Citation for the published paper:
Melin, Ylva; Petersson, Hans & Nordfjell, Tomas. (2009) Decomposition of stump and root systems of Norway spruce in Sweden : a modeling approach. *Forest Ecology and Management*. 257: 5, 1445-1451.
ISSN 0378-1127.
http://dx.doi.org/10.1016/j.foreco.2008.12.020

Title

Decomposition of stump and root systems of Norway spruce in Sweden – A modelling approach

Abstract

The demand for quantifying the biomass of stumps and roots and the carbon stored therein is related to aspects of biodiversity, site productivity, atmospheric carbon cycling issues, and the demand for bioenergy. This, in turn, creates a need to develop high-quality tools for estimating biomass and carbon-equivalents in the ground. The objective of this study was to develop decomposition functions for quantifying the remaining dry weight of the biomass of individual stumps and their associated roots in Norway spruce (*Picea abies* (L.) Karst.). The negative exponential model was chosen for this purpose, combined with a chronosequence approach, involving 99 stumps and their roots from three sites in Sweden. The results showed a relative decay rate of 4.6 % annually for stump and root systems. Based on this rate, the time required for the loss of 50 % ($t_{0.5}$) and 95 % ($t_{0.95}$) of the wood is 15 and 64 years, respectively. Although there are many variables that affect decomposition, residual studies indicated that the remaining biomass could be predicted fairly accurately on the basis of the independent variables stump diameter and time.

1. Introduction

1.1 General

Dead wood is important for the maintenance of biodiversity in forests (Jonsson et al., 2005). Furthermore, stumps are essential habitats for certain lichens and bryophytes (Rudolphi, 2007; Caruso, 2008). Soil organic carbon has an important role in site productivity because of its effects on bulk density, water holding capacity, microbial populations and cation-exchange capacity (Johnson, 1993). The proportion biomass below a potential stump cut constitutes a major pool of organic matter, and this pool accounts for approximately 20 % of the total living tree biomass (Hakkila, 1989). There are strong forces driving the change from energy derived from fossil fuels to more carbon neutral energy sources, such as forest fuels (European Commission, 1997). There are also economic incentives for having carbon stored in sinks, although the more rapidly CO_2 returns to the atmosphere through natural decomposition, the greater the incentives for using stumps and roots as forest fuel. However, if decomposition occurs slowly, stumps might be more valuable as a carbon sink than as fuel. Many variables affect microbial activity in the decomposition process, including temperature, moisture and substrate quality (Mackensen and Bauhus, 1999). Other factors that affect the decay rate of woody debris are the ratio of bark to wood (Fahey et al., 1988), proportion sapwood and heartwood and tree species (cf. Harmon et al., 2000). Slope aspect (Harmon et al., 1986), log diameter (MacMillan, 1988), and contact with the forest floor do also influence on the decay rate (Hytteborn and Packham, 1987; Ganjegunte et al., 2004). Most studies examining the decomposition of coarse woody debris of Norway spruce have concentrated on the above-ground biomass (Krankina and Harmon, 1995; Naesset, 1999;

Harmon et al., 2000; Shorohova et al., 2008) (Table 1); the decomposition process of below-ground biomass in coarse roots has been less thoroughly investigated.

1.2 Different field work approaches for estimating the decomposition rate

Most studies on the decomposition of dead wood have not extended over a long period of time and only few long-term studies have been undertaken (Hofgaard, 1993; Brown et al., 1996). It is, therefore, common practice to take samples with a range of known ages, or of different age classes, and to establish a chronosequence, rather than conducting a prolonged, time-series study (cf. Harmon et al. 2000) (Table 1).

With the aim of monitoring the remaining dead biomass, many studies base their estimates of decay rate on measurements of density (Krankina and Harmon, 1995; Naesset, 1999; Harmon et al., 2000; Chen et al., 2001; Yatskov et al., 2003; Mackensen and Bauhus, 2003a; Janisch et al., 2005; Shorohova et al., 2008) (Table 1). To convert from this measured density to the remaining biomass, estimates of volume are required. However, in general, it is not simple to determine the volume of severely decayed samples. One way of overcoming this problem is to base estimates on the direct measurement of dry weight. Only a few studies have taken this approach (e.g. Harmon et al., 2000).

Table 1
Relative decomposition rates for different components of Norway spruce. All studies used a decomposition model based on the single-exponential approach.

Components	Dependent variables	Method	Age of oldest sample, years	Annual decomposition rate	Location	References
Stumps	Density	Chronosequence	40	0.052	Finland	(Shorohova et al., 2008)
Logs, snags and stumps	Density	Chronosequence	60	0.034	NW Russia	(Krankina and Harmon, 1995)
Logs and snags	Biomass	One-time regression analysis [a]	54[b]	0.033	NW Russia	(Harmon et al., 2000)
Logs and snags	Biomass	Chronosequence	54 [b]	0.048	NW Russia	(Harmon et al., 2000)
Logs and snags	Biomass	Vector method [c]	54 [b]	0.067	NW Russia	(Harmon et al., 2000)
Logs and snags	Density	One-time regression analysis [a]	54 [b]	0.027	NW Russia	(Harmon et al., 2000)
Logs and snags	Density	Chronosequence	54 [b]	0.038	NW Russia	(Harmon et al., 2000)
Logs and snags	Density	Vector method [c]	54 [b]	0.037	NW Russia	(Harmon et al., 2000)
Logs	Biomass	Chronosequence	Not available	0.032	Russia	(Yatskov et al., 2003)
Logs	Density	Chronosequence	32	0.028-0.041[d] 0.033 [e]	SE Norway	(Naesset, 1999)

[a] Time series approach
[b] Mean age of six decomposed Norway spruce trees
[c] Hybrid of time-series and chronosequence
[d] The lower rate for diameters 7–10 cm, the higher rate for diameters > 25 cm
[e] The rate is the average for all cross-sections sampled.

1.3 Decomposition models

A robust model is required in order to make accurate predictions about decomposition and there are some options. The negative exponential model (can also be called an exponential decay model or a single-exponential model) of time is based on the assumption that the decomposition rate is proportional to the amount of remaining litter

(Olson, 1963). This model is the one most commonly used to estimate the decline in density of logs and coarse woody debris (Harmon et al., 1987; Naesset, 1999; Mackensen and Bauhus, 2003a; Mackensen et al., 2003b; Ganjegunte et al., 2004; Chen et al., 2005). Mäkinen et al. (2006) showed, however, that decomposition is not always correlated with the amount of substrate remaining and used the Gompertz and Chapman-Richard function to fit their data. The multiple-exponential model takes account of the fact that the substrate is not homogeneous, and that different components might decompose at different rates (Mackensen and Bauhus, 2003a). Both the negative and the multiple-exponential models assume that detritus is not transformed into more or less decomposable forms and this is a shortcoming (Harmon et al., 1986). The lag-time model is based on the observation that decay is slow during the initial stage of decomposition until decomposers have become established within the substrate (Harmon et al., 1986). The choice of independent variables in deterministic models is restricted to easily measured and robust variables. Usually when using such models, the remaining biomass is modeled by a variable correlated to the initial size of the stump system, time since death and species (e.g. Krankina and Harmon, 1995; Naesset, 1999; Harmon et al., 2000; Yatskov et al., 2003; Shorohova et al., 2008).

1.4 Objective

The objective of this study was to develop decomposition functions for quantifying the remaining biomass of individual stumps and their associated roots; the target species was Norway spruce (*Picea abies* (L.) Karst.).

2. Material and methods

2.1 General approach

To obtain a spatially representative sample, Norway spruce (*Picea abies* (L.) Karst.) stumps with roots from southern and northern Sweden were sampled. Fresh stumps with roots used previously in a study by Petersson and Ståhl (2006) were used to complement the dataset. The influence on the model of the variables ‘years since cutting’, ‘decomposition class’ and ‘diameter range’ (20–50 cm) was studied. To model decomposition, stumps with roots were manually excavated 0–39 years after clear cutting. To determine the relative decomposition rate, the biomass of the decomposed stumps and roots was related to the corresponding biomass of fresh ones inventoried by Petersson and Ståhl (2006) (Table 4). After felling, Norway spruce does not resprout from the stump, unlike many deciduous trees. Therefore, the decomposition process is considered to start during the same season as felling.

2.2 Dataset of decomposed stumps with roots

2.2.1 Study areas

The northern samples were collected in the county of Västerbotten (71°33´N; 16°93´E), in the vicinity of the Vindeln research station; this area has an annual precipitation of 591 mm and mean annual temperature of 1.5 °C (Alexandersson and Eggertsson, 2001). The southern samples were sampled in the county of Småland (63°38´N; 14°37´E) in the vicinity of the Asa research area; here the annual precipitation is 687 mm and the mean annual temperature is 6.1 °C (Alexandersson and Eggertsson, 2001) (Fig. 1). In total, 71 stumps with roots were collected from 18 subjectively selected stands: nine in the north and nine in the south. The cross callipered mean diameter within each age group of stumps was 19.7–43.7 cm (Table 4). No stump was higher than 0.5 m. The average elevation of the northern stands was 273 m.a.s.l and the corresponding elevation of the southern stands was 260 m.a.s.l. The latitudinal distance between the locations was 1400 km.

At both locations, stands were subjectively selected on the basis of the following criteria: i) the soil class should be sandy to gravel moraine; ii) before cutting, if possible, Norway spruce should have been the dominant species (basal weighted area at breast height); and iii) the variation in time since cutting should be equally spread over 1–39 years. The time elapsed since cutting was determined from compartment registers kept by the Vindeln and Asa research stations.

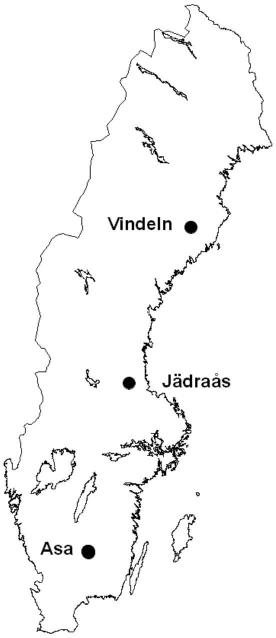

Fig. 1. Map of Sweden. Fresh and decomposed stumps with roots were collected close to the Vindeln and Asa research stations. Only fresh stumps with root systems were collected near the Jädraås research station.

2.2.2 Sampling of stumps with roots within stands

Within each surveyed stand, two single starting points were selected subjectively by two field teams consisting of two persons each. From these points, a search direction was randomly selected; moving in this direction, the first Norway spruce stump found that had a perpendicular stump diameter of 20 to 50 cm, was sampled. Within each stand, up to eight samples were collected with the restriction that sampled stumps should be at least 20 m apart.

2.2.3 Field work

For each sampled *stump*, the geographical position of the pith was determined using a GPS (Garmin 12) based on the RT 90 datum. The diameter (over bark if this was present) was measured with a calliper across the major and minor axes of the cross-section. The decay class of each stump was based on the decay class system of the Swedish NFI (Table 2). The decay class was defined as the dominant decay class from several measurements, determined with a knife at points located systematically around the stump.

Table 2
Decomposition classes according to the Swedish National Forest Inventory (SLU, 1994)

Decomposition class	Wood properties
0	Raw wood. Trees that died recently, not yet dried up.
1	Solid dead wood. The volume of the stem consists of more than 90 % solid wood and the stem has a hard exterior surface. The wood is only slightly affected by wood-decaying organisms.
2	Somewhat decayed wood. The volume of the stem consists of 10–25 % soft wood. The remaining wood is solid.
3	Decayed dead wood. The volume of the stem consists of 26-75 % soft or very soft wood.
4	Very decayed dead wood. The volume of the stem consists of 76-100 % soft or very soft wood. A tool can be pressed through the stem. However, a solid core may be present.

The cross-sectional area of the top of each sampled stump was subsequently divided into four sectors based on the cardinal points (north-south and east-west directions originating from the pith); one of the sectors was sampled at a probability proportional to cross-section area per sector. The sampled sector was sawed out and removed from the remaining stump using a chain saw or knife, depending on how decomposed the stump was. Sapwood and heartwood were not subdivided. The stump section was then transferred to the laboratory.

The *roots* originating from the sampled stump section were carefully revealed and the diameter of the base of each root was measured (minor and major axis, over bark if it was present). One root, with all laterals attached to it, was randomly selected, excavated with hand tools and traced into the ground down to a diameter of approximately 1 cm. Hand tools were used to remove the soil around the roots and the excavated root was removed from the stump using a chain saw or a handsaw, depending on the diameter and the stage of decomposition. All roots that had been attached to the stump were assumed to be in the same decomposition class as the stump. For practical reasons, vertical roots attached directly beneath the stump could not be excavated, so were not sampled. Finally, root samples were transferred to the laboratory for further analysis.

2.3 Analysis

In the laboratory, the stump and root samples were sawn into smaller pieces, in order to standardize the time required for drying to constant weight. Drying was at 85° C and lasted to constant weight and at least 48 h; samples were then weighed using a Mettler PE 4000 electronic balance [0.1g].

To calculate the total biomass of the stump and root systems, the dry weight and cross-section area of the sampled stump-sector were measured. The dry weight of each non-sampled stump-sector was assumed to be proportional to its measured cross-section area. The total dry weight of each stump was defined as the sum of the measured or calculated dry weights of all four sectors.

To estimate the dry weight of the remaining roots, which were not sampled and for which only diameter was measured, simple regression functions, one per decomposition class, were developed based on the sampled and excavated roots (Table 3).

Table 3
Dry weight functions (DWr, [g]) per decomposition class for roots for which only diameter was measured (d, [cm]).

Decomposition class*	Root functions	R^2	RMSE
1	DWr = 567,6d – 3819	0,5456	4504
2	DWr = 496,2d – 2938	0,6227	3408
3	DWr = 350,1d – 2278	0,5996	1674
4	DWr = 348,0d – 2893	0,7237	1754

*See Table 2 for explanation

The diameter over bark at the cut (i.e. where the root was attached to the stump) was used as the independent variable in these functions. The simple additive model was assumed to be approximately linear and neither transformations of the dependent nor the independent variables seemed to improve the goodness of fit much. After applying the simple functions to roots for which only diameter was measured, the total dry weight of roots per sector was calculated. This dry weight of roots was assumed to be proportional to the corresponding measured stump cross-section area, and thus, the dry weight of roots for the non-sampled sectors was estimated by weighting the measured stump cross-section area by the dry weight of roots from the sampled sector. The total dry weight of roots was defined as the sum of the measured and calculated dry weights from all four sectors (Table 4).

Table 4
Summary statistics relating to fresh and decomposed Norway spruce stump and root systems; in total 99 stumps with root systems were used as observations in the models.

Location	Year since clear cut	Number of stump and root systems	Mean diameter of stump at stump height [cm]	Mean decay class of stumps	Mean base diameter of roots [cm]	Mean Dry Weight, Stump and root systems [g]
Vindeln (north)	0	6[a]	11.6	1.0	-	9590
	1	3[b]	32.8	1.0	15.4	52499
	7	3[b]	26.4	1.0	17.8	32736
	9	5[b]	33.0	1.2	16.6	36923
	13	7[b]	37.6	2.0	17.6	49169
	19	6[b]	32.7	2.6	14.7	20103
	26	7[b]	25.0	3.4	11.0	12579
	32	3[b]	25.6	4.0	12.2	11564
	34	8[b]	25.6	4.0	10.6	6742
Jädraås (central)	0	6[a]	16.1	1.0	-	12266
Asa (south)	0	16[a]	23.8	1.0	-	62148
	1	2[b]	39.7	1.0	14.7	52967
	5	6[b]	43.7	1.0	16.6	99806
	9	1[c]	32.9	2.0	11.5	19292
	13	3[b]	32.7	2.6	15.2	19489
	14	3[b]	32.5	2.6	23.1	37240
	17	1[c]	19.7	3.0	12.0	9798
	18	1[c]	31.7	3.0	14.7	20115
	27	6[b]	36.8	4.0	18.2	27233
	34	1[b]	30.5	4.0	34.4	68673
	35	3[b]	31.8	4.0	11.3	5632
	38	1[c]	33.7	4.0	14.4	12139
	39	1[c]	27.9	4.0	14.5	7540

- Information not available

[a] Fresh stump and root systems inventoried in 2002 (Petersson and Ståhl, 2006)

[b] Decomposed stump and root systems sampled in 2003

[c] Decomposed stump and root systems sampled in 2007

2.4 Dataset of fresh stump and root systems

Petersson and Ståhl (2006) developed functions for estimating the below-ground biomass of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*) and Birch (*Betula pubescens, Betula pendula*) in Sweden. In the present study, the Norway spruces inventoried by Petersson and Ståhl (2006) (in total 28 stump and root systems) were used to represent the dry weight of fresh stump and root systems down to a minimum root diameter of about 2 mm.

The fresh stumps and roots, from the data set of Peterson and Ståhl (2006), were sampled from the same locations as the decomposed ones, with the exception of six stumps from Jädraås, central Sweden. The annual precipitation in Jädraås (67°45´N; 15°38´E, about 206 m.a.s.l) is 598 mm and the mean annual temperature 3.4 °C (Alexandersson and Eggertsson, 2001) (Fig. 1). The soil classes on which the subjectively selected stands were growing were sandy to gravel moraine (22 stump and roots systems) and peat (six stump and root systems).

2.5 Selection of the decomposition model

The remaining dry weight was modeled by the negative exponential model using stump-diameter and the number of years since cutting as independent variables (Formula (1)). However, diameter measurements for individual stumps are not always available; in this case it might be convenient to develop a stump size independent decomposition model. For this purpose, a crude model using only the number of years since cutting was developed. Such a model could be obtained by dividing the stump size dependent decomposition model for decomposed stumps and root systems by the corresponding one of fresh stump and root systems (Formula (3)). This division does not only factor out two parameters and the independent variable stump-diameter, but also makes the complementing decomposition model relative. Compared to the original absolute model, the relative decomposition model might be applied on, for example, both the individual level and stand level data. One prerequisite for using this type of relative decomposition model is that the relative decomposition rate must be more-or-less independent of stump size. To complement the stump size-dependent decomposition model (Formula (1)), a relative decomposition model was developed (Formula (3)) and the necessary independence from stump size was evaluated by examining the residuals. The goodness of fit of the model was analyzed from estimates of the coefficient of determination (R^2), the root mean square error (RMSE) and the residual studies. Parameter estimates were evaluated using standard t-tests. Statistical analyses were conducted using the Statistical Analysis Software (SAS Institute Inc. 2004).

3. Results

3.1 Function

To estimate the dry weight of decomposed stump and root systems (DW_t, [g]), the following model was employed:

$$DW_t = \beta_0 \times dia^{\beta 1} \times e^{\beta 2t} \times \varepsilon, \qquad \text{Formula [1]}$$

where dia is the stump-diameter [cm], t is the number of years since cutting, and β_0, β_1 and β_2 are parameters. Finally, ε was an assumed normally distributed random variable with constant variance. For linearization, the model was transformed by the natural logarithm:

$$\ln DW_t = \ln\beta_0 + \beta_1 \ln dia + \beta_2 t + \ln\varepsilon \qquad \text{Formula [2]}$$

Retransformation of Formula [2] and assuming that decomposition was independent of diameter, produced the model:

$$DW_t / DW_0 = e^{\beta_2 t} \qquad \text{Formula [3]}$$

where DW_0 is the dry weight of fresh stump and root systems. Formula [3] represents the relative decomposition function. Parameter estimates for Formula [2] (not corrected for logarithmic bias) and test quantities are presented in Table 5.

Table 5

Parameter estimates and test quantities for the stump and root system decomposition function (Norway spruce)

Parameter	Parameter estimate	t-test	RMSE	R^2
β_0	2.7443	6.17	0.6389	0.7542
β_1	2.3064	16.60		
β_2	-0.0460	-8.89		

Note: RMSE = root mean square error. R^2 = coefficient of determination

To study whether the relative decomposition rate was more-or-less independent of stump size, residuals were plotted by stump size. No clear trend was found (Fig. 2a). Neither time since cutting, nor decomposition class showed distinct trends when plotted against the residuals (Fig. 2 b and 2c). The residuals suggest that there is high within-location variability (Fig. 2d).

4. Discussion

The decomposition model is developed and intended for stumps with attached roots. The fact that stumps and roots may decompose differently cannot be eliminated and therefore, it is recommended to model the two components separately.

The negative exponential model is the most common approach for determining the decomposition of wood. However, one limitation should be noted: it takes no account of the fact that decomposition rate may vary during the decomposition process, and thus a multi-exponential function may be more suitable, as proposed by Mackensen and Bauhus (2003a). The residuals plotted against year since cutting do not indicate the need for including a lag phase in the model (the time for microbes to colonize the substrate) (Fig. 2b). Similarly, the residuals by decomposition class do not indicate the need for separate functions for modelling heartwood and sapwood (Fig. 2c).

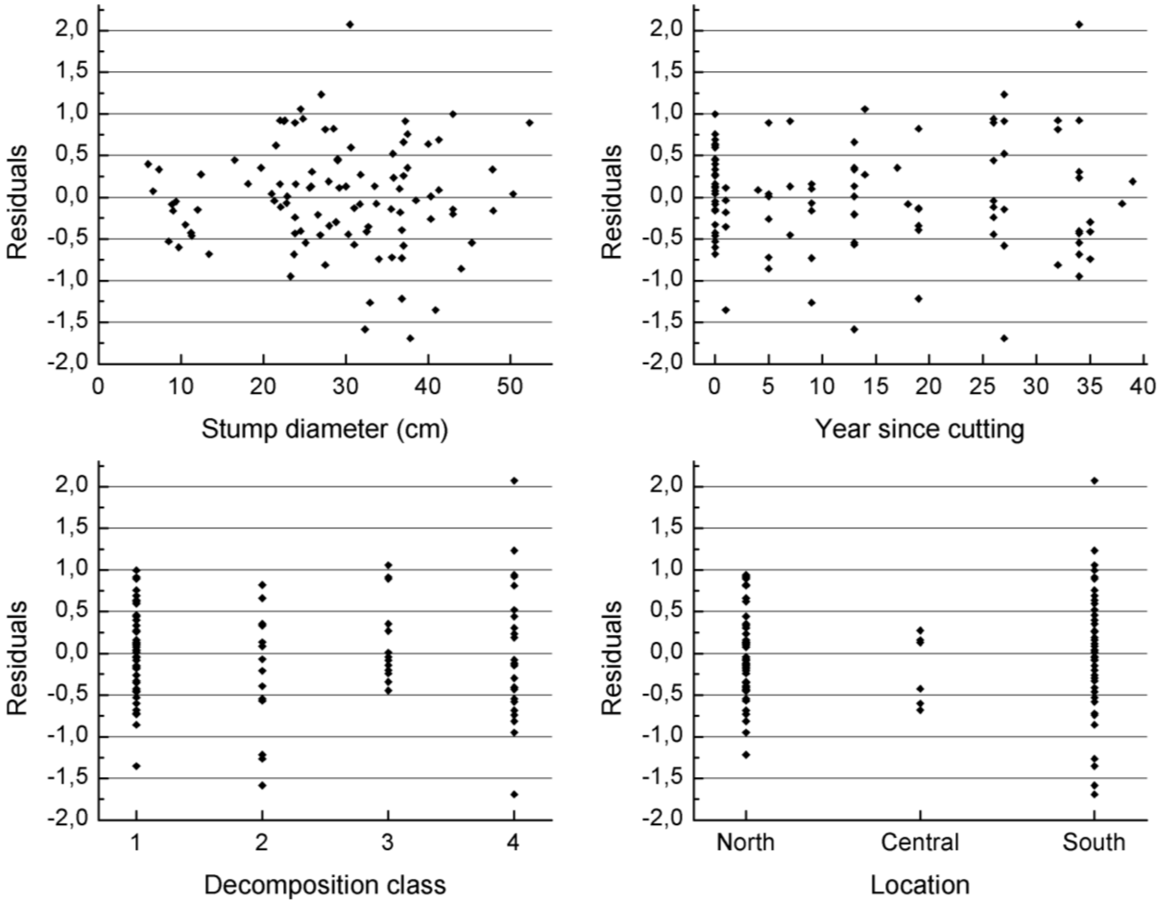

Fig. 2. Residuals from the relative decomposition model plotted against: a) stump diameter; b) year since cutting; c) decomposition class; and d) location.

To study the biomass remaining in stump and root systems, direct measurements of total dry weight of samples were used rather than combined estimates of volume and density. This method was chosen mainly from reasons of accuracy. In a pilot study separate estimates of volume and density indicated a lower accuracy, mainly originating from problems associated with measuring volume, than achieved with direct measurements of dry weight of biomass.

The decayed stump and root systems represent clear-felled areas and only two locations. However, within locations, several conditions and types of stands and sites were represented. The independent variables selected for the functions were limited to stump diameter and time. At least within the range of stump sizes studied, the relative decomposition rate was more-or-less independent of stump size. However, this does not prove that no such dependence exists. The magnitude of this dependence is probably too small to be reflected in the model and the residual studies of diameter indicated only a slight cone shape (Fig. 2a). This distribution of the data may have a natural explanation because stumps with a small diameter cannot vary as much as larger stumps. Previous studies have produced different results. Naesset (1999) and MacMillan (1988) showed that Norway spruce logs with a greater diameter had a significantly higher decomposition rate than logs with smaller diameters. However, Brown et al. (1996) encountered a faster decay rate for small logs than for large logs. Residual studies relating to location indicate greater within-location variation than that between the two locations (Asa and Vindeln) (Fig. 2d). Decomposition class was also examined using residual studies and no trend was found (Fig. 2c). Although there are many variables that affect decomposition, it was possible to predict the remaining biomass quite accurately using just the independent variables stump diameter and time.

In the sampling design, one key concern is associated with the sample of older decomposed material in the field; this is an issue in many chronosequences. Stumps that have been resistant to decomposition are most likely to be found and more susceptible stumps will tend to be overlooked. This might lead to an underestimate of the decomposition rate since a lower proportion of highly decomposed stumps will have been found and included in the sample. We assumed that our selected stumps constituted a random sample of all the original stumps, and thus assumed that traces of stumps up to 39 years old were present. In fact, at sampling, it was possible to determine the original diameter of all stumps. The chronosequence covered the first 39 years of decomposition, which means that from 40 years on, the model can only be an extrapolation. However, according to the function developed, only about 15% of the initial biomass would remain after 39 years, so the potential for incorrect asymptotic extrapolation has a limited influence on the results. The chronosequence approach could simply be combined with direct measurement of any remaining biomass.

No vertical roots were excavated as part of the sample, and the biomass of vertical roots was estimated in the same way as other roots, with only the diameter measured. There is a risk that the shape and size of the vertical roots is different from other roots, but from visual assessments we concluded that any bias was of little importance. Technical considerations prevented the excavation of vertical roots. Fresh stumps and their roots were inventoried down to a diameter of 2 mm and decomposed stumps with roots were inventoried down to 10 mm. The major reasons for using different minimum root diameter thresholds were that it was almost impossible to trace decomposed roots in the soil and because the exclusion of decomposed roots (2-10 mm) was assumed to have a limited influence on estimates. When plotting residuals by decomposition class (Figure 2c), class 1 (fresh stump systems) did not deviate from the decomposed classes (2-4). This was an indication of a minor influence on estimates by using different root diameter thresholds. Also the difficulty with determining whether the severely decomposed roots were still woody material or should be considered to have become part of the soil was assumed to have minor impact on the predictions.

From the literature, the annual relative Norway spruce decomposition rate recorded mainly for logs, but also for snags and stumps, is in the range 3.2 %–5.2 %. The value of 4.6 % recorded in the present study was within the upper quartile (Fig. 3). This may be due to closer contact with decomposers encountered by stumps with roots compared with logs. In addition, increased moisture content in the soil and in turn in the stumps and roots may increase the rate of decomposition. The R^2 value determined in this study was 0.754; this can be compared with the results reported by Shorohova et al. (2008), who examined decomposition of the above-ground part of the Norway spruce stump and obtained an R^2 value of 0.896.

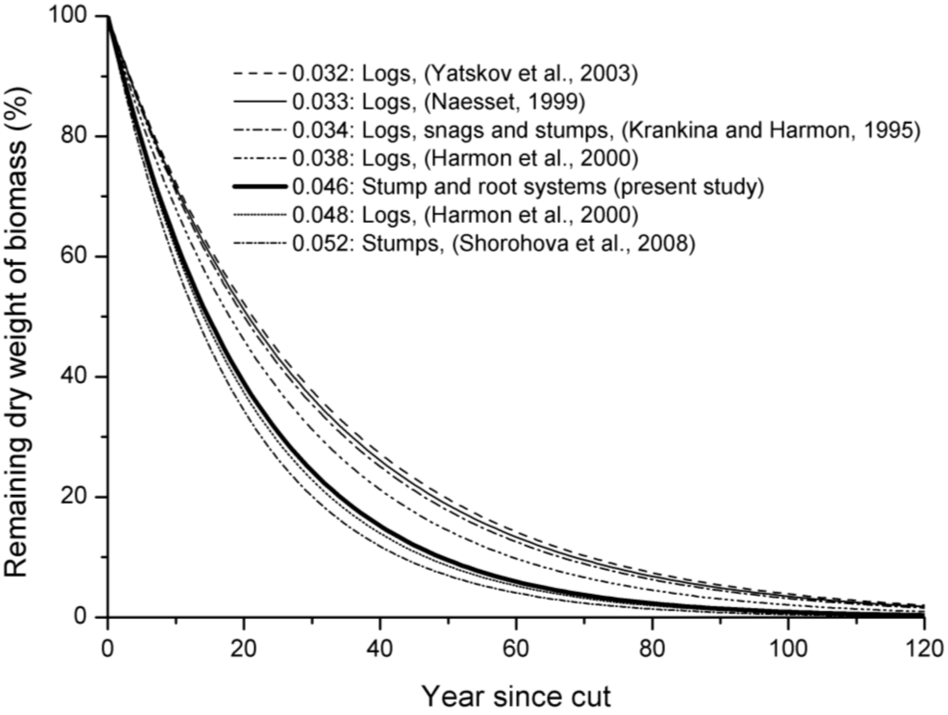

Fig. 3. Decomposition functions from previous studies of logs, snags and stumps of Norway spruce (see also Table 1). The present study of stump and root systems is included. All studies were based on a chronosequence approach.

The present study is, to our knowledge, the first to model relative decomposition rate for combined stump and root systems of Norway spruce. The advantage with this relative approach is that it is simple to apply the function in practice without unduly compromising accuracy. However, when applying this method, it must be remembered that the function was developed using data from only two locations. When applying the relative function the time required for the loss of 50 % ($t_{0.5}$) and 95 % ($t_{0.95}$) of the wood is 15 and 64 years, respectively.

5. Conclusions

The negative exponential model seems appropriate for modelling the decomposition of Norway spruce stump and root systems. Although there are many variables affecting decomposition, the remaining biomass could be predicted fairly accurately using just the independent variables stump diameter and time. The relative decomposition rate was estimated to be 4.6 % annually.

Acknowledgements

This study was financed by the Swedish Energy Agency and the Department of Forest Resource Management, Swedish University of Agricultural Sciences. The authors gratefully thank the staff at the Asa, Jädraås and Vindeln research stations for their help with extracting background information on the sampling areas from their archives. We also sincerely acknowledge all the workers who undertook the hard work in the field. Sören Holm at the Department of Forest Resource Management, SLU provided very useful assistance with the statistical analyses.

References

Alexandersson, H., Eggertsson, C., 2001. Temperaturen och nederbörden i Sverige 1961-1990. Referensnormaler - utgåva 2. Meteorologi. SMHI. (in Swedish).

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

Caruso, A., 2008. Lichen diversity on stems, slash and stumps in managed boreal forests. Ph.D. dissertation, Acta Universitatis Agriculturae Sueciae, 2008:3. Swedish University of Agricultural Sciences, Uppsala, Sweden.

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

Chen, X.Y., Wei, X.H., Scherer, R., 2005. Influence of wildfire and harvest on biomass, carbon pool, and decomposition of large woody debris in forested streams of southern interior British Columbia. For. Ecol. Manage. 208, 101-114.

European Commission., 1997. Energy for the future: Renewable Sources of Energy. *In* White paper for a Community Strategy and Action Plan. Com(97)599 final (26/11/1997).

Fahey, T.J., Hughes, J.W., Pu, M., Arthur, M.A., 1988. Root decomposition and nutrient flux following whole-tree harvest of northern hardwood forest. For. Sci. 34, 744-768.

Ganjegunte, G.K., Condron, L.M., Clinton, P.W., Davis, M.R., Mahieu, N., 2004. Decomposition and nutrient release from radiata pine (*Pinus radiata*) coarse woody debris. For. Ecol. Manage. 187, 197-211.

Hakkila, P. 1989. Utilization of Residual Forest Biomass. Springer-Verlag, Berlin, Heidelberg, New York.

Harmon, M.E. , Cromak, K., Smith, B.G., 1987. Coarse woody debris in mixed-conifer forests, Sequoia-national-park, California. Can. J. For. 17, 1265-1272.

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

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

Hofgaard, A., 1993. 50 Years of Change in a Swedish Boreal Old-Growth *Picea abies* Forest. Journal of Vegetation Science. 4, 773-782.

Hytteborn, H., Packham, J.R., 1987. Decay rate of *Picea abies* logs and the storm gap theory: a re-examination of Sernander Plot III, Fiby urskog, central Sweden. Journal of Arboricult. 11, 299-311.

Janisch, J.E., Harmon, M.E., Chen, H., Fasth, B., Sexton, J., 2005. Decomposition of coarse woody debris originating by clearcutting of an old-growth conifer forest. Ecoscience. 12, 151-160.

Johnson, D.W., 1993. Carbon in forest soils-research needs. New Zealand Journal of Forestry Science. 23, 354-366.

Jonsson, B.G., Kruys, N., Ranius, T., 2005. Ecology of species living on dead wood – Lessons for dead wood management. Silva Fennica. 39, 289-309.

Krankina, O.N., Harmon, M.E., 1995. Dynamics of the Dead Wood Carbon Pool in Northwestern Russian Boreal Forests. Water Air Soil Pollut. 82, 227-238.

Mackensen, J., Bauhus, J. 1999. The decay of coarse woody debris. National carbon accounting system Ed. D.o.f. ANU. Australian Greenhouse office.

Mackensen, J., Bauhus, J., 2003a. Density loss and respiration rates in coarse woody debris of *Pinus radiata*, *Eucalyptus regnans* and *Eucalyptus maculata*. Soil Biology & Biochemistry. 35, 177-186.

Mackensen, J., Bauhus, J., Webber, E., 2003b. Decomposition rates of coarse woody debris – A review with particular emphasis on Australian tree species. Australian Journal of Botany. 51, 27-37.

MacMillan, P.C., 1988. Decomposition of coarse woody debris in old-growth Indiana forest. Can. J. For. Res. 18, 1353-1362.

Mäkinen, H., Hynynen, J., Siitonen, J., Sievänen, R., 2006. Predicting the decomposition of Scots pine, Norway spruce, and birch stems in Finland. Ecological Applications. 16, 1865-1879.

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

Olson, J.S., 1963. Energy storage and the balance of producers and decomposers in ecological systems. Ecology. 44, 322-331.

Petersson, H., Ståhl, G., 2006. Functions for below-ground biomass of *Pinus sylvestris*, *Picea abies*, *Betula pendula* and *Betula pubescens* in Sweden. Scand. J. For. Res. 21, 84-93.

Rudolphi, J., 2007. Bryophytes, lichens and dead wood in young managed boreal forests. Ph.D. dissertation, Acta Universitatis Agriculturae Sueciae, 2007:88. Swedish University of Agricultural Sciences, Uppsala, Sweden.

Shorohova, E., Kapitsa, E., Vanha, M.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.

SLU., 1994. Swedish University of Agricultural Sciences, Dep. of National Forest Inventory. Instruktion för fältarbetet vid riksskogstaxeringen år 1994. (in Swedish).

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