

Thermonuclear 'bomb' ^{14}C and its use in modelling soil C dynamics – an assessment of a simple soil C turnover model

Aroon Parshotam and Kevin Tate
Landcare Research,
Palmerston North, New Zealand

Abstract

Thermonuclear 'bomb' ^{14}C can serve as a pollution-induced tracer for the depth penetration, migration and turnover of organic matter in soils. Thus, measurement of bomb ^{14}C in soils potentially allows soil carbon (C) movement and turnover to be modelled and global climate change, land-use change and CO_2 fertilisation effects to be assessed. We assess here a simple model of soil C turnover developed by O'Brien (1984, *Soil Biol. Biochem.* **16**, 115-120). This model is used to estimate soil C inputs, turnover times and downward diffusivity in a soil profile from soil ^{14}C measurements. An extension of this model is described and analytical solutions are derived for the model equations. A recent compilation of ^{14}C in New Zealand soils provides the opportunity to test the model in different soils, and to examine the distribution of 'old' C in soil profiles. In this work, two adjacent sites under mountain beech and tussock grassland are examined. The model equations, which describe the distribution and movement of ^{14}C in soils, may be useful for linking processes that occur on widely differing temporal and spatial scales.

1. Introduction

Atmospheric CO_2 , enriched by thermonuclear 'bomb' ^{14}C , has caused a marked increase in the ^{14}C concentration of soil organic matter. The 'bomb' effect is a major obstacle in the ^{14}C -dating of topsoil layers, but can serve as a valuable tracer for the depth penetration, migration and turnover of soil organic matter. This effect, in conjunction with measurements of ^{13}C and ^{14}C in soil and plant components, has provided an opportunity to model carbon movement and turnover in soils (O'Brien and Stout, 1978; O'Brien, 1984), with global climate change (Becker-Heidmann and Scharpenseel, 1992), land-use change (Harrison, *et al.*, 1993a) and CO_2 fertilisation effects (Harrison, *et al.*, 1993b).

This paper assesses the simple model of soil C turnover developed by O'Brien (1984) where data on soil ^{14}C , total C and soil density is used to estimate the soil C input rate into the soil, its decomposition time and the carbon diffusivity down a soil profile. An extension of the model which includes separate litter and mineral soil compartments is given. Further, analytical solutions are derived for the model equations. A recent compilation of ^{14}C in New Zealand soils (Lasey *et al.*, 1996) has provided the opportunity to test the model in different soils, and to examine the distribution of 'old' C in soil profiles. Two adjacent sites under mountain beech (*Nothofagus solandri* var. *cliffortioides*) and

tussock grassland (*Chionochloa pallens*) in the same climo-edaphic environment at the timberline in Craigieburn Forest Park, Canterbury, New Zealand, are examined.

2. Model

2.1 Model Description

It is assumed that there exists a steady state in which fresh C continually enters the soil surface at a fixed rate, that C is transported down the soil profile at a steady rate and, finally, that $\text{CO}_2\text{-C}$ is lost from the soil by respiration at a fixed and steady rate (see Fig 1).

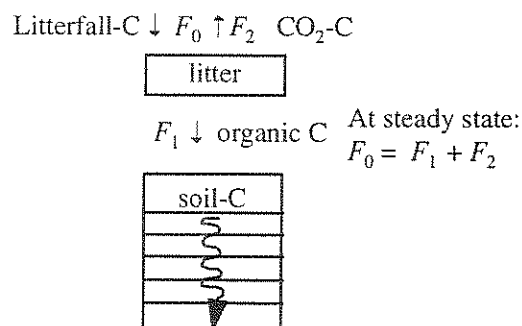


Figure 1: Movement of organic C into the litter and soil

2.2 Model Assumptions

The model is based on the diffusion of ^{14}C down a soil profile (see O'Brien, 1984) with the following assumptions for litter and mineral soil:

- The specific activity of plant material entering the litter layer is the same as that of the atmospheric CO_2 .
- Available 'bomb' ^{14}C measured at Makara, (Wellington, New Zealand) expressed as an annual average is representative for New Zealand. Dilution of ^{12}C , ^{13}C isotopes by fossil carbon is ignored.
- Loss of ^{14}C by ^{14}C decay is ignored, or not distinguishable from respiration.
- There is no isotopic fractionation within the system by physical, chemical or biological processes.
- The decomposition rate of litter-C and of soil-C is proportional to their respective C contents, i.e. first order kinetics is obeyed.
- All vertical movement of C in the soil is due to simple diffusion with a constant mean diffusivity, D , over each depth increment.
- The distribution of 'old' C is more or less constant throughout the soil profile and the distribution of 'modern' C, which falls markedly with depth, is in a steady state.

2.3 Model Equations

Total C

The model equation for litter-C, $C_L(t)$ is

$$\frac{dC_L(t)}{dt} = F_0 - k_L C_L(t), \quad (1)$$

with the initial condition $C_L(t_0) = C_{L0}$ and of 'modern' soil-C, $C_s(t, z)$ this is

$$\frac{\partial C_s(t, z)}{\partial t} = D \frac{\partial^2 C_s(t, z)}{\partial z^2} - k_s C_s(t, z), \quad (2)$$

for at time t and depth, $0 < z < l$, with the initial condition $C_s(t_0, z) = C_{s0}(z)$ and the boundary conditions $C_s(t, 0) = C_L(t)$, $C_s(t, l) = 0$. F_0 is the input rate of C into the litter layer, l the depth of the soil column, D is the diffusivity, k_L is a first-order litter-C decay rate coefficient, and k_s is a first-order soil-C decay rate coefficient.

The full solution of the transient problem is, for constant input rate, F_0 , given for $t_0 = 0$, by

$$C_L(t) = C_{L0} e^{-k_L t} + k_L^{-1} (1 - e^{-k_L t}) F_0 \quad (3)$$

$$C_s(t, z) = \frac{2}{l} \sum_{n=1}^{\infty} e^{-\alpha_n t} \sin \frac{n\pi z}{l} \left\{ \int_0^l C_{s0}(z') \sin \frac{n\pi z'}{l} dz' + \frac{n\pi D}{l} \left[\right. \right.$$

$$\left. \left. \frac{C_{L0} - k_L^{-1} F_0}{\alpha - k_L} (e^{(\alpha - k_L)t} - 1) + \frac{k_L^{-1} F_0}{\alpha} (e^{\alpha t} - 1) \right] \right\}, \quad (4)$$

where $\alpha = k_s + D n^2 \pi^2 / l^2$. The steady state solutions

$$\lim_{t \rightarrow \infty} C_L(t) = \hat{C}_L \quad \text{and} \quad \lim_{t \rightarrow \infty} C_s(t, z) = \hat{C}_s(z),$$

satisfies (1) and (2), with the time derivative set equal to zero. At steady state, $C_L(t, z) \equiv \hat{C}_L(z)$ and $C_s(t, z) \equiv \hat{C}_s(z)$, so that

$$F_0 = k_L \hat{C}_L(z), \quad (5)$$

$$D \frac{\partial^2 \hat{C}_s(z)}{\partial z^2} = k_L \hat{C}_s(z), \quad (6)$$

with the boundary conditions $\hat{C}_s(0) = \hat{C}_L = F_0 / k_L$ and $\hat{C}_s(l) = 0$. (6) has the solution

$$\hat{C}_s(z) = F_0 k_L^{-1} ((1 + \varepsilon) e^{z/z_0} - \varepsilon e^{-z/z_0}), \quad (7)$$

where $\varepsilon = 1 / (e^{-2l/z_0} - 1)$, and $z_0 = (D / k_L)^{1/2}$. For large l (i.e., if the soil column is assumed to be infinitely long), this is

$$\hat{C}_s(z) = F_0 k_L^{-1} e^{-z/z_0}. \quad (8)$$

The flux of C into the soil surface layer of the soil ($z = 0$) is given by

$$F_1 = -D \frac{d\hat{C}_s}{dz} \Big|_{z=0} = -D \frac{\hat{C}_L}{z_0} (1 + 2\varepsilon). \quad (9)$$

and for large l ,

$$F_1 = D \hat{C}_L / z_0, \quad (10)$$

$$D = z_0^2 k_s, \quad (11)$$

where \hat{C}_L is the concentration of "modern" C at the soil surface.

Bomb ^{14}C enrichment, $\Delta^{14}\text{C}$

Excess ^{14}C is measured by $\Delta^{14}\text{C}$ values. These give the ^{14}C enrichment or depletion of the sample in parts per thousand (‰) with respect to a ^{14}C standard, after normalising to a fixed $^{13}\text{C}/^{12}\text{C}$ ratio to remove any isotopic fractionation that may have taken place. These may be calculated from

$$\Delta^{14}\text{C} = \left(\frac{A_{SN}}{A_{abs}} - 1 \right) \times 1000 \text{‰}, \quad (12)$$

where A_{abs} is the decay corrected, absolute international standard activity (Stuiver and Pollach, 1977). Positive values of $\Delta^{14}\text{C}$ indicate the

presence of newer 'bomb' ^{14}C and negative values indicate that the ^{14}C has had significant time to undergo radioactive decay. $\Delta^{14}\text{C} = s(t)/^{14}R_0$, where

$$s(t) = \left(\frac{^{14}C_{\text{bomb}}}{C} \right), \quad (13)$$

and $^{14}R_0$ is the decay corrected ^{14}C content per gram of C of the radiometric standard (the $^{14}\text{C}/^{12}\text{C}$) ratio of the modern ^{14}C standard, taken to be 1.176×10^{-12} . In some cases, $^{14}R_0$ (which is cancelled out of the rate balance equations), will be ignored and $\Delta^{14}\text{C}$ is considered to be $s(t)$.

Litter

The total amount of ^{14}C present in the litter at time t , due to 'bomb' C photosynthesised since t_0 is given by

$$\frac{\partial^{14}C_L(t)}{\partial t} = s(t)F_0 - k_L^{14}C_L(t), \quad ^{14}C_L(t_0) = 0, \quad (14)$$

where the term $s(t)F_0$ is the specific activity of 'fresh' plant inputs, taken to be the same as for atmospheric CO_2 . Here, t_0 is the time of first appearance of bomb carbon in the atmospheric record and before this, $\Delta^{14}\text{C} = 0$. (14) has the solution

$$^{14}C_L(t) = F_0 e^{-k_L t} \int_{t_0}^t e^{k_L t'} s(t') dt', \quad (15)$$

and since $s(t)$ is given as a series of annual averages, $s(iT) = \Delta^{14}C_i$ where $T = 1$ year, (15) may be expressed in the following discrete form

$$^{14}C_L(kT) = F_0 k_L^{-1} (1 - e^{-k_L T}) M_k(k_L), \quad (16)$$

where

$$M_k(k_L) = \sum_{i=i_0}^k s(iT) e^{-(k-i)k_L T} \quad (17)$$

for year k , and initial year, i_0 . Thus, $^{14}C_L / \hat{C}_L$, the average $\Delta^{14}\text{C}$ in the litter is given by

$$\frac{^{14}C_L}{\hat{C}_L} = (1 - e^{-k_L T}) M_k(k_L). \quad (18)$$

At steady state, $F_0 = k_L W_L$, where W_L is the total mass of litter C in kg m^{-2} , so that the average level of ^{14}C in the litter is given by

$$(1 - e^{-k_L T}) M_k(k_L) = \frac{^{14}C_L}{W_L}. \quad (19)$$

The mean turnover time for litter C, k_L^{-1} , can then be estimated from (19) by matching $^{14}C_L/W$ to the closest computed value for $(1 - e^{-k_L T}) M_k(k_L)$.

$^{14}C_L$ and W_L are determined from measurements of litter $\Delta^{14}\text{C}$ and organic C. Using this value of k_L , the C input rate to the litter, F_0 , may be calculated from (5). The unique maximum value and time for its occurrence may be calculated from (18).

Soil

The total amount of ^{14}C present in the soil at time t , due to 'bomb' C from litter from time, t_0 , may be obtained by considering two cases, a single compartment model without diffusion effects and a multilayered model with diffusion effects.

i) Single compartment model

The total 'bomb' carbon in the soil profile, $^{14}C_s$ at time t is given by

$$\frac{\partial^{14}C_s(t)}{\partial t} = F_1 s_L(t) - k_s^{14}C_s(t), \quad ^{14}C_s(t_0) = 0, \quad (20)$$

where the input rate of 'bomb' carbon from litter to soil, at time t , is $F_1 s_L(t)$ where $s_L(t) = ^{14}C_L / \hat{C}_L$, represents the average $\Delta^{14}\text{C}$ in the litter. (20) has the solution

$$^{14}C_s(t) = F_1 e^{-k_s t} \int_{t_0}^t e^{k_s t'} s_L(t') dt', \quad (22)$$

which may also be expressed in the discrete form

$$^{14}C_s(kT) = F_1 k_s^{-1} (1 - e^{-k_s T}) (1 - e^{-k_L T}) P_k(k_s, k_L) \quad (23)$$

where

$$P_k(k_s, k_L) = \sum_{i=i_0}^k M_i(k_L) e^{-(k-i)k_s T} \\ = \frac{M_k(k_s) - e^{(k_s - k_L)T} M_k(k_L)}{1 - e^{(k_s - k_L)T}}. \quad (24)$$

Thus, $^{14}C_s / \hat{C}_s$, which represents the average $\Delta^{14}\text{C}$ in the soil, is given by

$$\frac{^{14}C_s}{\hat{C}_s} = (1 - e^{-k_s T}) (1 - e^{-k_L T}) P_k(k_s, k_L). \quad (25)$$

At steady state, $F_1 = k_s W$, where W is the total mass of soil C in kg m^{-2} , so that

$$(1 - e^{-k_s T}) (1 - e^{-k_L T}) P_k(k_s, k_L) = \frac{^{14}C_s}{W}. \quad (26)$$

From k_L^{-1} , the mean turnover time for litter C, the mean soil C turnover time, k_s^{-1} , may be estimated from (26) by matching $^{14}C_s/W$ to the closest computed value for $(1 - e^{-k_s T}) (1 - e^{-k_L T}) P_k(k_s, k_L)$. $^{14}C_s$ and W are determined from measurements of

soil $\Delta^{14}\text{C}$ and organic C. Using this value of k_s , the C input rate to the mineral soil, F_1 , may be calculated from $F_1 = k_s W$. The diffusivity of the mobile C in the soil profile may be approximated from (11) if it is assumed that the soil depth l is very large.

ii) Multi-layered, diffusion model

The total 'bomb' carbon in the soil profile, $^{14}\text{C}_s$ at time t with diffusion effects, is given by

$$\frac{\partial^{14}\text{C}_s(t, z)}{\partial t} = D \frac{\partial^2^{14}\text{C}_s(t, z)}{\partial z^2} - k_s^{14}\text{C}_s(t, z), \quad (27)$$

with the initial condition $^{14}\text{C}_s(t_0, z) = ^{14}\text{C}_{s0}(z) = 0$ and boundary conditions $^{14}\text{C}_s(t, 0) = ^{14}\text{C}_L(t)$ and $^{14}\text{C}_s(t, l) = 0$. (27) has the solution

$$^{14}\text{C}_s(t, z) = \frac{2}{l} \sum_{n=1}^{\infty} e^{-\alpha(t-t_0)} \sin\left(\frac{n\pi z}{l}\right) \left\{ \frac{n\pi D}{l} \int_{t_0}^t e^{\alpha\lambda} ^{14}\text{C}_L(\lambda) d\lambda \right\} \quad (28)$$

and since $s_L(t)$ is given as a series of annual averages, this solution may be expressed in the discrete form

$$^{14}\text{C}_s(kT, z) = \frac{2F_0 k_L^{-1} (1 - e^{-k_L T})}{l} \sum_{n=1}^{\infty} e^{\alpha_n T} \sin\left(\frac{n\pi z}{l}\right) \left\{ \frac{n\pi D}{l} \alpha^{-1} (1 - e^{-\alpha T}) \right\} P_k(\alpha, k_L), \quad (29)$$

The ratio $^{14}\text{C}_s / \hat{\text{C}}_s(t)$, may be derived from (7) and (29). k_s and D are estimated simultaneously from the exact solution, with initial estimates derived from the single-compartment, soil model.

3. Data description

3.1 Field data and sites

Soil C storage, turnover and movement are examined from soil C and $\Delta^{14}\text{C}$ data at adjacent sites under mountain beech, and tussock grassland, in the same climo-edaphic environment at timberline in Craigieburn Forest Park, Canterbury, New Zealand. The sites, soil C and $\Delta^{14}\text{C}$ data are described by Tate *et al.* (submitted). Values of atmospheric $\Delta^{14}\text{C}$ at Makara between December 1954 and June 1987 used in the model have been reported by Manning *et al.* (1990). The sampling procedures and correction factors, are given by Lasseby *et al.* (1996).

3.2 Treatment of data

The parameters k_L and F_0 , signifying the turnover of litter and input rate of plant material into litter,

are estimated from the litter model. The parameters k_s , F_1 and D , characterising the movement, turnover and input of soil C from litter, can be estimated in the following way:

i) Single compartment model

1) If data on deeper soil horizons are available, compute $C_j \Delta^{14}\text{C}_j$ for each horizons and estimate the average $C \Delta^{14}\text{C}$. Then compute $\Delta^{14}\text{C}_j$ for the surface horizons, from $C \Delta^{14}\text{C}_j / C_j$. The increase in ^{14}C in the upper horizons $\Delta^{14}\text{C}_j'$ is taken to be $\Delta^{14}\text{C}_j - \Delta^{14}\text{C}_j'$. If it is not possible to estimate $\Delta^{14}\text{C}_j$, then $\Delta^{14}\text{C}_j'$ is assumed to be the same as $\Delta^{14}\text{C}_j$ for those upper horizons, if positive.

2) Modern C % = C% - 'old' C%, where percent 'old' C is $C \Delta^{14}\text{C} / 100$.

3) From the measured (sampled in year, k) $\Delta^{14}\text{C}_j$, % carbon C_j , density P_j and depth of horizon, l_j cm, calculate

$$T_k = \sum_j l_j P_j C_j \Delta^{14}\text{C}_j' 10^{-2}. \quad (30)$$

This is summed over those horizons for which positive values of $\Delta^{14}\text{C}_j'$ have been obtained.

4) Estimate the total carbon $W_j = l_j P_j C_j 10^{-2}$ in each horizon, j , where C_j is modern C and the sum of total C in all horizons, W .

5) Estimate the steady state soil carbon model depth parameter, $z_0 = 100W / P_0 C_0$, where C_0 and P_0 are the % C and soil density in the top horizon of the soil (O'Brien and Stout, 1978).

7) Estimate k_s from (26) and F_1 from $F_1 = k_s W$.

6) The soil C diffusivity D may be calculated from $D = z_0^2 k_s$.

The rate of CO_2 -C efflux from the litter, F_2 , may be calculated from the difference between the litter C input rate, F_0 , and the flux of C into the soil, F_1 . If the soil density data, P_j , is not available, it is still possible to estimate the above parameters, by assuming that $P_j = 1$ for each horizon. In many cases, the error involved in doing this will not be great (O'Brien, 1984).

ii) Multi-layered, diffusion model

1) and 2) and 3) are repeated, as above.

4) k_s and D are estimated simultaneously, from the exact solution using a nonlinear parameter estimation algorithm, given estimates for k_L . Earlier estimates of these parameters from the single compartment model may be used as initial estimates. F_1 is calculated from (9).

4. Results

Estimates of litter and soil C turnover times, annual C inputs and soil C diffusivities for tussock grassland and beech forest sites are presented in Tables 1-3. Detailed calculations are given in Table 4.

	k_L^{-1} (yr)	F_0 (g cm ⁻² yr ⁻¹)
Tussock grassland	49.6	4.4×10^{-3}
Beech forest	24.5	5.3×10^{-4}

Table 1: Litter C turnover times and input rate estimates: Litter model.

	k_s^{-1} (yr)	F_1 (g cm ⁻² yr ⁻¹)	D (cm ² g ⁻¹)
Tussock grassland	38.2	0.035	21.44
Beech forest	74.5	0.018	9.00

Table 2: Soil C turnover times, input rates and diffusivity estimates: Single-compartment model.

	k_s^{-1} (yr)	D (cm ² g ⁻¹)
Tussock grassland	75	18
Beech forest	74.1	6.1

Table 3: Soil C turnover times and diffusivity estimates: Multi-layered soil model.

Atmospheric $\Delta^{14}\text{C}$, and model $\Delta^{14}\text{C}$ simulations are seen in Figure 2.

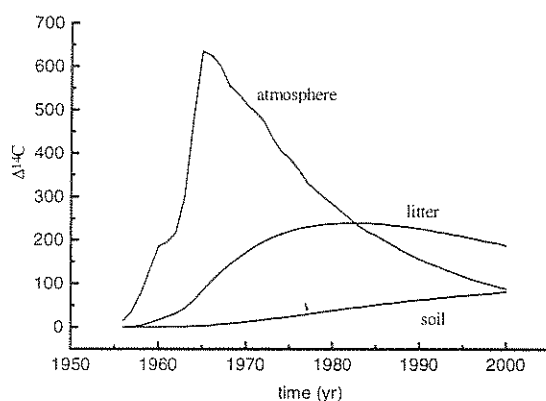


Figure 2: Atmospheric $\Delta^{14}\text{C}$, litter and single-compartment soil model simulations of beech forest $\Delta^{14}\text{C}$

5. Discussion

The turnover time for the litter (Table 1) is only approximate, because of the slow change in the

level of $\Delta^{14}\text{C}$ in atmospheric CO_2 during recent years. The estimate for litter C turnover time in the beech forest is twice that for a lowland beech forest where warmer temperatures encourage more rapid decomposition (Tate *et al.*, 1993). The litterfall estimated from the single-compartment model, however, is smaller by a factor of 3 than estimates given by Tate *et al.* (submitted). The litter C turnover time of the tussock grassland site is twice that for a range of tussock grasslands in South Island, New Zealand (Tate, 1992). The wide variation in the estimated turnover times for litter C can result in a range of annual C inputs into the soil. The soil C input rate in the beech forest ($0.018 \text{ g cm}^{-2} \text{ yr}^{-1}$) is in agreement with other beech forest site estimates ($0.017 \text{ g cm}^{-2} \text{ yr}^{-1}$, O'Brien (1984); $0.024 \text{ g cm}^{-2} \text{ yr}^{-1}$, Tate *et al.*, (1993)). A surprising result from modelling C turnover times for the litter and mineral soil is that the turnover times for litter in the grassland site exceeds that for the soil (Tables 1 and 2). The lower input in grassland than in forest soil (Table 2) is consistent with data in Tate *et al.* (submitted). The higher proportion of 'old' C in the grassland site, is consistent with decomposition being restricted in this profile by intermittent waterlogging and the apparent accumulation of recalcitrant organic matter (Tate *et al.*, submitted). The diffusivity of the beech forest soil (Table 3) is very similar to values reported for a lowland New Zealand beech forest soil (Tate *et al.*, 1993). However, the very high diffusivity D in the grassland soil, which indicates greater mixing or vertical movement, is inconsistent with the slow rate of turnover of soil C and the accumulation of recalcitrant organic matter (Tate *et al.*, submitted). Further work is required to reconcile these results.

6. Conclusions

The increase in ^{14}C in the upper layer of soil from the incorporation of 'bomb' C, may be used to study the movement and turnover of soil-C and litter-C. It may also be used to calculate the organic carbon input rate into the litter and soil, its decomposition times and the carbon diffusivity down a soil profile from data on one soil profile (including litter) on ^{14}C , total C and soil density. We modified an existing model, derived analytical solutions for the model equations and tested it with data from two adjacent sites under mountain beech and tussock grassland.

The model equations, which describe the distribution and movement of ^{14}C in soils, are also valid for site-specific ^{14}C -labelled plant decomposition studies and may be useful for linking processes that occur on widely differing temporal and spatial scales.

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soil depth (cm)	bulk density (g cm^{-3})	C (%)	$\Delta^{14}\text{C}$ (‰)	$C_j\Delta^{14}C_j$	'new' C (%)	$\overline{\Delta^{14}\text{C}}$ (‰) (before bomb)	$\Delta^{14}\text{C}'$ (‰)	T_{92} (g cm^{-2} ‰)	W_j (g cm^{-3})	T_{92}/W	z_0 (cm)
TUSOCK											
0-3	0.04	18	154.7	-	-	-	154.7	3.34	0.022	154.7	
3-13	0.49	10.3	47.9		9.44	-83.8	131.8	66.5	0.463		
13-19	0.61	6.73	-58.9		5.87	-128.4	69.5	17.1	0.215		
19-28	0.69	4.04	-167.3		3.18	-213.9	46.6	11.7	0.197		
28-35	0.76	3.46	-277.3	-959	2.60	-249.7	-27.6		0.138		
35-46	0.82	2.5	-387.3	-968	1.64	-345.6	-41.7		0.148		
46-54	1.08	2.2	-414	-911	1.34	-392.7	-21.3		0.116		
54-66	0.73	1.4	-440	(-616)	0.54	-617	177.1		0.047		
sum, Σ								95.3	1.324		
mean, μ				-864						71.98	28.6
BEECH											
0-3	0.12	36.1	216	-	-	-	216	28.1	0.13	216	
3-13	0.39	13.8	146.5		13.43	-26.7	173.2	46.6	0.262		
13-19	0.45	6.4	19.3		6.03	-57.5	76.8	24.3	0.299		
19-28	0.62	3.3	-35.9		2.93	-111.5	75.6	23.2	0.272		
28-35	0.98	2.2	-155		1.83	-167.2	-12.2		0.179		
35-46	1.05	1.7	-246.5	-419.1	1.33	-216.4	-30.1		0.140		
46-54	1.12	1.0	-315	-315	0.63	-367.9	-52.9		0.078		
54-66	1.18	0.83	-445.3	-369.6	0.46	-443.3	-2.0		0.125		
sum, Σ								94.1	1.356		
mean, μ				-367.9						69.4	25.9

Table 4: Summary of calculations. The top 3 cm is the litter layer