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Mean residence time of O horizon carbon along a climatic gradient in Scandinavia estimated by ^{14}C measurements of archived soils

Mats Fröberg^{1*}, Edward Tipping², Johan Stendahl¹, Nicholas Clarke³,
Charlotte Bryant⁴

1. Swedish University of Agricultural Sciences, Department of Soil and Environment, P.O. Box 7001, SE-75007 Uppsala, Sweden.
2. Lancaster Environmental Centre, Centre for Ecology and Hydrology, Lancaster LA1 4AP, England
3. Norwegian Forest and Landscape Institute, N-1431 Ås, Norway
4. NERC Radiocarbon Facility (Environment), Scottish Enterprise Technology Park, Glasgow G75 0QF, Scotland

* Corresponding author.
Email: mats.froberg@mark.slu.se,
tel: +46 18 67 22 33

Abstract

We used two datasets of ^{14}C analyses of archived soil samples to study carbon turnover in O horizons from spruce dominated old-growth stands on well-drained podsoles in Scandinavia. The main data set was obtained from archived samples from the National Forest Soil Inventory in Sweden and represents a climatic gradient in temperature. Composite samples from 1966, 1972, 1983 and 2000 from four different regions in a latitude gradient ranging from 57 to 67°N were analysed for ^{14}C content. Along this gradient the C stock in the O horizon ranges from 2.1 kg m⁻² in the north to 3.7 kg m⁻² in the southwest. The other data set contains ^{14}C analyses from 1986, 1987, 1991, 1996 and 2004 from the O horizons in Birkenes, Norway. Mean residence times (MRT) were calculated using a two compartment model, with a litter decomposition compartment using mass loss data from the literature for the three first years of decomposition and a humus decomposition compartment with a fitted constant turnover rate. We hypothesized that the climatic gradient would result in different C turnover in different parts of the country between northern and southern Sweden. The use of archived soil samples was very valuable for constraining the MRT calculations, which showed that there were differences between the regions. Longest MRT was found in the northernmost region (41 years), with decreasing residence times through the middle (36 years) and central Sweden (28 years), then again increasing in the southwestern region (40 years). The size of the soil organic carbon (SOC) pool in the O horizon was mainly related to differences in litter input and to a lesser degree to MRT. Because N deposition leads both to larger litter input and to longer MRT, we suggest that N deposition contributes significantly to the latitudinal SOC gradient in Scandinavia, with approximately twice as much SOC in the O horizon in the south compared to the north. The data from Birkenes was in good agreement with the Swedish dataset with MRT estimated to 34 years.

Introduction

Forest soils contain large amounts of carbon. The size of this carbon stock is largely dependent on environmental factors, such as climate, moisture, nutrient status etc. Soil organic carbon (SOC) stocks in Scandinavian forest soils generally decrease with latitude (Liski & Westman 1997; Ågren et al. 2007; Olsson et al. 2009), although the reason for this is not yet fully understood. Differences in climate have been suggested as a likely mechanism by some authors (Liski & Westman, 1997; Callesen et al. 2003), while others have proposed that the differences in SOC stocks are mainly due to a gradient in N deposition (Kleja et al. 2008). The size of the SOC stock is determined by both the rate of litter input and by how long the carbon stays in the soil, i.e. the mean residence time (MRT). Quantifying the residence time of carbon is difficult. The initial decomposition of litter may be studied with litter bag techniques for a period of a few years. This pool of more or less recognizable litter in the soil is however relatively small, compared to the large pool of humified organic matter. Significant amounts of humified organic matter in northern coniferous forests are stored in the uppermost organic horizon (the O horizon) and represent a carbon pool with turnover times on a timescale highly relevant to management of ecosystem carbon fluxes. Faster cycling pools, such as fresh litter, will rapidly be transformed to CO₂, whereas slower cycling pools, such as stabilized organic matter in the mineral soil, in general respond slowly due to small fluxes through the pools. To quantify the MRT of the carbon in the O horizon is therefore of major interest.

Different models for the turnover of SOC have been proposed. Many models use two or more separate pools of carbon with different discrete turnover rates (e.g. Century model, Parton et al. 1988). Some models contain inert pools which do not decompose (e.g. RothC model, Jenkinson, 1990). In other models a continuum of turnover rates is used (e.g. Q-model, Ågren & Bosatta, 1987) or the mineralization may continuously slow down with time, until it reaches a limit where a fraction of the carbon becomes inert (e.g. Berg et al. 1996). Due to the slow turnover time in the bulk of SOC, it is difficult to verify the models. Radiocarbon has been used in many studies to get information about SOC cycling and age. This is mainly done by taking advantage of the “bomb carbon” produced by the atmospheric enrichment of ¹⁴CO₂ due to weapons testing in the 1950s and 1960s. Atmospheric ¹⁴C concentration peaked in 1964 and has since rapidly decreased, which enables ¹⁴C based information to be resolved on a decadal time scale, whereas traditional use of radioactive decay of ¹⁴C gives information on a timescale of centuries or millennia. In most soil studies however, sample ¹⁴C values are based on sampling at a single point in time. There are major problems associated with this, because there are numerous possible trajectories of the ¹⁴C curve over time which may have resulted in a given ¹⁴C for the year when the sample was taken (Trumbore, 2000), especially if the turnover rates of the organic matter are allowed to change with degree of decomposition, and it is therefore not possible to verify the choice of decomposition model. With several ¹⁴C measurements on samples collected at different points in time it is possible to constrain not only the turnover rates, but also the decomposition model itself and to get information about the distribution of different turnover times of SOC (e.g. Trumbore et al. 1996; Harkness

et al. 1986). Here we have analysed archived soils from 1966 to 2004 with the goal of studying the distribution of mean residence times of SOC in O-horizons from forest. One aim was to study how the turnover of SOC in different regions with different climate in Sweden differ from each other. We hypothesized that the climatic differences in Sweden would result in differences in turnover, with shorter residence times for SOC in warmer climate.

Methods

Datasets

Swedish dataset

The Swedish National Forest Soil Inventory comprises today about 23 500 permanent sample plots in a stratified national grid system (denser in the southern part of the country) which are re-analysed within a 10-year cycle. Prior to 1983, temporary plots were used. This means that it was not possible to collect samples from the same particular sites for the whole time series stretching back to 1966. We instead chose to analyze samples from geographical regions (Fig. 1), which had similar stand and soil properties. Details about the regions are given in Table 1.

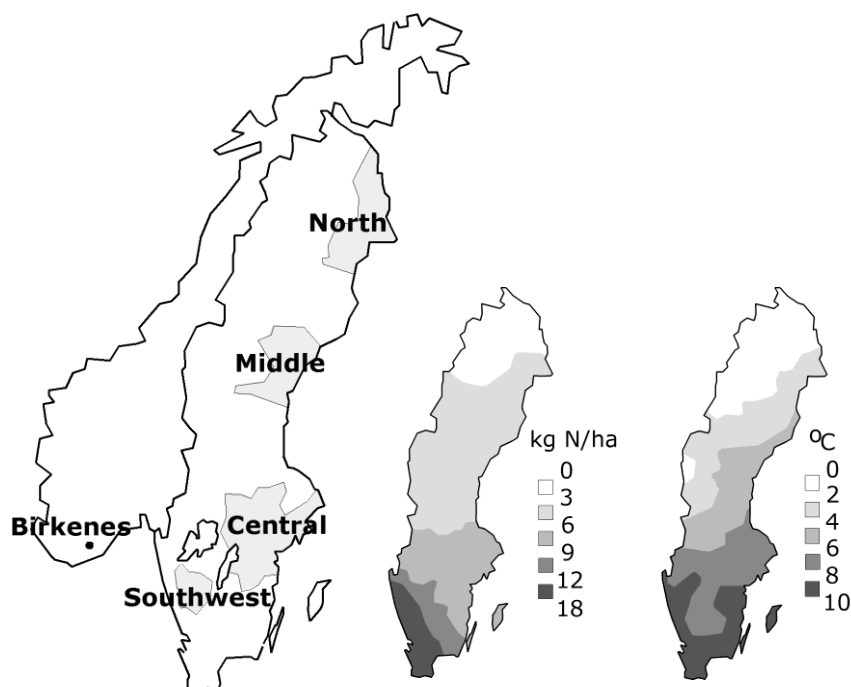


Figure 1. The four studied regions in Sweden and Birkenes, Norway together with mean annual temperature and N deposition in Sweden.

Table 1. Overview of the different regions in Sweden.

	North	Middle	Central	Southwest
County	Norrbottnen, Coast area	Västernorrland	Örebro, Västmanland, Stockholm, Södermanland, Östergötland	Älvsborg
Lat	66	63	59	57
Long	23	17	15	13
MAT	~0	~2	~5.5	~6
N dep (kg ha ⁻¹ y ⁻¹)	~3	~4	~8	~13
Soil type	Podzols	Podzols	Podzols	Podzols
Parent Material	Glacial till	Glacial till	Glacial till	Glacial till
Dominating tree species	Spruce	Spruce	Spruce	Spruce

Samples from four different years, 1966, 1972, 1983 and 2000 were obtained from the soil archive. Shorter time intervals were used early in the time series with the aim of maximizing information from the bomb C peak. Five random samples per year were chosen among sites that met the criteria. These were pooled to one composite sample for each of the selected years to represent a regional average. For the year 2000 it was not possible for all regions to obtain five samples that met the criteria and the composite samples therefore consisted of samples from 2-5 plots for this year. Each analyzed sample consisted of equal mass from each of the subsamples.

All analyzed samples from the archive were obtained from O-horizons. O-horizons in these soils are of mor-type, typically 5-10 cm deep. On average about one quarter of the total SOC stock down to one meter depth is found in the O horizon in this type of forest. Soil cores were used to take samples from a known area of the O-horizon. Subsamples from each plot were collected to one general sample per plot. The number of subsamples and diameter of soil cores have varied over the years, but the amount of O-horizon soil collected from each plot has consistently been approximately 1.5-2 liters. C stocks were calculated by multiplying the weight of the soil per area by the C concentration. Prior to 1983 only the depth of the O horizon was recorded in the survey and data on SOC stocks are therefore not available. Further information about the inventory data may be found in Berg et al. (2009) and Stendahl et al. (2010).

Samples from the archive were chosen with the aim of keeping site properties as similar as possible. Only mature stands classified as > 70% spruce and situated on podzol soils developed on till were selected. Furthermore only sites classified as having mesic soil moisture conditions were included. There were no observations of charcoal at any of the sites. The criteria chosen represent a very widespread and common forest type in Sweden

Site-specific needle litter fall was estimated using regressions of litter fall as a function of site productivity index, i.e. the expected height of the dominant trees at age 100 years (H_{100}). A new regression function for spruce was developed based on 13 Swedish sites (Berg et al. 1999) and 18 Finnish sites

(Saarsalmi et al. 2007). Site productivity index for the sites in the Finnish study was calculated from stand dominant height and stand age using functions by Hägglund (1981). The following function for spruce litter fall was obtained:

$$LF=0.00742 * H_{100} - 0.0225 \quad (R^2=0.60) \quad (1)$$

where LF is the needle litter fall (kg m^{-2}) and H_{100} is the dominant tree height (m) at age 100 years. Note that this is an estimate of needle litter only and that root litter and litter from understory vegetation is not included.

Birkenes dataset

The dataset from Birkenes represents five different points in time during 18 years, from 1986 to 2004, thus a significantly shorter range than the Swedish data set. This data set benefits however by high quality measurements of SOC stocks and litter inputs from one single site and is therefore a good complement to the Swedish dataset. Birkenes is situated in the south of Norway ($58^{\circ}23'N$ $8^{\circ}15'E$), about 30 km north of Kristiansand (Fig. 1), in the region of Norway with the mildest climate (mean annual temperature 5.5 °C) and also most impacted by relatively high nitrogen deposition (about $15 \text{ kg ha}^{-1} \text{ y}^{-1}$ in bulk precipitation, Wu et al. 2009). The site is therefore comparable to the southwestern region in Sweden, both in terms of temperature and N deposition. Like the Swedish sites, Birkenes is dominated by mature Norway spruce forest. Soil types are variable, but the data set used here are from podzols on till.

The Birkenes C stock and litterfall data are based on measured site-specific data of SOC stocks and litterfall (Michalzik et al. 2003) originating mostly from the Norwegian Monitoring Programme for Forest Damage. For both data sets, belowground litter and understory litter were not included due to lack of good data. The archived soils from Birkenes had been sampled in 1986, 1987 and 1991 using a soil auger in a systematic grid covering the plot of the Norwegian Monitoring Programme for Forest Damage. A composite sample was made from the 120 samples obtained. The more recent samples (1996 and 2004) were from 1 m^2 soil pits close to the plot.

¹⁴C analysis

Swedish samples: A known weight (approximately 1 g) of homogenized, dry sample was combusted to CO_2 in a high pressure bomb in the presence of oxygen. The CO_2 was cryogenically isolated and a sub-sample of CO_2 was converted to graphite by Fe/Zn reduction (Slota et al., 1987). A further sub-sample of CO_2 was used to measure $\delta^{13}\text{C}_{\text{VPDB}}$ using a dual-inlet mass spectrometer with a multiple ion beam collection facility (VG OPTIMA) for correcting ^{14}C data to -25 ‰ $\delta^{13}\text{C}_{\text{VPDB}}$. The samples were prepared to graphite at the NERC Radiocarbon Facility (Environment) and analysed at the Scottish Universities Environmental Research Centre (SUERC) AMS Laboratory using the National Electrostatics Corporation (NEC, Wisconsin, US) 250 kV single stage accelerator mass spectrometer (Freeman et al., 2008).

Birkenes samples: Bulk soil samples (sufficient to yield to yield 1-2g carbon) were oven-dried (80°C) and prepared to benzene for ^{14}C analysis by liquid scintillation counting using standard procedures at the NERC Radiocarbon Facility (Environment) (Harkness and Wilson, 1972). Stable carbon isotope ratios were measured on a sub-sample of benzene combusted to CO_2 , using a dual-inlet mass spectrometer with a multiple ion beam collection facility (VG OPTIMA) in order to normalise ^{14}C data to $-25\text{‰ } \delta^{13}\text{C}_{\text{VPDB}}$.

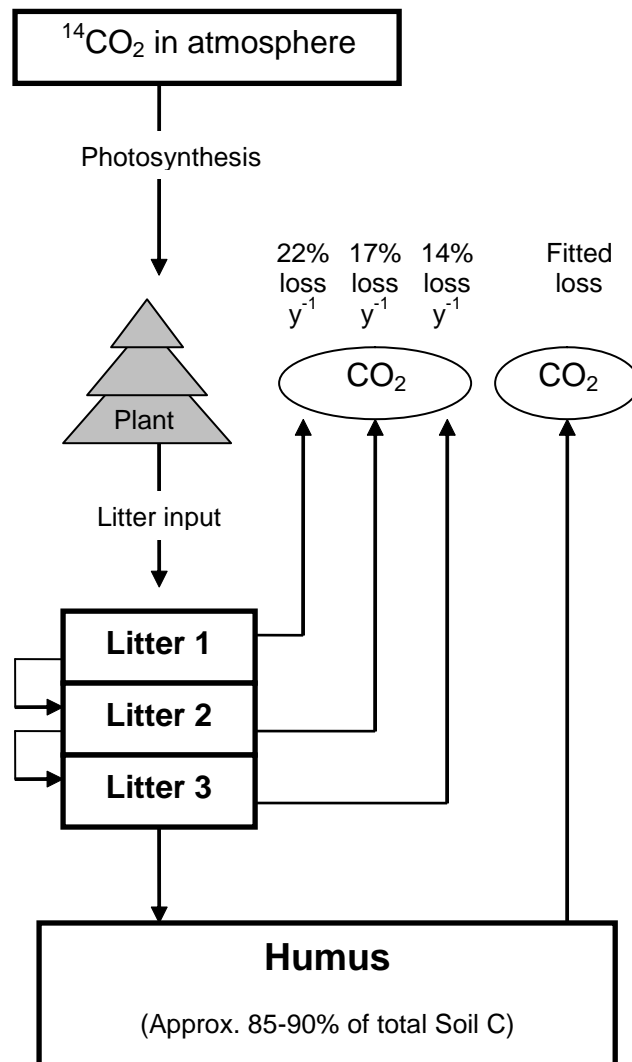


Figure 2. The litter for each year is labeled with ^{14}C according to the varying ^{14}C in the atmosphere. During the first three years the C remains in the litter pool, where 22%, 17% and 14% of the SOC is lost annually, together with the accompanying ^{14}C . After the third year the litter cohort is transferred to the humus pool. Litter input is equal to total CO_2 loss and kept constant between years (i.e. all C pools in the model are in 'steady state'). The ^{14}C concentration in the humus pool at each point in time is sensitive to the mean residence time (MRT), which is equal to $[\text{SOC pool}] / [\text{annual C flux}]$. Fitting is done by adjusting the litter/ CO_2 flux (and therefore MRT) in order to minimize the sum of squares for the difference between measured and modeled ^{14}C .

Estimating litterfall and mean residence times using ¹⁴C data

The ¹⁴C soil organic matter turnover model is a simple steady state model based on yearly cohorts of litter input (Figure 2). It is assumed that the plant material is labelled according to the varying ¹⁴C content in the atmosphere and therefore each year's litter has a unique ¹⁴C concentration. The ¹⁴C is slowly decaying with time, but otherwise acts like any other SOC. While the amount of SOC is kept constant, the ¹⁴C concentrations in all SOC pools are varying with time. SOC in the model is divided into a litter pool model acting during the three first years of decomposition and a humus pool in which the SOC decomposes with a constant rate (i.e. 1st order kinetics). Throughout this manuscript the term 'humus' is used as the name for this more slowly decomposing part of the O horizon. The model was run from year 1000 AD to allow steady state in ¹⁴C well before the bomb ¹⁴C peak. Atmospheric ¹⁴C data for the period 1000 to 2004 (Figure 3) were obtained from INTCAL04 to 1950 (Reimer et al., 2004), from Hua & Barbetti (2004) to 1998 (Northern Hemisphere zone 1), and from Levin & Kromer (2004) to 2003.

The litter pool consists of three cohorts of SOC with its accompanying ¹⁴C. The input rate to this pool is kept constant between years, but the ¹⁴C in each year's litter varies with the ¹⁴C concentration in the atmosphere. ¹⁴C for litter entering the system (¹⁴Clitt1) is calculated from equation 2.

$$^{14}\text{Clitt1}_y = ^{14}\text{Catm}_{(y-d)} \quad (2)$$

¹⁴Catm_(y-d) is the ¹⁴C concentration in the northern hemisphere atmosphere for a particular year (y), adjusted for a delay (d) in timing of ¹⁴C entering in the litter pool relative to the ¹⁴C concentration in the atmosphere.. The C in each yearly litter cohort keeps its ¹⁴C-integrity until it is transferred to the humus pool after three years as ¹⁴Clitt3.

In the litter pool a certain fraction of the C, with the accompanying amount of ¹⁴C, in each litter cohort is lost each year (equation 3). The size of the remaining carbon in each litter cohort (Litt) is calculated as a fraction (f) of the annual litter fall (LF).

$$\text{Litt}_i = f * \text{LF} \quad (3)$$

For the three years of litter decomposition in the model, f was set to 0.78, 0.61 and 0.47 for year 1, 2 and 3 respectively, based on literature data from Swedish litter bag studies using spruce needles (Johansson, 1986). The model is not particularly sensitive to the parameters in the litter decomposition model, as the litter pool contains only about 10-15% of the total pool in both humus and litter. Moreover the sensitivity to climatic differences for early-stage spruce litter decomposition in Scandinavia has been shown to be small (Berg et al. 2000). The fraction of litter lost from each cohort was therefore kept equal for all regions in this part of the model. After three years the remaining C and ¹⁴C in the litter is transferred to the humus pool, which means that the annual influx of carbon to the humus pool (Hum_{in}) is equal to 47% of annual litter fall.

The humus decomposition pool is a conventional steady state model in which a fraction of the humus pool is turned over annually. An equal amount of

C is lost annually, but this has a different ^{14}C concentration, equal to that in the total humus pool. The ^{14}C in the humus pool is calculated as

$$^{14}\text{CHum}_y = [^{14}\text{CHum}_{y-1} + (\text{Hum}_{\text{in}} * (^{14}\text{Clitt}_y - ^{14}\text{CHum}_{y-1})) / \text{Hum}] * e^{-\lambda} \quad (4)$$

where $^{14}\text{CHum}_{y-1}$ is the ^{14}C concentration in the humus pool for the previous year, Hum is the size of the humus pool and λ is the radioactive decay constant for ^{14}C .

MRT for the humus pool is equal to the size of the humus pool divided by annual humus input/output:

$$\text{MRT}_{\text{humus}} = \text{Hum} / \text{Hum}_{\text{in}} \quad (5)$$

The size of the annual carbon flux is optimized by minimizing the sum of squares for differences between the measured and the modelled ^{14}C for the total SOC pool, using the ‘Solver’ tool in Microsoft Excel. MRT estimated by this method is independent of the C stocks being used in the calculations. In practice, therefore, the size of the humus pool and the litter pools were estimated by matching the total SOC pool with data from the forest soil inventory and litter inputs were calculated from the relationship between annual fluxes and steady state pools. Steady state is an important model assumption. By choosing only old growth forests for our analyses we aimed to get as close to this ideal situation as possible.

Results

The MRT for the humus pool estimated by the ^{14}C model ranged from 28 to 41 years in the four different regions in Sweden (Table 2). The best fit to the ^{14}C data was obtained using a lag time of two years i.e. the atmospheric ^{14}C is shifted two years to allow for the time between photosynthesis and entry into the SOC pool. Measured and modelled ^{14}C with time are presented in Figure 3. The longest MRTs were found for the northern region, 41 years, and the southwestern region, 40 years, respectively. For the middle and central regions the MRTs were 36 and 28 years respectively (Table 2).

In contrast to MRT, the C stocks increased monotonously from north to south, with no exception for the southwestern region. C stocks ranged from 2.1 kg m⁻² in the north to 3.7 kg m⁻² in southwest (Table 2). Similarly, needle litterfall estimated from Swedish Forest Soil Inventory data increased from 43 g C m⁻² in the north to 94 g C m⁻² y⁻¹ in the south west, with the middle and central regions intermediate at 66 and 91 g C m⁻² y⁻¹ respectively. Total litter fall estimated from the ^{14}C model was different in magnitude, but had a similar pattern with 95 g m⁻² y⁻¹ in the north to 176 g m⁻² y⁻¹ in the southwest. Estimated by this method the litterfall in the central region was however slightly higher than in the southwest with 179 g m⁻² y⁻¹ (Table 2).

Birkenes had higher litter input and higher C stocks than all the regions in Sweden, whereas the MRT of 34 years was intermediate compared to the Swedish regions (Table 2).

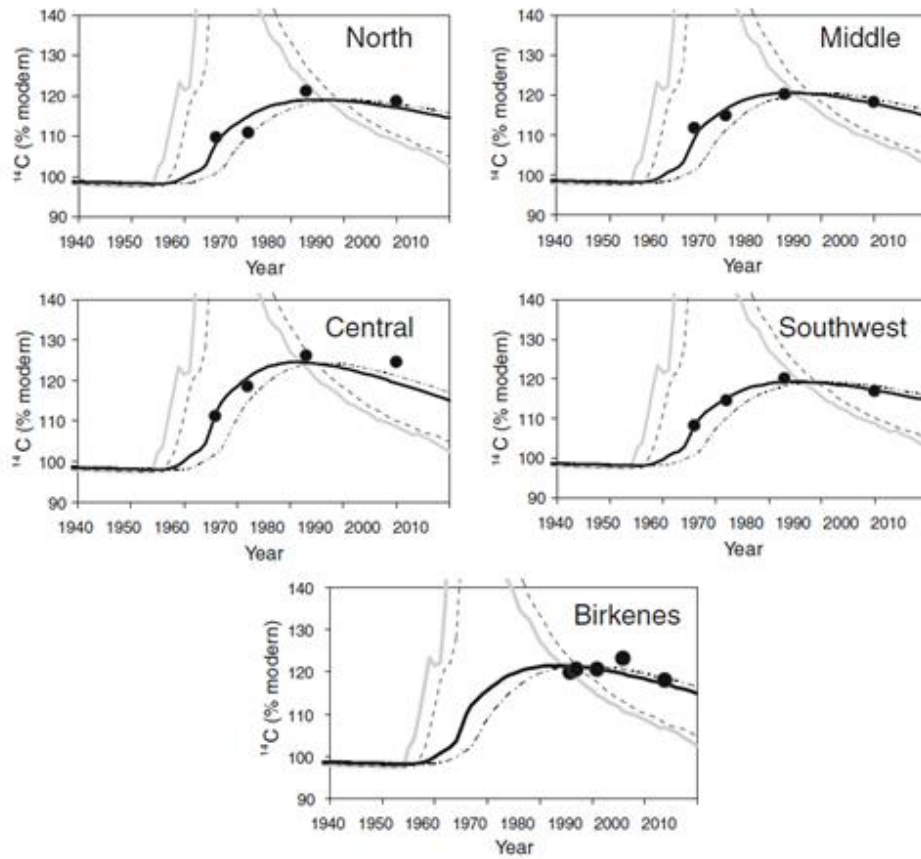


Figure 3. Measured and modeled ^{14}C for the four Swedish regions and Birkenes. Grey line represents measured atmospheric ^{14}C concentration. Broken lines represent the modeled litter and humus pools respectively and the solid black line the modeled combined ^{14}C for both these pools. Dots represent measured ^{14}C .

Table 2. Carbon stocks (with Standard error) and aboveground litterfall estimated from inventory data and modelled total litterfall and MRT.

	North	Middle	Central	South-west	Birkenes
Inventory data					
C stock (kg m^{-2})	2.1 ± 0.2	2.2 ± 0.1	2.8 ± 0.2	3.7 ± 0.2	5.3
Aboveground litterfall ($\text{g C m}^{-2} \text{y}^{-1}$)	43	66	91	94	140
^{14}C model					
Total litter inputs ($\text{g C m}^{-2} \text{y}^{-1}$)	95	111	179	176	311
MRT, humus pool (y)	41	36	28	40	34

Discussion

The determination of MRTs was made possible by the use of archived soil samples. By fitting a line through several points instead of though just one point in time greatly improves the robustness of the MRT. In addition, as the bomb-¹⁴C peak is gradually disappearing and is now close to pre-bomb levels, the separation in ¹⁴C concentration for SOM pools with different residence times is currently not particularly useful for determination of MRT. In our simple model we separate the litter decomposition stage from humus decomposition into a two-box model. We did not expect this simple model to give such a good fit to the ¹⁴C data, but by use of the long time series of ¹⁴C measurements, the model is well-constrained. For a single site, local environmental factors may play a significant role for both litter production and decomposition rates, but the Birkenes dataset was anyway in good agreement with the Swedish regional data, which supports the general applicability of the ¹⁴C decomposition model for O-horizons in Scandinavian forests.

An important result from the data presented here was that there was no need for either a recalcitrant pool of SOC or a wide range of different turnover times, but instead the data suggest an initial phase of rapid C loss during a few years, followed by a stage with a slower but more or less constant mineralization rate. The results instead suggest that decomposition of SOM in pure organic horizons without interactions with mineral soil particles proceeds at a steady pace. The results thus challenge the view that a certain fraction of litter is recalcitrant (Berg, 2000).

The estimates of litter inputs from inventory data and from ¹⁴C data are in good agreement once root litter and understory vegetation litter have been taken into consideration. Needle litter inputs estimated from inventory data were on average 51% of total litter inputs estimated from ¹⁴C data. As a comparison, root and understory vegetation contributed to about 40% of the litter input to the O horizon in three intensively monitored spruce stands at different sites in Sweden (Kleja et al. 2008). With understory vegetation and root litter inputs taken into account, litterfall estimated by the two different methods are both similar in magnitude and show similar geographical patterns.

The amount of organic matter in soils is a function of both litter inputs and the MRT. We conclude however, from the data in this study that litter input is the main governing factor for differences in SOC stocks between regions. Both litter inputs and MRT differ between regions, but the relative difference is smaller for MRT. Annual litter inputs range from 95 g C m⁻² in the northern region to 311 g m⁻² in Birkenes, which is a more than threefold increase. The relative differences for SOC stocks were similar in magnitude, ranging from 2.1 to 5.3 kg C m⁻². In contrast, the difference between the shortest and longest MRT is only about 50% (from 28 to 41 years). The differences in SOC stocks were therefore much better explained by litter input than by MRT. The significant difference in SOC stocks between the central region and the southwestern region, despite small differences in litter inputs, illustrates however that both factors need to be taken into account.

Given the small dataset and the uncertainties of the MRTs, the implications of the data should be interpreted with caution. Nevertheless, based on

the data presented here we hypothesize that the differences in MRT and SOC stocks between regions may be explained by a combination of differences in climate and differences in N deposition. Temperature has been found to be well correlated with mineralization rate of soil organic matter in numerous studies from both laboratory and field (Hyvönen et al. 2007). Differences in temperature may therefore explain the decrease in MRT from the northern via the middle to the central region. Temperature differences cannot, however, explain the high MRT in the southwest, which has a mean temperature equal to or slightly warmer than the central region (Table 1). Here the long MRT may instead be explained by high N deposition, which has been shown to result in slower decomposition of humified organic matter (Berg & Matzner, 1997; Hyvönen et al. 2007). There is a gradient in N deposition along the whole country with lowest N deposition in the north and highest in the southwest. The inhibiting effect of N deposition on organic matter mineralization may therefore also occur in the other regions, but is likely more pronounced in the southwestern region, where N deposition is highest. At Birkenes too, high N deposition might explain the MRT being higher than expected from the mild climate. The trend with increasing SOC stocks with latitude across Scandinavia has in some previous studies been interpreted as an effect of a gradient in climate (Liski & Westman 1997; Callesen et al. 2003). It has however been suggested recently that the gradient in SOC is mainly related to a gradient in N deposition (Kleja et al. 2008), as N deposition has the dual effect of both increasing litter inputs and increasing MRT. This explanation is plausible, as it has been shown experimentally that biomass production in the types of forests found in Scandinavia are mainly limited by N and to a lesser degree by temperature (Jarvis & Linder 2000). Litterfall in turn is strongly related to production capacity and factors such as height, breast height diameter and basal area (Saarsalmi et al. 2007). From the data presented in this paper it was not possible to separate the effects of N deposition and temperature on litter input. It is likely that both factors are contributing to the strong gradient in litterfall from south to north.

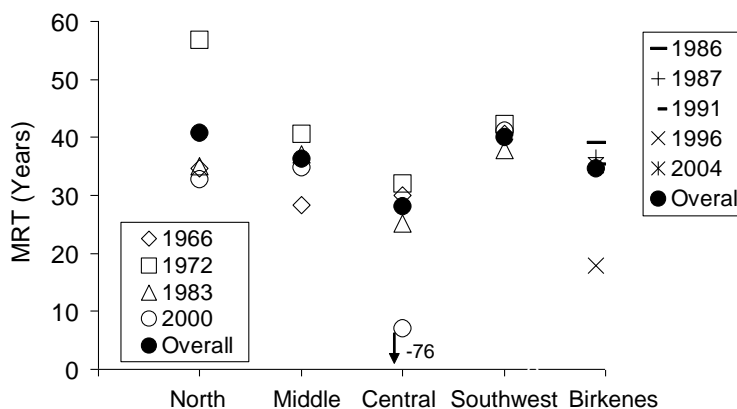


Figure 4. Model-estimate mean residence time for each single ^{14}C measurement. Symbols represent different years of sampling.

The calculated MRT for individual points were typically within 3-4 years of the MRT calculated from the overall best fit, but with some exceptions: one high MRT for the northern region of 57 years one low MRT for Birkenes of 18 years and one ^{14}C outside the rather narrow possible range for any positive MRTs for 2000 in the central region. (Figure 4). Within the range of the data, a difference in ^{14}C concentration of 1% corresponds to approximately 2-5 years difference in MRT, depending on the year of sampling. Steady state is an important assumption in the model. Berg et al. 2009 found an average annual increase in SOC stocks in Swedish spruce dominated forests of 24 g C m^{-2} during the last half century. This high level of increase in SOC as a result of higher litter inputs would increase the ^{14}C concentrations with about 4% during most of the post-bomb era, Such a change over time as a result of for example N deposition and altered management practices has not been taken into account in this first attempt to take advantage of the archived soils from the Swedish forest soil inventory. More ^{14}C data would make it meaningful to go beyond the simple steady state assumption and is necessary to confirm the spatial patterns and the explanations for these proposed here.

Concluding remarks

The use of archived soil samples was shown to be a very valuable tool for determination of soil organic matter mean residence times. An important observation from this study was that there were differences in MRT which could not be explained by the temperature gradient only, but must instead be related to other factors. One such factor may be N deposition.

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