given the attendant uncertainty created by this disturbance, different potential approaches warranted investigation. The buried decomposition bag method resulted in a lower decomposition rate-constant ($0.07 \pm 0.005 \text{ year}^{-1}$) and might be preferable to the trenched plot approach ($0.24 \pm 0.068 \text{ year}^{-1}$) in terms of reliability. The estimated rate-constant obtained via the trench plot method was very high, when compared to rate-constants of other studies (Silver and Miya 2001). The large difference between decomposition rate-constants resulting from the two methods may be partly due to an inability to determine the initial mass of the roots in the trenched plots, an altered rhizosphere environment and EM presence as well as sampling error. On the other hand, the altered state of the root samples used in the decomposition bag experiment, the barrier created by the mesh bags, as well as the disruption of the rhizosphere into which they were introduced, changed the natural phenology of root death and decomposition and may have slowed the initial decomposition rate-constant. Hence, the methodology adopted will significantly influence the decomposition rate-constant obtained.

Acknowledgements This research was funded by the National Council for Forest Research and Development (COFORD) as part of the CARB/FOR II project. Thanks to Coillte Teoranta for granting permission to conduct the research in their forest. We are grateful to the entire CARB/FOR II project team and other colleagues who assisted with the manual excavations and sorting of root samples. We also would like to thank the staff of the Department of Forest Sciences, University of Helsinki, for assistance in conducting the C:N analysis in their laboratory. Finally, we thank Dr. Alfonso Escudero (Section Editor) and the independent reviewers for their constructive suggestions which helped to improve the manuscript.

References

- Aulen M, Shipley B, Bradley R (2011) Prediction of in situ root decomposition rates in an interspecific context from chemical and morphological traits. *Ann Bot* 109(1):287–297
- Beets PN, Hood IA, Kimberley MO, Oliver GR, Pearce SH, Gardner JF (2008) Coarse woody debris decay rates for seven indigenous tree species in the central North Island of New Zealand. *For Ecol Manage* 256:548–557

- Benner R, Fogel ML, Sprague EK (1991) Diagenesis of below-ground biomass of *Spartina alterniflora* in salt-marsh sediments. *Limnol Oceanogr* 36:1358–1374
- Berg B (1984) Decomposition of root litter and some factors regulating the process: long-term root litter decomposition in a Scots pine forest. *Soil Biol Biochem* 16:609–617
- Berg B, Johansson MB, Meentemeyer V, Kratz W (1998) Decomposition of tree root litter in a climatic transect of coniferous forests in northern Europe: a synthesis. *Scand J Forest Res* 13:402–412
- Black KG, Farrell EP (2006) Carbon sequestration and Irish forest ecosystems. COFORD, Dublin, pp 75–76
- Black K, Byrne KA, Mencuccini M, Tobin B, Nieuwenhuis M, Reidy B, Bolger T, Saiz G, Green C, Farrell ET, Osborne B (2009) Carbon stock and stock changes across a Sitka spruce chronosequence on surface-water gley soils. *Forestry* 82:255–272
- Bloomfield J, Vogt KA, Vogt DJ (1993) Decay rate and substrate quality of fine roots and foliage of two tropical tree species in the Luquillo Experimental Forest, Puerto Rico. *Plant Soil* 150:233–245
- Chen H, Harmon ME, Griffiths RP, Hicks W (2000) Effects of temperature and moisture on carbon respired from decomposing woody roots. *For Ecol Manage* 138:51–64
- Chen H, Harmon ME, Griffiths RP (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
- Coutts MP (1983) Development of the structural root system of Sitka spruce. *Forestry* 56:1–16
- Coutts MP, Nielsen CCN, Nicoll BC (1999) The development of symmetry, rigidity and anchorage in the structural root system of conifers. *Plant Soil* 217:1–15
- Creed IF, Webster KL, Morrison DL (2004) A comparison of techniques for measuring density and concentrations of carbon and nitrogen in coarse woody debris at different stages of decay. *Can J For Res* 34:744–753
- Fahey TJ, Arthur MA (1994) Further studies of root decomposition following harvest of a Northern hardwoods forest. *Forest Sci* 40:618–629
- Fitter AH (1985) Functioning of vesicular-arbuscular mycorrhizas under field conditions. *New Phytol* 99:257–265
- Forest Service (2008) Afforestation statistics. Forest Service, Department of Agriculture, Fisheries and Food, Johnstown Castle Estate, Co. Wexford
- Goebel M, Hobbie SE, Bartosz B, Zadworny M, Archibald DD, Oleksyn J, Reich PB, Eissenstat DM (2011) Decomposition of the finest root branching orders: linking below-ground dynamics to fine-root function and structure. *Ecol Monogr* 81:89–102
- Green C, Tobin B, O'Shea M, Farrell EP, Byrne KA (2007) Above- and belowground biomass measurements in an unthinned stand of Sitka spruce (*Picea sitchensis* (Bong) Carr.). *Eur J Forest Res* 126:179–188
- Harmon ME, Sexton J, Caldwell BA, Carpenter SE (1994) Fungal sporocarp mediated losses of Ca, Fe, K, Mg, Mn, N, P, and Zn from conifer logs in the early stages of decomposition. *Can J For Res* 24:1883–1893
- Hobbie SE, Oleksyn J, Eissenstat DM, Reich PB (2010) Fine root decomposition rates do not mirror those of leaf litter among temperate tree species. *Oecologia* 162:505–513
- John B, Pandey HN, Tripathi RS (2001) Vertical distribution and seasonal changes of fine and coarse root mass in *Pinus kesiya* Royle Ex. Gordon forest of three different ages. *Acta Oecol* 22:293–300
- John B, Pandey HN, Tripathi RS (2002) Decomposition of fine roots of *Pinus kesiya* and turnover of organic matter, N and P of coarse and fine pine roots and herbaceous roots and rhizomes in subtropical pine forest stands of different ages. *Biol Fert Soils* 35:238–246
- Johnsen K, Maier C, Kress L (2005) Quantifying root lateral distribution and turnover using pine trees with a distinct stable carbon isotope signature. *Funct Ecol* 19:81–87
- Jonsson MT, Jonsson BG (2007) Assessing coarse woody debris in Swedish woodland key habitats: implications for conservation and management. *For Ecol Manage* 242:363–373
- Keplin B, Hüttl RF (2001) Decomposition of root litter in *Pinus sylvestris* L. and *Pinus nigra* stands on carboniferous substrates in the Lusatian lignite mining district. *Ecol Eng* 17:285–296
- Knorr M, Frey SD, Curtis PS (2005) Nitrogen additions and litter decomposition: a meta-analysis. *Ecology* 86:3252–3257
- Laclau P (2003) Biomass and carbon sequestration of *ponderosa* pine plantations and native cypress forests in northwest Patagonia. *For Ecol Manage* 180:317–333
- Laiho R, Finér L (1996) Changes in root biomass after water-level drawdown on pine mires in southern Finland. *Scand J Forest Res* 11:251–260
- Langley JA, Chapman SK, Hungate BA (2006) Ectomycorrhizae colonization slows root decomposition: the post-mortem fungal legacy. *Ecol Lett* 9:955–959
- Lin C, Yusheng Y, Guo J, Chen G, Xie J (2010) Fine root decomposition of evergreen broadleaved and coniferous tree species in mid-subtropical China: dynamics of dry mass, nutrient and organic fractions. *Plant Soil* 338:311–327
- Ludovici KH, Zarnoch SJ, Richter DD (2002) Modeling in-situ pine root decomposition using data from a 60-year chronosequence. *Can J For Res* 32:1675–1684
- Manlay RJ, Kairé M, Masse D, Chotte J-L, Ciornei G, Floret C (2002) Carbon, nitrogen and phosphorus allocation in agro-ecosystems of a West African savanna: I. The plant component under semi-permanent cultivation. *Agr Ecosyst Environ* 88:215–232
- Manlay RJ, Masse D, Chevallier T, Russell-Smith A, Friot D, Feller C (2004) Post-fallow decomposition of woody roots in the West African savanna. *Plant Soil* 260:123–136
- Mao R, Zeng D-H, Li L-J (2011) Fresh root decomposition pattern of two contrasting tree species from temperate agroforestry systems: effects of root diameter and nitrogen enrichment of soil. *Plant Soil* 347(1–2):115–124
- Melin Y, Petersson H, Nordfjell T (2009) Decomposition of stump and root systems of Norway spruce in Sweden—a modelling approach. *For Ecol Manage* 257:1445–1451
- Misra RK, Turnbull CRA, Cromer RN, Gibbons AK, LaSala AV (1998) Below- and above-ground growth of *Eucalyptus nitens* in a young plantation: I. Biomass. *For Ecol Manage* 106:283–293
- Nambiar EKS (1987) Do nutrients retranslocate from fine roots? *Can J For Res* 17:913–918
- Nicoll BC, Ray D (1996) Adaptive growth of tree root systems in response to wind action and site conditions. *Tree Physiol* 16:899–904

- Nicoll BC, Berthier S, Achim A, Gouskou K, Danjon F, van Beek LPH (2006) The architecture of *Picea sitchensis* structural root systems on horizontal and sloping terrain. *Tree Physiol* 20:701–712
- Nieuwenhuis M, Wills JM (2002) The effect of cultivation technique on root architecture of young Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees on surface water gleys. *New Forest* 24:195–213
- Nieuwenhuis M, Wills J, Gardiner J, Sundstrom E, Keane M (2003) The effect of soil cultivation methods on rooting depth of young Sitka spruce (*Picea sitchensis* (Bong.) Carr.) trees on wet mineral soils in Ireland. *Forestry* 76:466–477
- Olajuyigbe SO, Tobin B, Gardiner P, Nieuwenhuis M (2011) Stocks and decay dynamics of above- and belowground coarse woody debris in managed Sitka spruce forests in Ireland. *For Ecol Manage* 262:1109–1118
- Olajuyigbe SO, Tobin B, Saunders M, Nieuwenhuis M (2012) Forest thinning and soil respiration in a managed Sitka spruce forest in Ireland. *Agr Forest Meteorol* 157:86–95
- Olson JS (1963) Energy storage and the balance of producers and decomposers in ecological systems. *Ecology* 44:322–331
- Ostertag R, Hobbie SE (1999) Early stages of root and leaf decomposition in Hawaiian forests: effects of nutrient availability. *Oecologia* 121:564–573
- Palviainen M, Finér L, Laiho R, Shorohova E, Kapista E, Vanha-Majamaa I (2010) Carbon and nitrogen release from decomposing Scots pine, Norway spruce and Silver birch stumps. *For Ecol Manage* 259:390–398
- Petersson H, Melin Y (2010) Estimating the biomass and carbon pool of stump systems at a national scale. *For Ecol Manage* 260:466–471
- Ray D, Nicoll BC (1998) The effect of soil water-table depth on root-plate development and stability of Sitka spruce. *Forestry* 71:169–182
- Resh SC, Battaglia M, Worledge D, Ladiges S (2003) Coarse root biomass for eucalypt plantations in Tasmania, Australia: sources of variation and methods for assessment. *Trees-Struct Funct* 17:389–399
- Saiz G, Black K, Reidy B, Lopez S, Farrell EP (2007) Assessment of soil CO₂ efflux and its components using a process-based model in a young temperate forest site. *Geoderma* 139:79–89
- Sayer EJ, Tanner LH (2010) A new approach to trenching experiments for measuring root-rhizosphere respiration in a lowland tropical forest. *Soil Biol Biochem* 42:347–352
- Shorohova E, Kapista E, Vanha-Majamaa I (2008) Decomposition of stumps in a chronosequence after clear-felling vs. clear-felling with prescribed burning in a southern boreal forest in Finland. *For Ecol Manage* 255:3606–3612
- Silver WE, Miya RK (2001) Global patterns in root decomposition: comparisons of climate and litter quality effects. *Oecologia* 129:407–419
- Silver WL, Vogt KA (1993) Fine root dynamics following single and multiple disturbances in a subtropical wet forest ecosystem. *J Ecol* 81:729–738
- Silver WL, Neff J, McGroddy M, Veldkamp E, Keller M, Cosme R (2000) Effects of soil texture on belowground carbon and nutrient storage in a lowland Amazonian forest ecosystem. *Ecosystems* 3:193–209
- Soethe N, Lehmann J, Engels C (2007) Carbon and nutrient stocks in roots of forests at different altitudes in the Ecuadorian Andes. *J Trop Ecol* 23:319–328
- Subke J-A, Inglima I, Cotrufo FM (2006) Trends and methodological impacts in soil CO₂ efflux partitioning: a meta-analytical review. *Glob Change Biol* 12:921–943
- Teklay T (2007) Decomposition and nutrient release from pruning residues of two indigenous agroforestry species during the wet and dry seasons. *Nutr Cycl Agroecosys* 77:115–126
- Tobin B, Nieuwenhuis M (2007) Biomass expansion factors for Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Ireland. *Eur J Forest Res* 126:189–196
- Tobin B, Black K, McGurdy L, Nieuwenhuis M (2007a) Estimates of decay rates of components of coarse woody debris in thinned Sitka spruce forests. *Forestry* 80:455–469
- Tobin B, Čermák J, Chiatante D, Danjon F, Di Iorio A, Dupuy L, Eshel A, Jourdan C, Kalliokoski T, Laiho R, Nadezhdina N, Nicoll B, Pagès L, Silva J, Spanos I (2007b) Towards developmental modelling of tree root systems. *Plant Biosyst* 141:481–501
- Vogt KA, Vogt DJ, Bloomfield J (1991) Input of organic matter to the soil by tree root. In: McMichael BL, Persson H (eds) *Plant roots and their environment*. Elsevier, Amsterdam, pp 171–190
- Weedon JT, Cornwell WK, Cornelissen JHC, Zanne AE, Wirth C, Coomes DA (2009) Global meta-analysis of wood decomposition rates: a role for trait variation among tree species? *Ecol Lett* 12:45–56
- Wills J, Sundstrom E, Nieuwenhuis M, Keane M (2001) The impact of soil preparation method on water-table depth in Irish forest plantations on wet mineral soils. *Ir For* 58:46–58
- Yang F-F, Li Y-L, Zhou G-Y, Wenigmann KO, Zhang D-Q, Wenigmann M, Liu S-Z, Zhang Q-M (2010) Dynamics of coarse woody debris and decomposition rates in an old-growth forest in lower tropical China. *For Ecol Manage* 259:1666–1672
- Zeng D-H, Mao R, Chang SX, Li L-J, Yang D (2010) Carbon mineralization of tree leaf litter and crop residues from poplar-based agroforestry systems in Northeast China: a laboratory study. *Appl Soil Ecol* 44:133–137