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Accumulation of carbon and nitrogen in Swedish forest soils over stand age

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Abstract

Forest disturbance and harvesting regimes may affect the carbon (C) amounts stored in forest soils. The amount of soil C decreases after harvest and recovers gradually. Earlier chronosequence studies have suggested 50% decrease of the forest floor within the first 15 years after harvest. Increased decomposition rates and decreased litter input are considered to be the main factors that cause reduction of C pools in the soils.

The study utilized data from the Swedish National Forest Inventory and the National Forest Soil Inventory from all forest land in Sweden. The aim was to estimate the rate of gains and losses of soil organic C and nitrogen (N) over the forest stand age and to compare the results with data from literature. In the analysis climate, tree species composition, site index and soil moisture was considered to be the major variables that affect litter input and the decomposition rate. I separated the data in two categories for each variable, namely; south-north, spruce-pine, high-low and moist-dry for each variable respectively.

Comparisons of the two categories of each variable was made and the amounts of soil organic C in the O horizon of northern sites, pine dominant forests, low SI and dry soils were 44%, 24%, 30 % and 10% lower compared to southern, spruce, high SI and moist soils respectively. The same comparison showed that the N amount were 64%, 44%, 60% and 12% lower for the respective groups. Third order polynomial regressions were used to evaluate the effects of the variables by category. All categories followed the same time trend with decreasing amounts of C and N in the O horizon until a stand age between 29 to 50 years. However, the magnitude of the change varied between 9 to 30% of the initial carbon amount. Thereafter the amount increased until the stand reached 100 years of age. Climate and tree composition were found to be key factors for determining the variation in soil organic C and N over stand age in Swedish forest soils

Key words: Soil organic carbon, Nitrogen, Stand age, Decomposition, Litter input.

Popular science summary

Forests and their soils are important pools of carbon and nitrogen, and determine to a large degree the cycle of those two elements in the atmosphere. Forests' capacity to absorb or release carbon varies over time, and a forest behaves either as carbon source or as a sink. Understanding the dynamic role of those cycles is important to mitigate climate change but also to improve forest management schemes and productivity of the soils.

W. Covington (1981), collected soil samples from different aged forests and measured the amounts of carbon in the soil of each of them. The aim of this chronosequence study was to establish a curve showing how carbon increases or decreases in relation to the forest age. Covington's study showed that after harvest soil carbon amounts decrease and reaches a minimum value after 15 years, which corresponds to about 50% of the initial – consequently forests behave as carbon sources after clear-cut. After that age carbon starts to accumulate in the soil until it reaches the initial values – forests behave as carbon sinks. He attributed those results to decreased rates of litter input and increased decomposition rates from microorganisms in the soil during the initial years. The study turned to be very influential and widely applied, but at the same the study faced a lot of criticism.

In this study I have utilized data from the Swedish National Forest Inventory and the National Forest Soil Inventory from all forest land in Sweden. The aim of this study is to determine how carbon and nitrogen are accumulated in the forest soils of Sweden over the age of the forests. In the analysis I assumed that there are different variables that affect decomposition rates and litter input in forests, e.g.; climate, tree species composition, site index and soil moisture. I separated the data in two categories for each variable, namely; south-north, spruce-pine, high-low and moist-dry.

The results suggest that indeed there is a decrease of carbon and nitrogen over the first years of the stand after harvest; however the amount of carbon lost from soil due to decomposition is much less than the 50% observed by Covington. The results suggest that the initial decrease of carbon corresponds to about 13 to 27 % over the first 29 to 50 years of stand age. The amounts of carbon in the O horizon (humus layer) of the soil of northern sites, pine dominant forests, low site index and dry soils were 44%, 24%, 30 % and 10% lower compared to southern, spruce, high site index and moist soils, respectively. The same comparison showed that the nitrogen amount were 64%, 44%, 60% and 12% lower for the respective groups.

From this study we can conclude that there is indeed a reduction of carbon in the forest soils over the first years after harvest. However, the amounts lost and the periods in which losses occur depend on site specific variables. Climate and tree composition were found to be key variables for soil organic carbon and nitrogen variation over stand age in Swedish forest soils.

Contents

Introduction

Background

A good knowledge of the carbon (C) and nitrogen (N) dynamics in forest soils is a key to understand the role of forest in mitigating climate change and the long-term sustainability of forest management practices. The amounts and concentrations of C and N in soil organic matter are often used as indicators of soil fertility (Johnson and Curtis, 2001). Changes in the soil organic matter pool can result in significant contributions to emissions or uptake of green-house gases from forests. Out of the global terrestrial C budget, forest ecosystems contain 80% of the aboveground and 40% of the belowground C (Dixon, 1994). From the global forest C (1150 Pg), it is estimated that approximately two thirds is stored in the forest soils (800 Pg) (Johnson and Curtis, 2001). In tropical forests, soils contain much less C than biomass C, whereas in boreal forests, the soil C exceeds the C amount stored in the biomass, partly due to accelerated decomposition rates in warmer climates (Schlesinger, 1977). Furthermore, the biomass of managed boreal forests has increased over the past century while that of tropical forests has decreased (Eliasson, 2007). Biomass increase in boreal forests can partly be attributed to active forest management (Van Minnen, 2008). In Sweden, the introduction of a law on forest management and management practises like clear-cutting, re-planting and regular thinning techniques on even-aged species have led to (1) an increase in the standing biomass and (2) an increased harvest rate (Östlund et al., 1997, Andersson and Östlund, 2004)

The availability of N in the soils is determined by processes of N mineralization, N immobilization, denitrification and organic matter decomposition (Yano et al., 2000). The cycle of N in the forests can strongly influence the C cycle as N is often the limiting nutrient in tree growth. In addition, the uptake of C depends on N availability in the plants both directly as part of the process of photosynthesis and indirectly by influencing the structure and size of the plant-leaf development (Eliasson, 2007, Van Minnen, 2008). In addition, because of the close connection between C and N, indices as the C:N ratio in the terrestrial systems are often used to indicate the fertility of the forest soil and changes of the index can indicate differences in the rates of litter decomposition (Van Minnen, 2008). Litter-fall is the largest inflow of C and nutrients to the forest floor, hence it is important for the forest-soil system and nutrient cycling (Starr et al., 2005).

The accumulation of C and N varies within different soil horizons and depths. Stevenson and Cole (1999) defined Soil Organic Matter (SOM) as all the components that can be partitioned in the following pools: litter, light fraction, microbial biomass, faunal biomass, belowground plant constituents, water soluble organics and stable humus. Humus is defined as the homogenous substance formed by the degraded litter of dead animals and plants. Soil organic carbon (SOC) refers to the amount of C that occurs in the SOM. SOM is abundant in the O (organic) horizon. The O horizon (or organic layer) is distinguished from the mineral soil when the fraction of C content in the former exceeds 20% (Yanai et al., 2003). It is classified according to the degree of the decomposition of the organic material in three layers; (1) the O_i or L layer consists of undecomposed litter, (2) the O_e or F layer, contains partly decomposed yet recognizable material and the (3) O_a or humified layer incorporates well decomposed material whose origin can no longer be recognized (Soil Survey Staff, 1999, Yanai et al.,2003). Commonly, the "forest floor" describes the part of the soil that includes the O horizon, however in some cases the mineral soil is also incorporated in the term e.g. (Johnson, 1992, Yanai et al., 2003). The dynamic growth of trees in the forests directly influences the forest soils. As the forest cover and biomass changes over time, so does the C and N amount in the soils. Today, because soils act as sources or sinks of C and determine the flux of the global C cycle, a considerable amount of research has been conducted in trying to link patterns and long term effects of C and N accumulation in the soil in connection to the forest age.

In an early study, Covington (1981) sampled plots from different aged forest stands having comparable site conditions. He used the plots for a chronosequence study in which he was able to illustrate the way C is accumulated in the forest floor over the rotation period. This study turned out to be influential, and the results triggered other researchers to review, verify or perform similar studies, most of them based either on chronosequence studies or modelling techniques. Furthermore, his results were widely applied for estimation of carbon storage to different regions, different soil types and depth and also applied to global carbon budgets; "It (Covington's study) is so widely believed, that it is used without citation which accords it the status of a paradigm in ecosystem science" (Yanai et al., 2003).

The forest floor development

The Changes of the O horizon mass follows a primary decline during the first years of the stand. After some years, the O horizon amount reaches a minimum value and starts increasing until it reaches a maximum amount. A small decline is thereafter observed, due to the fact that the trees have reached and passed the maximum rates of litter-fall, and finally the forest floor mass is stabilized (Sartz and Hutringer, 1950). Covington (1981) suggested that 15 years after harvest, the humus mass has reached the minimum value. He found that after this time the O horizon mass was reduced with up to 50% compared to the initial amount, corresponding to 30.7 $Mg \cdot ha^{-1}$ of forest floor organic matter (c. 1.6 $kg \cdot m^{-2}$ of SOC). Thereafter the O horizon amount increased rapidly for the next 50 years. When the stand reached maturity the increase in O horizon amount levelled off. Federer (1984) replicated and verified Covington's curve, however he suggested that the organic fraction of the forest floor may continue to decline over the first 40 years after harvest. Olsson (1996) observed a net reduction of C pools of about 17-22% at 15 years after harvest, a less dramatic but yet significant reduction. Peltoniemi (2004) using a simulation model, suggested a decrease of the O horizon amount of on average 9% about 16 to 22 years after clear cutting.

In his study, Covington (1981) used 14 sites in hardwood forests of different age after clear cutting, in New Hampshire, USA. His samples were selected under the assumption that the major variables influencing the forest floor accumulation are soil drainage, topographic position, site quality, slope and elevation. Such variables will determine the decomposition rates, which, during the initial period after clear-cut, are higher than accumulation. Once young trees grow older and a higher amount of biomass leads to a higher litter-fall rate, the O horizon starts developing and the accumulation rate increases and will finally reach a maximum level (Sartz and Hutringer, 1950).

The two major factors that Covington (1981) had put forward to explain his results were (1) the accelerated rates of decomposition during the first years after disturbance caused by harvest and (2) the changes of litter input over time.

The gradual development of forests over time influences the litter input and hence the nutrient pools in the soil. During the first years after establishment of the stand, litter input is low. When the stand is between 10 to 20 years of age, the litter input increases to its greater rate and levels off when trees reach an age of 30 to 50 years (Covington, 1981). Albrektson (1988) proposed maximum rates of litter input at stands of 50 years and decreased input thereafter. The trees starts to shed branch litter 10 years after stand establishment in managed forests, followed by a period of high input when the stand is young and lower inputs when it is older (Lehtonen et al., 2004). Covington and Aber (1980) suggested that, for some tree species in secondary succession, the canopy is closed 4 years after disturbance. They suggested that the accelerated rate of decomposition would decrease thereafter because of re-occurrence of moisture and temperature balances under a closed canopy. However, this interpretation was not entirely supported by Covington's results (Covington, 1981). He therefore suggested that the rates of decomposition at the earlier years were increased due to a higher concentration of nutrients in the leaves - which in turn are correlated to the nutrient availability in the soil. Thus, during the early years of succession, leaves have higher concentrations of nutrients and the litter they produce decompose easier than in older stands (Mitchel and Chandler, 1939, Mitchel, 1936, Scott, 1955, Covington, 1981). The above mentioned may indicate that accelerated rates of decomposition during the early years of the stand are attributed to increased temperature and moisture due to the open canopy of the area. But even after canopy closure (when moisture and temperature will return to initial values), the nutrient concentration of the leaves is relatively high and decomposes easier. The estimated times mentioned above are characterizing northern hardwood forests, where rotation periods are shorter than for boreal conifer forests.

The relations between forest stand age, litter input and decomposition rates that Covington suggested concern site specific Hardwood forests. Not only stand age affects decomposition rate and litter input. Site Index, tree composition, and climatic factors such as temperature, actual evapotranspiration, latitude, moisture are also factors that alter the rates of litter input and decomposition rates (Berg and Meentemeyer, 2001). The litter decay is a result of the soil microbial activity. However, the variables that will determine the degradation rate of the forest litter are climate and litter quality since they determine the conditions for the microbial activity (Nakatsubo et al., 1997, Lavelle et al., 1993, Prescott et al., 2000).

It is well known that humid and warmer climates have increased decomposition rates compared to colder and dryer, or wet, climates because in the first ones there is increased microbial activity and partly because of biomass growth which results in increased litter input to the forest floor (Kouki and Hokkanen, 1992). This is why decomposition rates are slower in boreal forests compared to temperate ones (Peltoniemi et al., 2004). Furthermore decreased decomposition rates and litter input at higher latitudes can also be attributed to shorter growing seasons (Albrektson, 1988, Starr et al., 2005).

Substrate quality of litter input is also a determinant of decomposition rates. Berg and Staaf (1980) indicate that there are at least three carbon compound groups; soluble compounds with fast turnover rates, cellulose and hemicelluloses with slower degradation rates and lastly parts of lignin and lignified cellulose and hemicelluloses that decompose very slowly. Nutrient availability in the soils is of major importance for the degradation rates of litter input. Initial decomposition rates are enhanced by increased concentrations of nutrients namely; N, P, S and K. However in later stages of decomposition, when the proportion of recalcitrant lignin compounds increases, it controls decay rates and retard the degradation (Starr et al., 2005, Berg et al., 2000). The most important factor for determining the rate of decay during the degradation of soluble compounds and cellulose is considered to be nutrient availability (Starr et al., 2005). Lignin will only influence the decay rate when its concentration is high and prevents nutrient release, unless concentration of nutrients “is exceptionally high” (Starr et al., 2005). Mellilo (1982) found a positive correlation between lignin-to-N ratios with the amount of litter biomass remaining in the forest floor, thus increase of the index implies slower decomposition rates and increase of the forest floor.

Tree species composition is influencing the chemical composition of litter input, and hence the decay of the litter-fall that can eventually influence the development of the forest floor and nutrient pools. Berg and Meentemeyer (2001) correlated the litter fall of pine and spruce species in connection to climatic variation and showed that there are increased amounts of litter input to the soil with increased evapotranspiration and warmer conditions. The results show higher litter input for spruce than for pine in the Scandinavian region. Peltoniemi (2004) estimated that needle litter-fall of pine is 60% of that for Norway spruce.

Site index is a variable that describes the potential productivity by taking into account several different site properties like soil texture, topography and soil moisture conditions. Since it is an index describing productivity (growth) of the site it may be correlated also to C storage in the O horizon.

Soil moisture is a factor that can significantly alter the biogeochemical cycles in the land-atmosphere system (Chen and Hu, 2004). In the unsaturated zone, the soil moisture conditions are resulting from a balance between precipitation, evapotranspiration and percolation towards the groundwater surface. While precipitation and evapotranspiration are climatic factors, the groundwater table level is also dependent on the topography of the landscape. Regions with shallow groundwater levels and significant hydraulic gradients between the root zone of the forest and the saturated zone can lead to continuous supplies of water to the root system, and the role of the groundwater level in variations of the root zone soil moisture becomes essential. The effect of groundwater can only be significant when the level is near the surface (Chen and Hu, 2004).

Most studies on soil carbon and nitrogen dynamics over stand age are either experimental results reflecting site specific conditions e.g. (Covington, 1981, Federer, 1984), or model estimations on a local or regional scale e.g.(Peltoniemi et al., 2004). In this study we used national forest and soil inventory data to study the C and N dynamics in Swedish forest soils. The data used were provided by the Swedish National Forest Soil Inventory and enabled an analysis of C and N variation over stand-age using the method of space-for-time substitution. The aim was to describe the temporal shifts of the C and N amount over stand age in Swedish forest soils and how this is influenced by stand and site properties. Based on the literature study and data availability we selected climate, tree species composition, site index and site moisture to be the most interesting variables. We present functions that describe how these variables affect the reductions and further increases of C and N amount in soils and compare the results to the influential model proposed by Covington (1981) and other data from literature.

Material and methods

The data used in this study is from the Swedish National Forest Inventory (NFI) and the Swedish Forest Soil Inventory (MI), using the inventory carried out between 1993 and 2002. The NFI and MI are repeated inventories providing information on forest and soil properties for Swedish forest land.

The forest inventory (NFI)

The NFI sampling method is designed to be objective and systematic. The sampling design utilizes square sample clusters (tracts) of sides approx. 800 to 1200m. Each tract consists of 8 sampling plots, 2 on each side of the square tract. Forest sampling tracts are systematically distributed but the sampling density and tract size varies in different regions. Therefore they represent different sizes of forest area. Sampling density in the south of Sweden is denser than in the north. The variable Areal Factor (AF) is used as an indicator of the forest area that each plot represents:

$$AF = \frac{\text{Total land area of county}}{\text{Sum of sampled area in county}}$$

The AF provides a weighing factor for the calculation of the average of each variable (V_i) for the stratum *i* as:

$$\widetilde{Vi} = \frac{\sum AFi * Vi}{\sum AFi}$$

Variables given and estimated from the NFI include: (1) The stand age of each plot (estimated as an average of the total number of trees in the plot). (2) The Least Cutting Age (LCA). It provides information on what, by law, is the minimum time of growth after which a forest can be harvested, ranges between 65 and 100 years. (3) The absolute stand age. Covington (1981) used absolute stand age as the independent variable in his functions. However, seen over a larger geographical area (like Sweden) there is not a constant relation between stand age and tree growth. Climate influences the growth of the tree and in Sweden a tree in the southern region reaches maturity at a younger age than a tree in northern region. Thus, in our analysis, the stand age of the trees was replaced by a variable called relative age (RA). The RA provides an indicator of the growth of the tree as a variable that takes into account the time of growth of a tree to reach maturity. It is a function of the LCA and the stand age, and it is estimated as:

$$RA = \frac{Stand\ age}{LCA * 1.1}$$

(4) The climate of Sweden can be broadly separated into two zones according to the biological border, *Limes Norrlandicus*, between boreal and temperate conditions (Gustafsson and Ahlen, 1996). In essence, the border between the two zones is the border between the boreal and the continental, cool summer climate of the cold temperate region separating the country between the north and the south (Gustafsson and Ahlen, 1996). Dependent variables

composing the climate of a site such as latitude, temperature, evapotranspiration can affect SOC storage on the O horizon. *Limes Norrlandicus* is a biological indicator presenting vegetation and biological patterns affected by the climatic factors of the site. The factor is closely correlated with the latitude, which can be considered as a representative measure of temperature conditions (Starr et al., 2005). (5) The tree species composition is estimated as the proportion of the total basal area that each species occupies in the plot in a relative proportional scale of 1/10 units. Data include species of pine (*Pinus sylvestris*), (*Pinus contorta*), spruce (*Picea abies*), beech (*Fagus sylvatica*), birch (*Betula sp.*), oak (*Quercus sp.*), aspen (*Populus tremula*) and other deciduous species. (6) The total mass of the stem, wood, bark, branches, needles and roots (7) The Site Index (SI) describes the potential of a tree species to grow on a particular site over a certain period, (e.g. 50 years), and is used as a measure of the productivity of the site.

The O horizon

Soil sampling by the MI was carried out on the permanent sampling plots of the NFI, with the difference that for every tract, 4 plots were sampled instead of 8 (1 on each side of the tract). The O horizon was sampled on all sites where the humus type was classified as mor (type 1 and type 2), moder, and peat-like mor. Peat soil types have been excluded from this study. The O horizon was morphologically separated from the mineral soil. The soil samples were dried, sieved in a 2 mm sieve and weighed. Since a certain area, determined by the area of the sampling augur and the number of subsamples the weight of the sample can be used to estimate the amount of O horizon material per area unit ($kg \cdot m^{-2}$).

The concentration of C and N was determined by elemental analysis using a LECO CHN analyser. The product of the element concentration to the soil amount provides the estimates of organic C and N amounts for each sampling plot ($kg\ m^{-2}$). The C to N ratio (C:N ratio) is the ratio (by weight) between C and N.

Mineral soil

The basic function used to determine the amount of carbon in a soil layer is based on the amount of carbon in a certain soil layer and the fraction of fine earth:

$$SOC_i = C_i \cdot Wfe_i$$

Where SOC_i is the amount of carbon found in soil layer $_i$ ($Mg \cdot ha^{-1}$) and C_i is the carbon concentration (%) in the fine earth fraction (<2 mm) and *Wfe*, is the amount of fine earth in the soil layer ($Mg\ ha^{-1}$). The amount of fine earth is dependent on the bulk density and amount of gravel, stones and boulders in the soil, hereafter referred to as stoniness. An empirical relationship between stoniness data collected 2003 and 2004 and a measured boulder frequency available for all the plots was used. Bulk density was predicted using a pedotransfer function,

$$BD = 1.5463 \cdot e^{-0.313\sqrt{C_i}} + 0.00207 \cdot AD$$

where C_i is the carbon concentration (%) in the fine earth fraction (<2 mm) and AD the average depth of the soil layer in cm.

After the estimates for stoniness and bulk density had been made the carbon amount in each sampled soil horizon at each plot was determined. Thereafter the soil carbon in soil horizons not sampled was determined by interpolation between layers and finally the soil carbon content down to 100 cm was calculated on a plot basis(SEPA, 2011).

Lastly, the classification of soil moisture class is based on expected depth of groundwater table (GWT). Dry sites are estimated to have a GWT > 2m, mesic sites to have a GWT between 1 to 2 m and sites with the GWT not deeper than 1m were considered to be fresh-moist, moist or wet depending on and wetness indicators.

Experimental design

This study used more than 5000 plots from all Swedish forest land. The data provided by the NFI and MI were used to divide the material into groups and the data on C and N amounts and C:N ratio was plotted against normalized stand age. The four variables that are studied in this paper are climate, tree composition, SI and soil moisture. Each variable was subject to division into two or more categories in order to determine if each variable affected the accumulation of C and N in the soil over stand age. Initially, the entire data was analysed for all Sweden without any subdivision.

Climate was considered by creating two categories of data dividing Sweden in boreal and temporal regions using the *Limes Norrlandicus* variable (Gustafsson and Ahlen, 1996). The boreal category is named North and the temperate zone is named South hereafter.

Tree species composition was divided into four categories; pine, spruce, deciduous forests and mixed forests according the species dominancy in each plot. The division was made by using the basal area proportion of each plot. Species with basal area representing >= 6/10 of the total basal area were considered to be the dominant species of the site. Sites with no species with a basal area of > 5/10 were considered as mixed forests.

The SI was used to separate the sites into fertile and less productive ones. When SI>25 then the sites were classified as “High” whereas when SI<25 sites were classified as “Low”.

Soil moisture was separated in two categories distinguishing “Dry” and “Moist” soils. Sites classified as either dry or mesic were considered “Dry” the remaining considered “Moist”.

For all the above mentioned categories, data was classified into 10 different RA classes of a range of 0.015 starting at a RA=0.075 and ending at RA=1.425. Changes of C, N mass and C:N ratio of the O horizon and mineral soil was analysed using RA as the independent variable. Once the groups were classified in RA classes we normalized the RA values as follows: For the group representing all Swedish data, we estimated the mean values of Stand age for each RA. For a RA closest to the value of 1, (in our case RA=0.975) we multiplied the mean value with the RA value. We then multiplied all RA class values with the same mean value of stand age. We used the same normalized values for all groups. In addition, the total amount of N was estimated for the site by adding the amount found in the O horizon with estimates of biomass N in order to estimate the total input and output for every RA interval. Lastly the C results were compared with the one provided by Covington (1981).

Statistical analysis

Once the NFI and MI data were divided in different categories, they all followed the same statistical analysis. C, N and C:N ratio, were log-transformed in order to obtain normal distribution in each category. Normality of the curve was tested by monitoring the skewness and kurtosis of each distribution curve and further tested with the Kolmogorov-Smirnov, the Cramer-Von Mises and the Anderson-Darling tests. Statistical summary over C, N, and C: N ratio was produced, indicating the mean of each variable, the number of observations for each class, the standard error, and the 95% confidence interval limits. ANOVA was further used to identify whether there were any significant differences between the means of each RA class and in case there were any, the Least Significant Difference (LSD) and the Tukey's Studentized Range (HSD) tests were used to identify within which classes the changes were significant.

Statistical analysis was made in order to obtain results presenting for each category the mean values of the logarithm of C, N and C: N ratio in each RA class along with the 95% upper and lower confidence limits. Those values were then back-transformed (exp(ln)) in order to obtain realistic amounts of C and N in kg·m^{-2} in the presentation.

The stand age of all categories was estimated by normalizing the RA. The mean value of stand age was calculated for RA=1 and thereafter all RA class values were multiplied by the average value of stand age that was calculated for RA = 1.

Lastly, for each category, a non-linear regression using a 3rd order polynomial model;

$$f(RA) = aRA^3 + bRA^2 + cRA + d$$

where a,b,c and are constants. performed. The regression was made for all categories (Table 2). In order to estimate the net balance of the N in the soil-forest system, the proportion of N concentration in each tree compartment-for each tree species- was used to estimate the total N in the soil and in the forest biomass volume (See table 1). The total N up-take was estimated by summing the mass of all stem, branches, needles and roots and multiplying by the proportion of the species occupancy (see Eq. 1) and the concentration of N in each tree compartment of the different species. The N concentration of birch was used for all deciduous species. The N concentrations were taken from an unpublished dataset collected at the NFI.

Table 1. Nitrogen concentrations (% of dry mass) in the different biomass components of pine, spruce and deciduous species

	Species		
Tree Fraction	Pine	Spruce	Deciduous
Stem	0.089	0.112	0.193
Branch	0.248	0.288	0.400
Needles	1.197	0.989	0
Roots	0.089	0.109	0.249

Equation 1. Estimation of N in each plot according to the fractions of table 1

$$\boldsymbol{N}(\boldsymbol{tc}) = \left(\mathbf{f} * \mathbf{m} * \left(\frac{\boldsymbol{Spruce}}{\mathbf{10}}\right)\right) + \left(\mathbf{f} * \mathbf{m} * \left(\frac{\boldsymbol{Pine}}{\mathbf{10}}\right)\right) + \left(\mathbf{f} * \mathbf{m} * \left(\frac{\boldsymbol{Deciduous}}{\mathbf{10}}\right)\right)$$

Where: N: total amount of Biomass N
m: Total mass of each tree compartment in each plot
f: the proportion of N up-taken in each tree compartment

Results

Soil Organic Carbon

All categories follow the same trend, SOC in the O horizon decreases in the young stands, then gradually increases until it the increase levels off. When the stand has reached older ages a small decrease is observed in some categories.

The regression coefficient, r^2, was estimated to determine the degree of correlation of the plotted variables. From the ten categories that we analyzed in this paper, plots from the southern region presented the highest correlation (r^2= 0.9) followed by Covington's data and Rich SI (r^2=0.86; r^2= 0.85 respectively). Categories characterized by poorer growth conditions showed lower values of r^2. However, spruce data had the lowest regression coefficient (r^2=0.32).

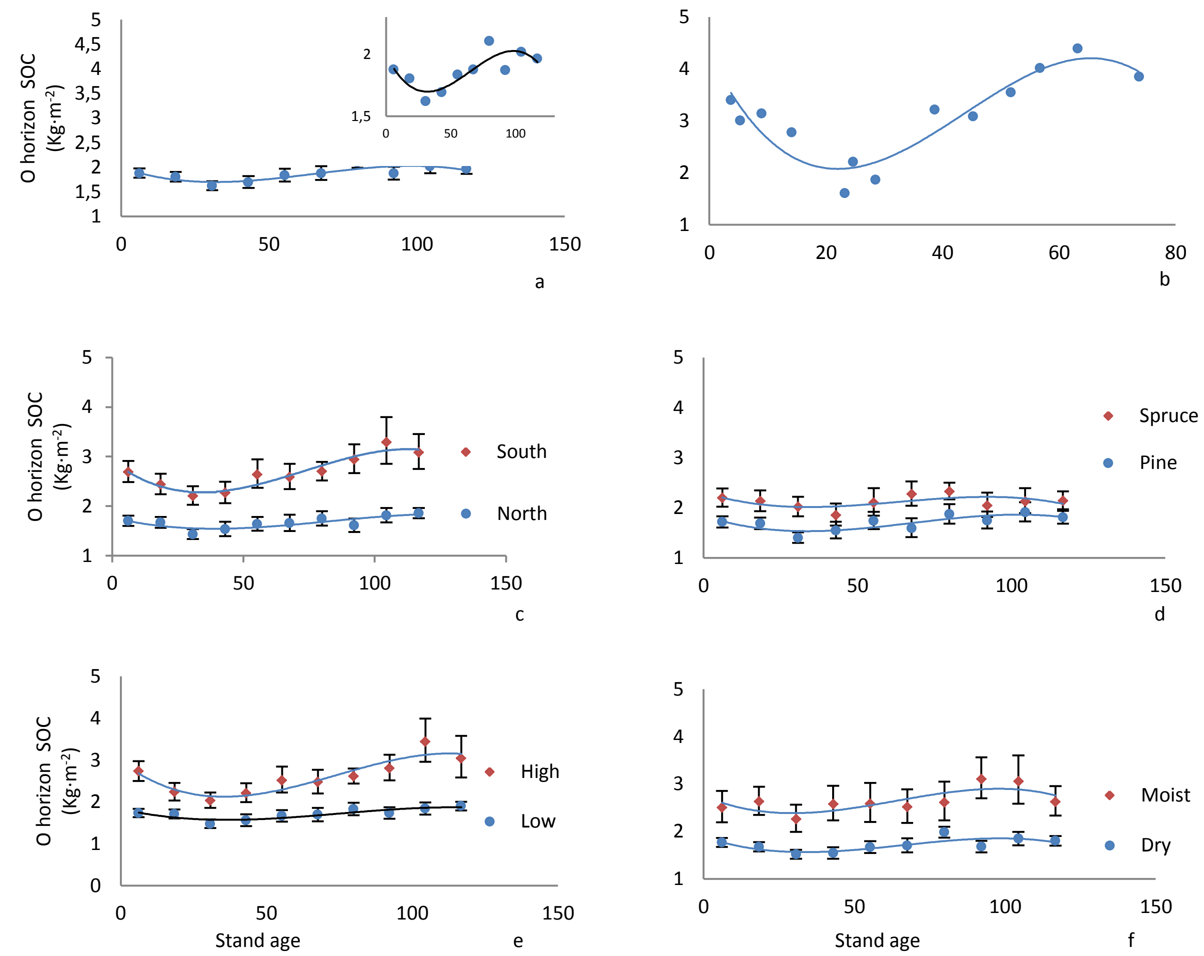

Figure 1. The mean of SOC (kg·m-2) vs normalized stand age for different variables and categories. The line is the 3rd order polynomial regression equation for each group. All data (a), Covington's data (b), climate regions (c), dominant tree species (d), SI (e) and soil moisture (f). The uncertainty bounds are 95% confidence intervals

Table 2. The third polynomial regression equations along with the regression coefficiets is presented for each group fpr SOC in the O horizon

	3^{rd} polynomial regression	Regression coefficient
Covington's data	$f(x) = -5\cdot10^{-5}\cdot x^3 + 6\cdot10^{-3}\cdot x^2 - 0.225\cdot x + 4.28$	$r^2 = 0.86$
All Sweden	$f(x) = -2\cdot10^{-6}\cdot x^3 + 4\cdot10^{-4}\cdot x^2 - 0.021\cdot x + 1.99$	$r^2 = 0.70$
South	$f(x) = -4\cdot10^{-6}\cdot x^3 + 8\cdot10^{-4}\cdot x^2 - 0.041\cdot x + 2.91$	$r^2 = 0.90$
North	$f(x) = -9\cdot10^{-7}\cdot x^3 + 2\cdot10^{-4}\cdot x^2 - 0.013\cdot x + 1.77$	$r^2 = 0.66$
Spruce	$f(x) = -2\cdot10^{-6}\cdot x^3 + 4\cdot10^{-4}\cdot x^2 - 0.019\cdot x + 2.31$	$r^2 = 0.32$
Pine	$f(x) = -2\cdot10^{-6}\cdot x^3 + 4\cdot10^{-4}\cdot x^2 - 0.021\cdot x + 1.84$	$r^2 = 0.64$
High	$f(x) = -4\cdot10^{-6}\cdot x^3 +1\cdot 10^{-3}\cdot x^2 - 0.054\cdot x + 2.97$	$r^2 = 0.85$
Low	$f(x) = -1\cdot10^{-6}\cdot x^3 + 3\cdot10^{-4}\cdot x^2 - 0.016\cdot x + 1.83$	$r^2 = 0.77$
Moist	$f(x) = -3\cdot10^{-6}\cdot x^3 + 6\cdot10^{-4}\cdot x^2 - 0.028\cdot x + 2.75$	$r^2 = 0.56$
Dry	$f(x) = -2\cdot10^{-6}\cdot x^3 + 4\cdot10^{-4}\cdot x^2 - 0.022\cdot x + 1.88$	$r^2 = 0.58$

From the regression equations given in Table 2 the results show that the intercept in Covington's data (d=4.28 kg·m^{-2}) is greater than for any other category, which means that the amount of C in the O horizon is greater in that type of forests than in the Swedish forests studied here. Plots in the southern region, high SI and moist soils have high amounts of SOC at initial stages of the rotation period (d= 2.91, d=2.97 and d=2.75 kg·m^{-2} respectively). In contrast, the lowest initial values of SOC in the O horizon are found in northern sites, pine forests and dry sites. The "*b*" constant of the regression indicates the curve's slope coefficient. Larger values of "*b*" indicate steeper and a greater amplitute in soil C pools over time. Again, Covington's data provide the steepest slope, significantly larger than the rest of the categories. The categories with the steeper slopes are data from high SI and the southern regions, in contrast low SI and plots in the northern regions that have more gradual curves. The negative value of the "*a*" constant that was found in all the regressions indicate the initial decrease of SOC. A positive values of the "*a*" constant would have implied initial increase of SOC, which we did not find in any category.

Table 3 below, provides information on the overall difference between paired categories, that is comparison within each variable. Climate is the variable with the the biggest influence on SOC in the O horizon. Amounts of SOC in the O horizon are more than 40 % less in the northern region (south= 2.60 Kg·m^{-2}; north= 1.66 Kg·m^{-2}) compared to the south. The age in which the minimum and maximum values of SOC of the O horizon (see Table 3.) were estimated by using the derivatives of the 3^{rd} order regression functions (Figure 2). Given the initial amounts of SOC ("d" constant) and the calculated minimum values, we estimated the relative decrease during that period.

Table 3. Comparison of accumulation of SOC in 10 different groups SOC minima and maxima derived from the regression equations and the relative decrease from the initial value. The relative difference of the mean values of SOC between paired categories is presented on the last column.

	Stand age of:		Percentage of difference	
	Minimum SOC (years)	Maximum SOC (years)	Decrease from initial value	paired categories Comparison
Sweden	36	97	16.5%	
Covington	22	70	51%	
South	35	96	22%	44%
North	50	99	15%	
Spruce	32	101	15%	24%
Pine	36	97	18%	
High	33	132	27.5%	30%
Low	32	169	13%	
Moist	29	103	13.5%	10%
Dry	37	96	18.5%	

SOC amount decreased with 51% in Covington's study over the first 22 years of the stand. None of the rest equations from this study show such a dramatic decrease. Instead, they vary between 15 % to more than 27 % decrease during the first 32 to 50 years of the stand age (see table3).

Covington (1981) used a gamma function to describe his data. His curve did not converge with our data when I tried to fit his equation in our data, thus we were not able to use the same function. Instead we used the 3rd order polynom equation described earlier (see Figure 2). The interpretation of the data becomes a little bit different with the two eqations. For example the polynom equation suggests minimum values of SOC 22 years after harvest compared to the gamma function that gave a minima at 15 years (Covington, 1981). The steepness of the polynom curve during the period of accumulation of SOC is also somewhat less pronounced than in the gamma equation. Finally, the "gamma" function does not account for the observed decrease of SOC on ages > 70 years.

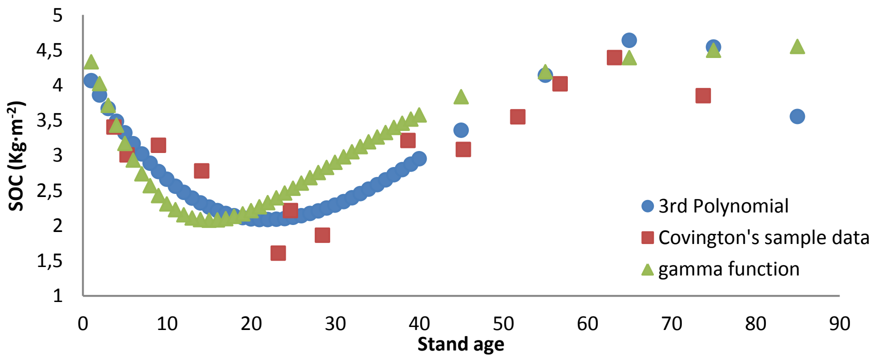

Figure 2. Covington's sampling data plotted on SOC ($Kg{\cdot}m^{-2}$) over the stand age. Covington's "gamma" function and our 3rd order polynomial regression are fitted to Covington's data

Organic Nitrogen

The results of N amount in the O horizon are very similar to SOC. Plots of N on the O horizon over the relative age show similar trends as that of C (see appendix I). N amount in the O horizon initially decreases and reaches a minimum value. Thereafter N is again accumulated in the O horizon and further increases again. In mature and old stands, the N amount decreases again approaching the initial values. The minimum value for N is in all groups given at an age of 32 years of the stand (RA = 0.375) except for that of spruce forests where the minimum value is observed at the stand age of 43 years (RA = 0.525). The loss of N over those first years account from 9 % up to 30 % decrease in N amount and differences between the separated categories of the variables vary from 12 % to 65 % (see table 2).

Biomass N was estimated in the study by using data on N concentration and the amount of biomass in different tree compartments of each species (see eq.1). The trend of biomass N follows a sigmoidal curve of low uptake during the first years of the stand, increased rates of uptakes and later on N in the plants stabilizes or sometimes losses are observed (see appendix I). Figure (3) presents the amount of N summed from (1) the biomass N system and (2) the changes observed during each RA class (≈12 years of stand age interval) in the O horizon. On the graph, the summed bar indicates possible losses or gains in the system by the following way: If there are losses from the O horizon over a given period, we can assume that N has become available through mineralization. If the released N exceeds the values up-taken from the biomass, it means that there is excess of N and it might be leached. If the loads of biomass N exceed the N released from the O horizon, it means that Biomass has another source of N (e.g. deposition). If there are both increases in the N up-take and O horizon it means that there is another source providing N (e.g. deposition). Lastly if there is loss of N over a period in the biomass N could imply that the system has reached maturity. Negative values of the sum indicate that the biomass increase is not as big as the N reduction from the O-horizon during a specified RA interval. That signifies that there is an excess of N. On the other hand, positive values of the sum indicate that the biomass have increased needs of N than the changes in the O horizon, thus deposition might be a source for up-take.

Table 4. The relative decrease of Organic N during the initial years of the stand are presented, and the relative difference between categories falling within the same variable

	Relative differences	
	Decrease from initial value	Paired Comparisons
Sweden	10 %	
South	15 %	65 %
North	14 %	
Spruce	13 %	44 %
Pine	16 %	
High	30 %	60 %
Low	13 %	
Moist	12 %	12 %
Dry	9 %	

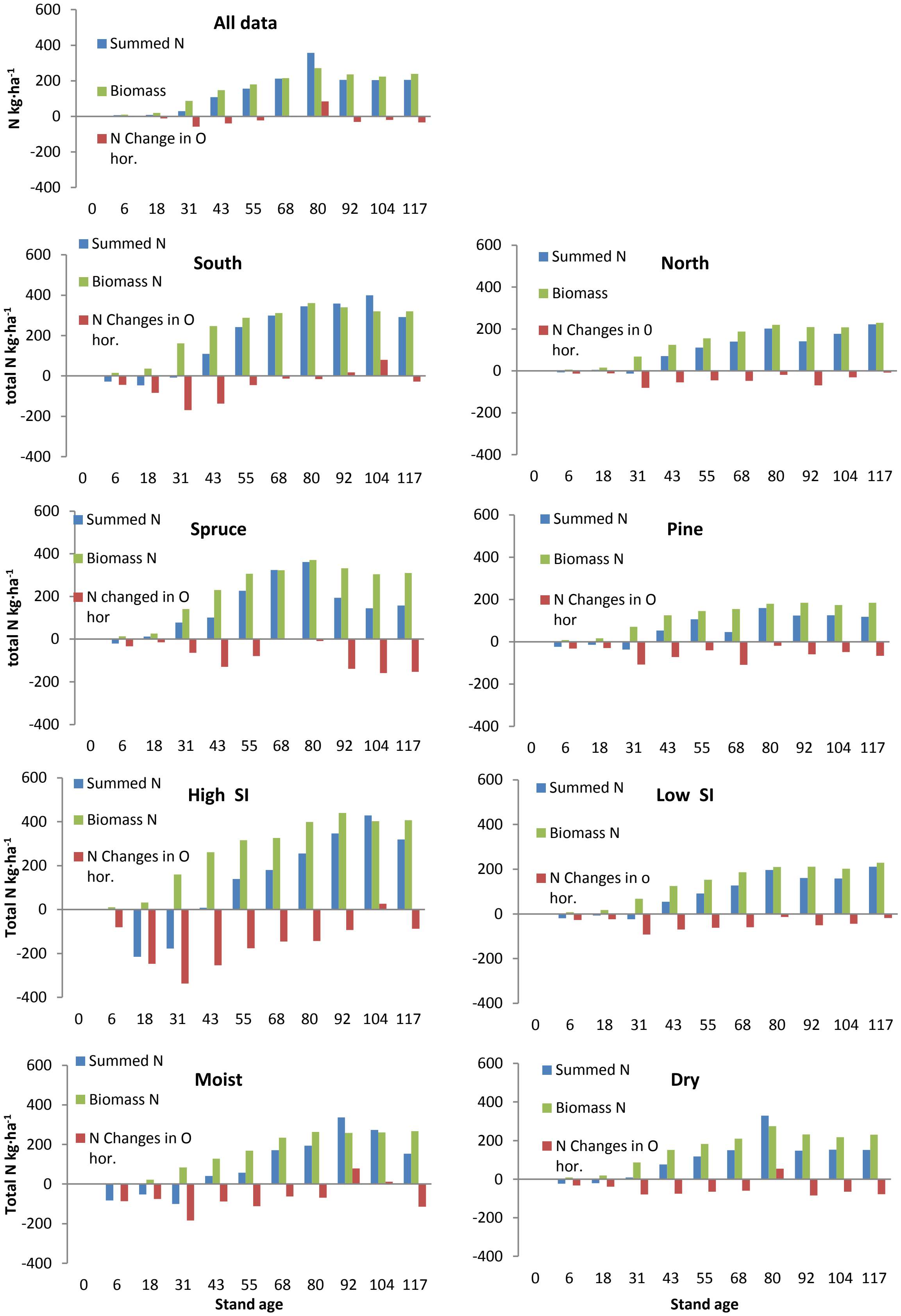

Figure 3. Summed amount of N (kg·ha^{-1}) between the changes observed in the O horizon and N up-taken from the trees of each site for each RA class (years), the Biomass up-take and the accumulated changes of N in the O horizon are illustrated in the graphs. RA has been normalized as stand age. The figures are presenting categories of climate, tree composition SI and moisture variables

In our results there is a decrease of N from the O horizon on the early years of the stand for all groups. During the first 30 years of the stand, most groups show that there is an excess of N. For the following years N is relatively stable, where biomass does not increase dramatically and changes in The O horizon are not very pronounced and on the later years of the stand, we observe decreases of biomass up-take and sometimes increases of the amount of N in the O horizon.

C:N ratio

The C:N ratio is plotted in Figure 4 for the different categories. It shows a discrete decrease of the index during the first years of the stand, later, the index values increase and decrease again at middle ages of the stand and increase again at late stages of the stand. This trend is less pronounced for moist soils and high SI, where the data do not show the initial decrease, but stay rather stable.

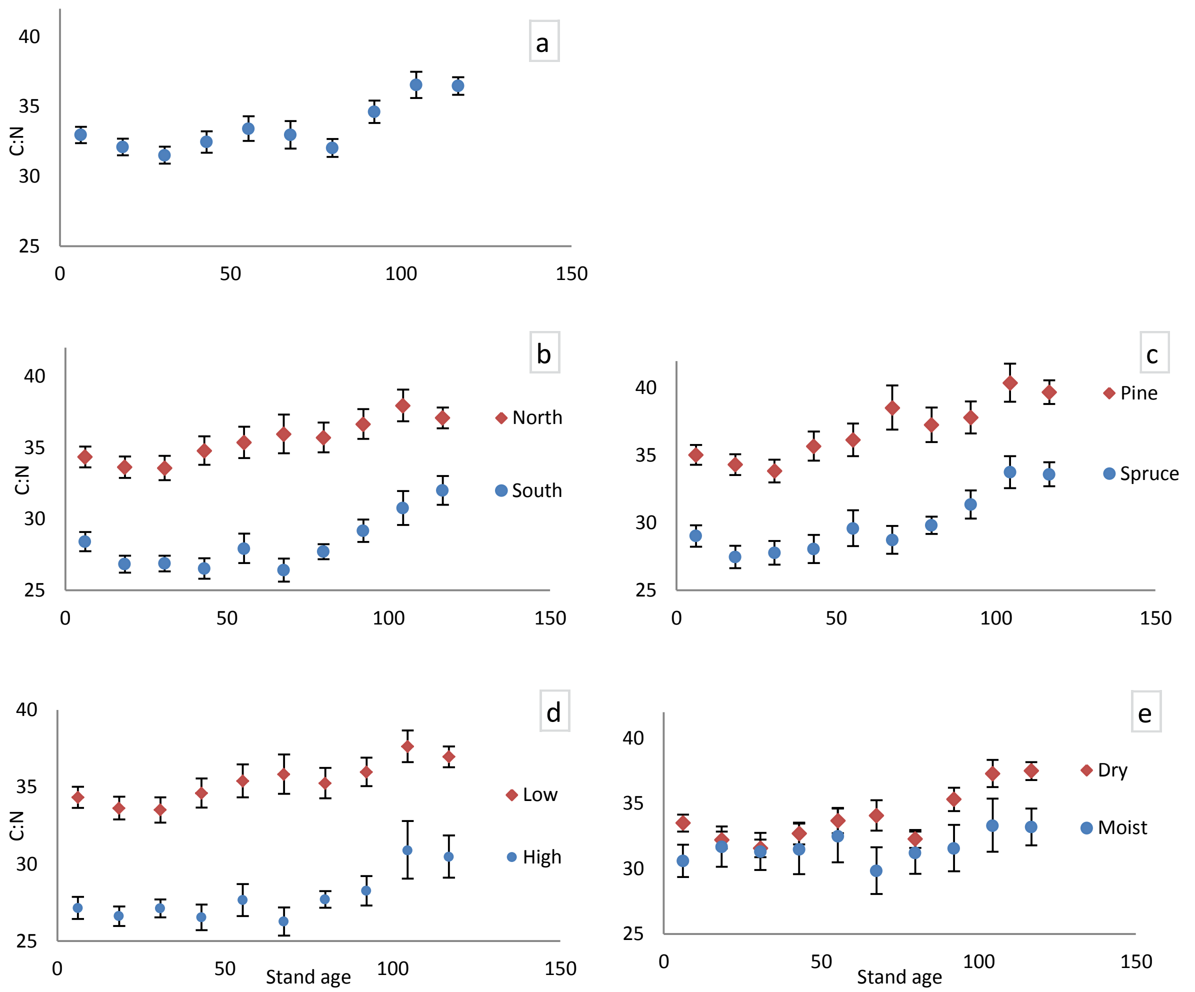

Figure 4. The C:N ratio vs. the normalized stand age (years); (a) all sweden, (b) climate, (c) tree species, (d) stand index and (e) site moisture. Error bars indicate 95% confidence intervals

For all variables the categories that have shown low values of SOC or N have higher C:N ratios. The C:N ratio is 20% lower in the southern region compared to northern, 17% lower in spruce forests compared to pine, 22% lower for high SI compared to low and 6% lower for moist soils compared to dry.

Lastly an interesting observation is that all C:N value tend to increase and be considerably higher over the late ages of the stand. A particular high increase is observed on groups of southern regions, spruce forests and high SI, but is also observed in the rest groups.

Mineral Soil

The changes of C and N mass in the mineral soil do not follow any noticeable trend over stand age (see appendix II). The amounts both of C and N were higher in the mineral soil than in the O horizon. However ANOVA tests showed no significant differences of C and N over the stand age. Paired categories separated within the studied variables did not have such pronounced differences as they had in the O horizon.

From the four variables studied in this paper, climate, tree species composition and SI show no effect on the amount of N in the mineral soil. Tree composition is the only variable for C that was found to have pronounced differences between paired categories, namely; There was 24% less C in pine forests compared to spruce (spruce: 7.38 $kg{\cdot}m^{-2}$, n= 1829; pine: 5.60 $kg{\cdot}m^{-2}$, n= 2559). On the same content for N, soil moisture is the only variable that provides distinct differences in N amounts. Dry soils have 33% less N content than moist soils. (Moist: 0.198 $kg{\cdot}m^{-2}$, n= 913, dry: 0.136 $kg{\cdot}m^{-2}$, n= 4168). Data from the mineral soil, when divided into RA classes showed larger variability. This contributes to the difficulty of finding significant differences

Discussion

Organic carbon

Our results from the SNFI and MI data that were analysed for SOC over the stand age confirm the expected trend that has been presented by earlier studies (Covington, 1981, Federer, 1984, Peltoniemi et al., 2004). A decrease of SOC during the initial years of the stand is caused because the rate of decomposition is higher than the rate of litter input. This results in a decreased amount of C in the soil. When the stand grows, the litter input is gradually increasing (litter input exceeds decomposition rates) and SOC increases and finally reaches a maximum. The C amount is then stabilized at about the same values as in the early years of the stand. The time after harvest, in which the stand reaches those observed minima and maxima are influenced by variables of climate, tree composition, SI and soil moisture (Tables 2; Figure 2.). In addition, high amounts of SOC are found in southern Sweden, spruce dominant forests, moist sites and sites with a high SI. The same groups, except spruce, have more pronounce variation over stand age.

We compared Covington's "gamma" function with the 3rd polynomial regression that we fitted to his data (Figure 2). Covington's curve has a minimum amount of SOC 15 years after harvest, compared to 22 years when using our type of equation. The steepness of the decreasing curve indicates the same amount of SOC lost (about 50 % of the amount compared to initial values), but the subsequent increase is slower in our regression. Covington's results suggest that the maximum amount of SOC is found 64 years after harvest whereas our regression suggests that amount to be reached first at 70 years after harvest. Furthermore, the levelling-off to the initial amounts of SOC with a slight decrease is not taken into account in the gamma function used by Covington. There is one draw-back of fitting a 3rd polynomial function to the data. The regression seems to fit relatively accurate with the trend of SOC over the stand age and illustrates both the decomposition process over the initial years and the build-up of the O horizon and indicates a maximum value. The disadvantage of the regression is that it does not stabilize when the stand have reached maturity but continue to decrease. For very old stands, the regression tends to decrease to values of 0 or even negative. However this does not prevent us from using the regression over the stand age where we have sufficient data.

Covington's data show considerably higher initial values of C and steeper decreases and increases of the SOC during the stand development. In no case did our results come close to Covington's values of initial SOC of 4.3 kg·m^{-2} or a 50% decrease of SOC at the minimum. In Sweden decomposition rates and further accumulation of the SOM are slower (lower values of constant "*b*"). Peltoniemi (2004) and Olsson (1996) observed smaller decreases (9% and 16% respectively) that occurred in stands older than 15 years. Federer (1984) also suggested prolonged periods of humus decrease (40 years). Their results seem to be more comparable with our results than Covington's.

Both Olsson (1996) and Peltoniemi (2004) have worked on boreal forests (Sweden and Finland, respectively) with pine and/or spruce dominant forests. When looking at our results in combination with previous studies, we can conclude that tree composition and the climate (latitude) are two important variables that account for the major differences in accumulation of SOC and N in the O horizon

Our results and regression analysis demonstrated increased SOC in southern regions compared to the northern regions. The "*Limes norrlandicus*" variable identified that SOC in the O horizon of boreal (northern) region is, overall, 45 % lower compared to temperate (southern) region. Covington (1981) suggested that slower decomposition rates and litter input to be the major explanation for the accumulation of humus in the O horizon. In addition (Bray and Gorham, 1964, Rodin and Bazilevich, 1967, Albrektson, 1988) observed negative correlations of litter input with latitude. Covington (1981) suggested that the maximum rate of litter input takes place at 10 year old stands and the rate decreases again on stands of 50 years. Our curves do not seem to agree with that estimate. Instead one can assume that maximum and minimum rates of the stand in northern coniferous forests come at later ages of the stand (ca. 30 years after harvest for minimum values and ca.90 years for maximum).Our suggested lower values of SOC in the O horizon in the boreal region could be partly attributed to lower temperature and shorter vegetation periods that limit litter input from the forest vegetation(Albrektson, 1988, Bray and Gorham, 1964, Peterson et al., 1983).

Decomposition rates of litter by microorganisms such as fungi and bacteria are not only constrained by climatic variables but also by the litter quality(Kelly and Henderson, 1978, Berg and Staaf, 1980). Tree composition affects the substrate quality of litter, and hence also the accumulation of SOC in the O horizon (Berg et al., 2000). The observed increased amounts of SOC in Covington's data, and the steep curve of accelerated decomposition rate and SOC build-up, are affected by the fact that conifers compared to hardwood (with which Covington has worked) have increased concentrations of lignin and decreased concentrations of nutrients (Berg and McClaugherty, 2003). Those two variables make decomposition of the litter harder. Comparison of chemical composition of conifers show that spruce has increased concentrations of both lignin and nutrients in the needles, thus litter input are expected to be decomposed harder (Reurslag and Berg, 1993, Berg and McClaugherty, 2003, Gosz, 1981). In agreement with previous studies (Berg and Meentemeyer, 2001, Peltoniemi et al., 2004), our data show smaller values of SOC in pine forests compared with spruce. The minimum amount of SOC is expected to be at 32 and 36 years of the stand for spruce and pine respectively. Berg et al. (2000) suggested that spruce needles stay attached on the branches of the tree for several months after their death. This might imply leaching of nutrient during the time that leaves are on the branches. That can lead to slower decay of the litter once it is on the ground because of increased lignin concentrations in the needles. According to such an assumption, spruce would have decreased decomposition rates and higher amounts of SOC compared to pine.

Tree composition and the following litter input to the forest floor and decomposition rates are affected by climatic variations. Ground climatic regulating factors, are well correlated to decomposition rates of pine. For spruce instead, the relationships between temperature, precipitation, water balance and decomposition rates are poor (Jansson and Berg, 1985, Berg et al., 2000). Albrekston (1988) confirmed Bray and Gorham's (1964) results of decreased litter-fall for pine stands when the latitude increases. However this is not the case for spruce stands. The substrate quality – rather than the latitude gradient – is the predominant factor of decomposition rates in the case of spruce (Berg et al., 2000).Increased litter-fall in both southern and northern regions could therefore explain the higher amounts of SOC in spruce forests compared to pine. In this study we have not taken into consideration interactions between tree composition and climatic variation, it is thus difficult to further conclude on the implications of tree composition to the O horizon development over stand age. However we know from our data that spruce dominates in the southern region, whereas pine dominates in northern sites.

Relationships between soil moisture and decomposition rates are positive. The microbial biomass weight is positively affected by increased soil moisture and subsequently the decomposition rate is higher (Donnelly et al., 1990). The amount of SOC in the group of dry soils is by 12% less than the group of moist soils. In addition moist soils present relatively high uncertainty ranges, probably due to the smaller number of data that fall within the moist class. In this study we have excluded histosols (peat soils), a type of soil that would most commonly be found in moist soil group. There are considerably less sites with the humus form mor in moist classes (n=913 compared to dry where n=4,168). In this study the contribution of the groundwater table level has been taken into account, indicating the influence of the groundwater as a variable able to influence litter degradation rates. Influence from precipitation and evapotranspiration has not been taken account, and those are variables that would normally significantly contribute to soil moisture. Nonetheless, our results suggest that the varying groundwater level can actually affect the SOC formation in the O horizon.

Fertile sites with high values of SI have higher amounts of SOC and more rapid initial decrease of the SOC. High values of the SI indicate faster growth and consequently larger amounts of litter input (Albrektson, 1988). In this study values with low SI have found to have 30 % less SOC compared to sites with high SI.

Organic N

The changes of organic N in the O horizon indicated decreases during the first years of the rotation period and further increase again. Reduced amounts of N in the O horizon during the initial stages of the stand vary from 9 % to 30 % for the individual separated groups. This trend is discrete over the stand age for most of our groups and, like Covington (1981) and Federer (1984), no significant differences were observed over stand age in most groups (Only high SI and dry soil have presented significant differences of organic N over stand age ($P<0.0001$)).

The composition of trees in a forest along with their metabolic reactions affects the build-up of the organic mor layer (Högberg, 2004). Pine translocate nutrients from older needles to other tissues before shedding its' needles. It is a mechanisms developed by species growing on nutrient poor soils (Berg and Staaf, 1980, Berg and McClaugherty, 2003, Gosz, 1981). Forest soils dominated with pine have 44% lower values of N in the O horizon compared to spruce. The ability of pine to grow and dominate more N-poor sites (Berg and Meentemeyer, 2001) in combination with decreased nutrient cycling will eventually have an effect on accumulation of N in the soil. The amount of N is considerably higher for high SI (organic N is 65 % less in low SI). high SI indicates soils of larger capacity to store nutrients and thus increased amounts of N in the O horizon. Dry soils have not been found to have major differences (10 % decreased) from moist soils in the content of N in the O horizon. It might be expected that groundwater table near the surface might be a factor of increased losses of N by leaching from the O horizon.

In this study concentrations of N have been estimated for the O horizon, mineral soil and tree biomass. No further information has been provided concerning atmospheric deposition, losses to the groundwater and atmosphere, and therefore only rough estimates for the nutrient's cycle can be made. Overall gains and losses of N from the O horizon/biomass system were presented on Figure 3. N in biomass was not as high as the losses observed from the O horizon during the initial stages of the stand, for most of our groups. The increased losses of N from the O horizon imply excess of N in the sites, and further loss, perhaps transported to the mineral soil or leached below. Given the fact that N losses occur at the same time that SOC is at minimum values can enhance the assumption of the decomposition of litter and further mineralization of N. Further on, for most groups N in the O horizon is decreased also during the middle ages of the stand. However, in this case losses that occur from the O horizon are not enough to support accumulation of N in biomass. For this reason we can assume that there is need for additional N in the system. During the late ages of the stand, we observe both a decrease of N in the biomass, which might imply that the trees have reached maturity and decreased their productivity.

C:N ratio

There is small decrease of C:N values during the first years of the stand, observed as a pattern in all our categories. The C:N ratio thereafter undergoes an overall increase over stand age indicating a build-up of carbon richer organic matter compounds. Olsson, (1996) also has observed decreased values of C:N during the first 8 to 15 years of the stand. Our results suggest somewhat longer periods. Decreasing C:N ratios indicate increased mineralization (Olsson et al., 1996).

The initial small decrease of C:N ratio can be attributed partially to the fact that degradation is faster than litter input. N remains relatively stable in the soil, compared to C that accumulates and reduces at faster rates. There has been no indication of increased C during the later period, yet all comparisons have shown decreases of N during the late years of the stand. Mineralization and leaching could be the main factors of this release, because the C content also decreases during those years. Decreases of N from the O horizon in the southern region, high SI and moist soils followed by increased values of N in the mineral soil support that assumption (See appendix II); however it is difficult to draw such a conclusion given the limitations of the data we have worked on. In addition a high C:N ratio may indicate slower decomposition rates due to high lignin-to-N ratios that retard the decaying procedure (Berg et al., 2000). In connection with less productive sites this can explain the steeper increases of C:N ratio in old stands. Lastly, it is also possible that those increases are attributed to statistical error occurred from the nature of our sampling data. High values of RA imply unmanaged forests and thus decreased values of N in the soils (see below).

Mineral soil

We have not found any pattern describing the variation of the mineral soil over the stand age. Wide levels of confidence interval limits both in C and N have prevented us from taking into account the mineral soil further into our study. Furthermore, C and N do not seem to be affected by the studied variables. C seems to be significantly affected only by the variable of tree composition, whereas N is affected by soil moisture (see appendix II).

Implications of harvest regimes

Disturbance caused to a forest system will influence the development and mass of the organic matter in the soil after harvest. The magnitude of gains, losses or no effects on the O horizon mass and nutrient content is determined by residue management practices, site conditions, site preparation practices and harvesting regimes (Johnson and Curtis, 2001). Johnson & Curtis (2001) assumed that there is a significant difference in the effect on soil C and N among different harvest methods; saw-log harvest causes increases in soil C and N and whole-tree harvest causes slight decreases. Modeling studies of the effects of different harvesting practices on the soil show that the forest floor in a clear cut stand is 60% higher than complete harvest 15 years after disturbance (Aber et al., 1978). Olsson (1996), in a comparison of whole tree harvest, conventional harvesting and branch and stem harvest, indicates that the effect of harvest intensity in C storage is not as pronounced in the O horizon or mineral soil. Partial or total removal of forest canopy can cause increased decomposition rates due to increased soil temperature and moisture (Piene, 1978, Edwards and Rosstodd, 1983, Federer, 1984). The opinions on the subject are however contradicting, and studies also suggest that there is no evident increase in the decomposition rate after clear-cutting (Prescott et al., 2000, Yin et al., 1989), or that the long-term effect on C and N storage over the years is small (Johnson, 1992, Johnson and Curtis, 2001). Yanai (2003) argues that Covington's results can be interpreted with different explanations. Mechanical mixing of the soil during or after harvest can alter the amount of C and N in the soil. Types of disturbance like tillage in the soil are expected to cause localized effects increasing the variation of organic matter in the content of each layer. Whole tree harvest can expose mineral soil in 8 to 18% of the area, and other types of disturbance can cause an effect on up to 71 to 92% of the area (Martin, 1988, Yanai et al., 2003). In the case of mechanical mixing, organic content will not be lost from the soil system but buried deeper. This will decrease the rates of accelerated decomposition originally proposed by Covington (Salonius, 1983, Federer, 1984). In addition, chronosequence studies may be problematic in accordance to C measuring techniques because of different harvesting schemes that have been used in history (Yanai et al., 2003). Swedish forest management introduced clear cut harvest in the mid 50's, so stands older than 50 or 60 years have been subject to different harvest regimes. In this study we have not taken into consideration the implications of SOC with different harvesting regimes but we assume that the stands of different ages have been treated with different harvesting techniques. The contradicting literature of the effects of C and N accumulation in the O horizon and mineral soil, and our lack of data on each plots harvesting regime, makes it difficult to interpret our results on basis of harvesting regimes.

Statistical considerations

RA was determined by the stand age and the LCA. The fact that LCA varies within ages of 65 to 100, indicates that stands older than 100 years (RA>0.909) have reached maturity and can be harvested. Existence of old stands that their age exceeds the LCA signify less intensively or not at all managed forests, since they have not been harvested by the time allowed. A representative group of such forests could include protected-unmanaged areas or unproductive sites. Such forests would be more commonly found in northern regions of Sweden. Perhaps losses of N during the late stages of the stands in figure 3 are simply reflections of old unmanaged forests with the averaged N amounts in the soil being low. In some cases it can be verified by decreased values of mineral N over the same ages. This artefact can be seen in the late stages of all graphs, C, N (N in biomass and O horizon) and C:N. The increase of C:N ratio can partially be attributed to this factor and also decreased values of C and N on the graphs. Areas of older stands and protected sites are mainly found in the northern region of Sweden, which represent low productive sites (Fridman, 2000, Andersson and Östlund, 2004).

All our different comparisons based on this study's dataset have been plotted using the same stand age values. As has earlier been explained, the aim of this study is not to deliver information on growth rates. It is apparent that if we compared stand of the same age in the northern and southern region, there would be significant differences in growth rates, and thus C and N accumulation. However this was not the aim of this study. The RA provides an indicator of maturity, implying that trees of the same RA are in the same stage of development. Comparing stands over the RA instead of the real stand age can actually provide information of the implications of climate to the soil C and N development. We normalized the RA in order to communicate our data more easily.

Conclusions

Changes in the C and N stock in the forest floor are complex and dependent on multiple variables. In this study, we have managed to specify the trend of changes of C in the forest soils for the whole region of Sweden over the stand development, under the current management practices, and comparing to Covington's study have found smaller decreases of C over longer periods of the stand. In addition, we have presented how different fitted regressions have a significant effect on predicting the ages of minimum amounts of C in the forest floor. In addition, in agreement with our hypothesis, there is support in our data for the hypothesis that changes in climate, species composition, site index and soil moisture affect the accumulation of C and N in the forest soil over stand age. The O horizon follows a well-defined cycle over that time, and the mentioned variables only affect the magnitudes of changes rather than altering the direction of change. The highest regression coefficients are found in sites with initially high amounts of C and N, (Covington's data, southern regions, high SI), whereas in other cases the changes of C and N over stand age are less pronounced. Wide confidence intervals and less pronounced differences prevented us from observing any significant changes over the stand age or between the variables for the mineral soil. We studied the effects of each variable separately. It is still unclear and further studying to be conducted on how the different variables interact with each other in determining the accumulation of C and N in the O horizon over the stand age.

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Appendix I: Nitrogen in the O horizon and biomass system (graphs and regressions)

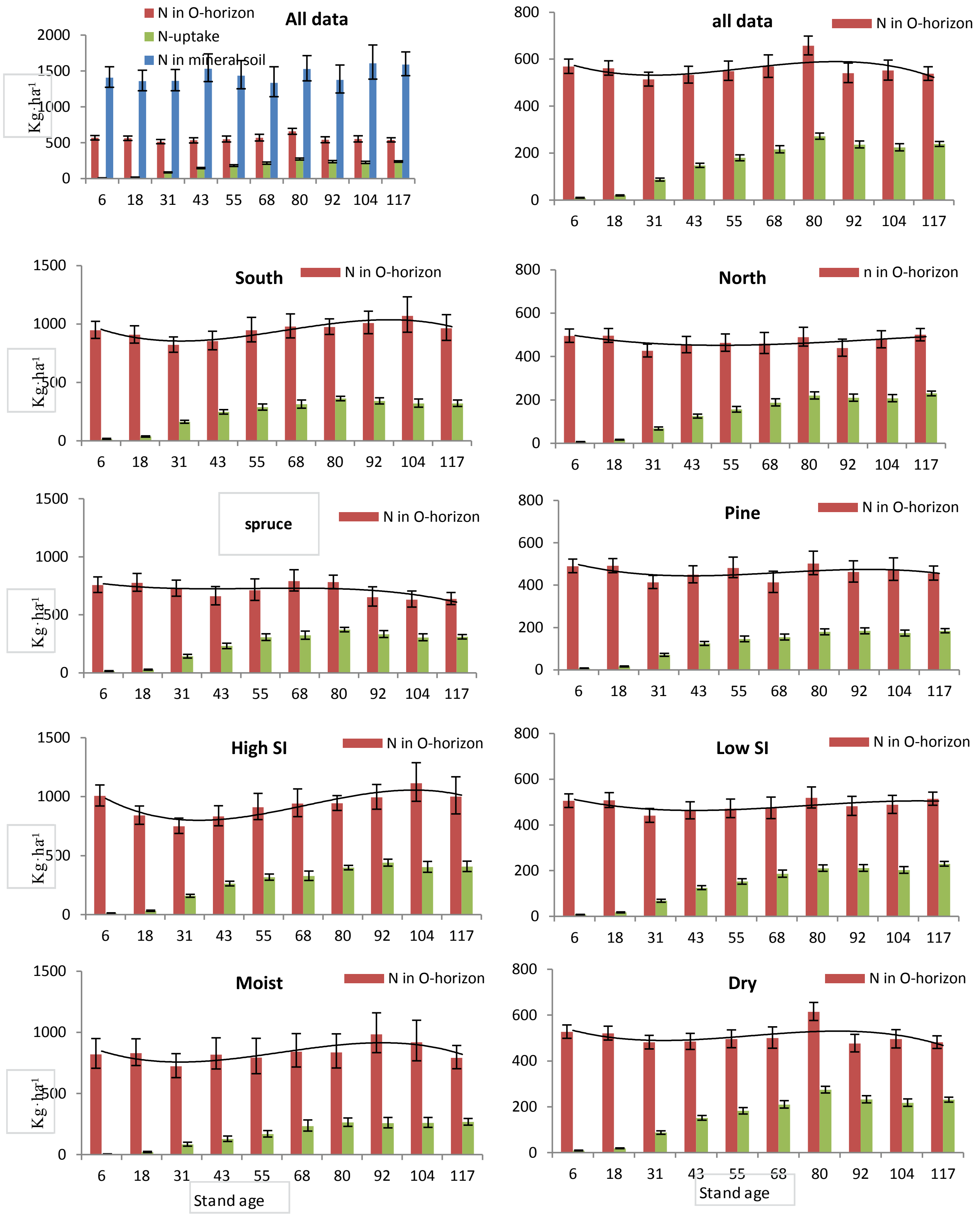

Figure 5. Accumulation of N over the stand age for O-horizon and biomass up-take Mean values of N ($Kg \cdot ha^{-1}$) for each RA class, and 95% CI are presented of N in the O horizon and the Biomass N are plotted over the stand age for all groups. In figure 5a also the N in the mineral soil is included, whereas in figure 5b, plots from all Sweden are plotted without the mineral N. figures 5c and d illustrate variations of N in the southern and northern region respectively. Figures 5e and 5f present groups of spruce and pine, figures 5g and 5h groups of high and low SI and lastly in figure 5i and 5j plots over soil moisture are illustrated

Table 5. The third polynomial regression equations along with the regression coefficients is presented for each group for N in the O horizon

	3rd polynomial regression	Regression coefficient
All Sweden	$f(x) = -2.00 \cdot 10^{-4} \cdot x^3 + 4.16 \cdot 10^{-3} \cdot x^2 - 1.98 \cdot x + 571.97$	$r^2 = 0.20$
South	$f(x) = -1.10 \cdot 10^{-3} \cdot x^3 + 2.15 \cdot 10^{-1} \cdot x^2 - 9.51 \cdot x + 991.21$	$r^2 = 0.83$
North	$f(x) = -7.00 \cdot 10^{-5} \cdot x^3 + 2.37 \cdot 10^{-2} \cdot x^2 - 2.10 \cdot x + 507.78$	$r^2 = 0.39$
Spruce	$f(x) = -290.90 \cdot x^3 + 565.04 \cdot x^2 - 342.14 \cdot x + 790.35$	$r^2 = 0.49$
Pine	$f(x) = -210.08 \cdot x^3 + 521.84 \cdot x^2 - 363.28 \cdot x + 521.62$	$r^2 = 0.26$
High	$f(x) = -945.63 \cdot x^3 + 237.37 \cdot 10 \cdot x^2 - 151.44 \cdot 10 \cdot x + 1087.00$	$r^2 = 0.84$
Low	$f(x) = -145.85 \cdot x^3 + 407.84 \cdot x^2 - 304.82 \cdot x + 532.32$	$r^2 = 0.48$
Moist	$f(x) = -731.45 \cdot x^3 + 163.61 \cdot 10 \cdot x^2 - 906.65 \cdot x + 906.32$	$r^2 = 0.62$
Dry	$f(x) = -316.20 \cdot x^3 + 685.97 \cdot x^2 - 400.06 \cdot x + 559.86$	$r^2 = 0.25$

Appendix II: The mineral soil

C in the Mineral soil

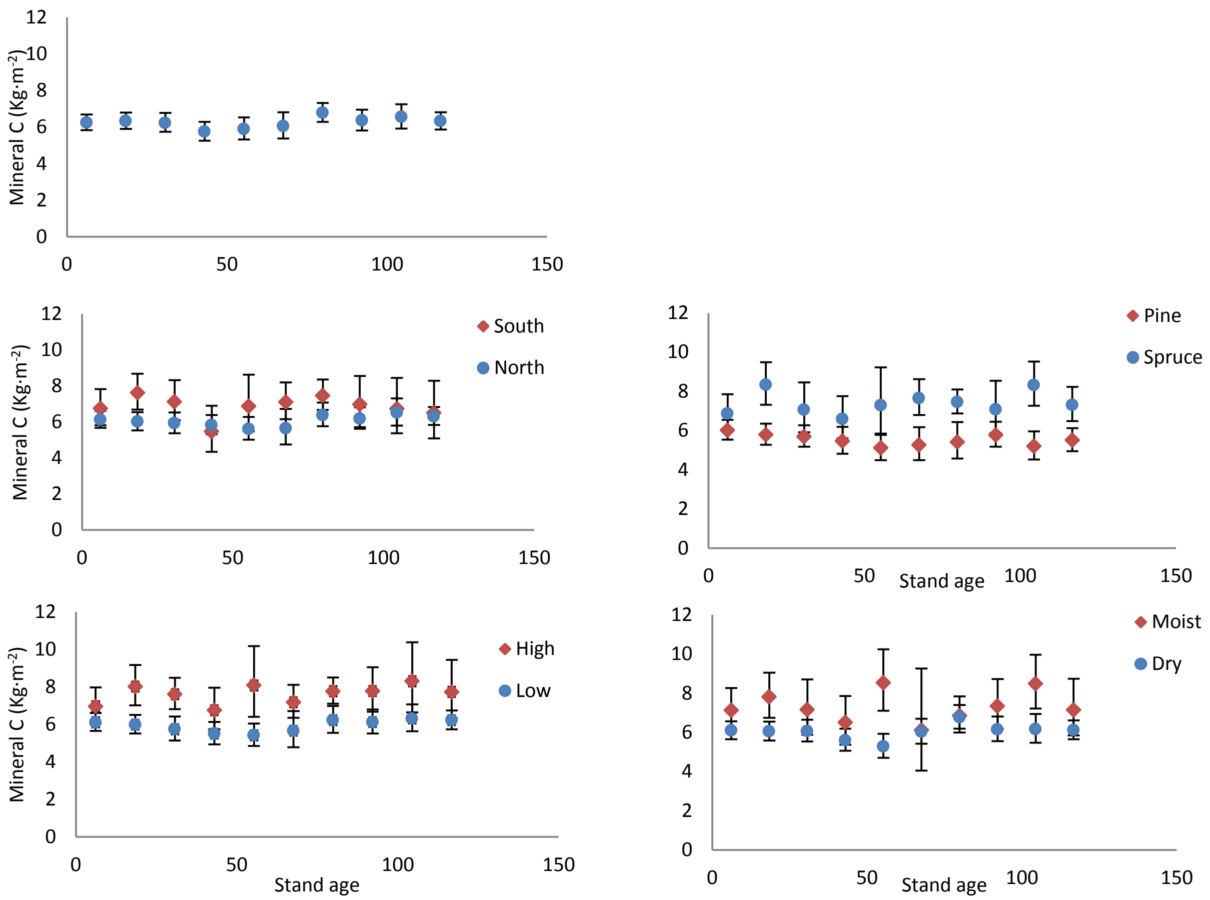

Figure 5. Mineral carbon over the stand age. Mean values of mineral C (kg·m^{-2}) for each RA class, 95% confidence intervals, for the 9 groups over the stand age, namely; all data, North and South, Spruce and Pine, High SI and Low Si, Moist soils and Dry soils

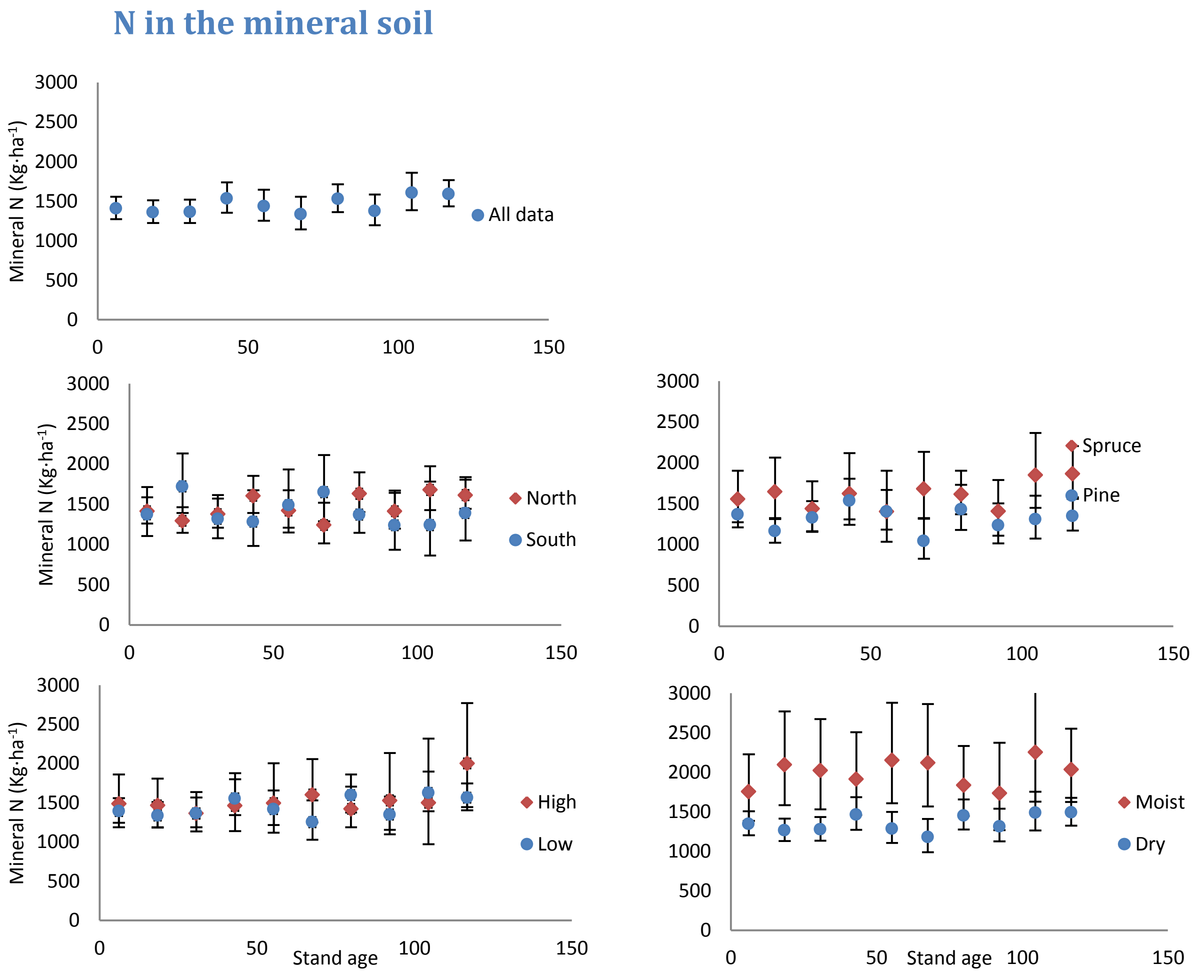

Figure 6. Mean values of mineral N (kg·ha^{-1}) for each RA class, 95% confidence intervals, for the 9 groups over the stand age, namely; all data, North and South, Spruce and Pine, High SI and Poor SI, Moist soils and Dry soils

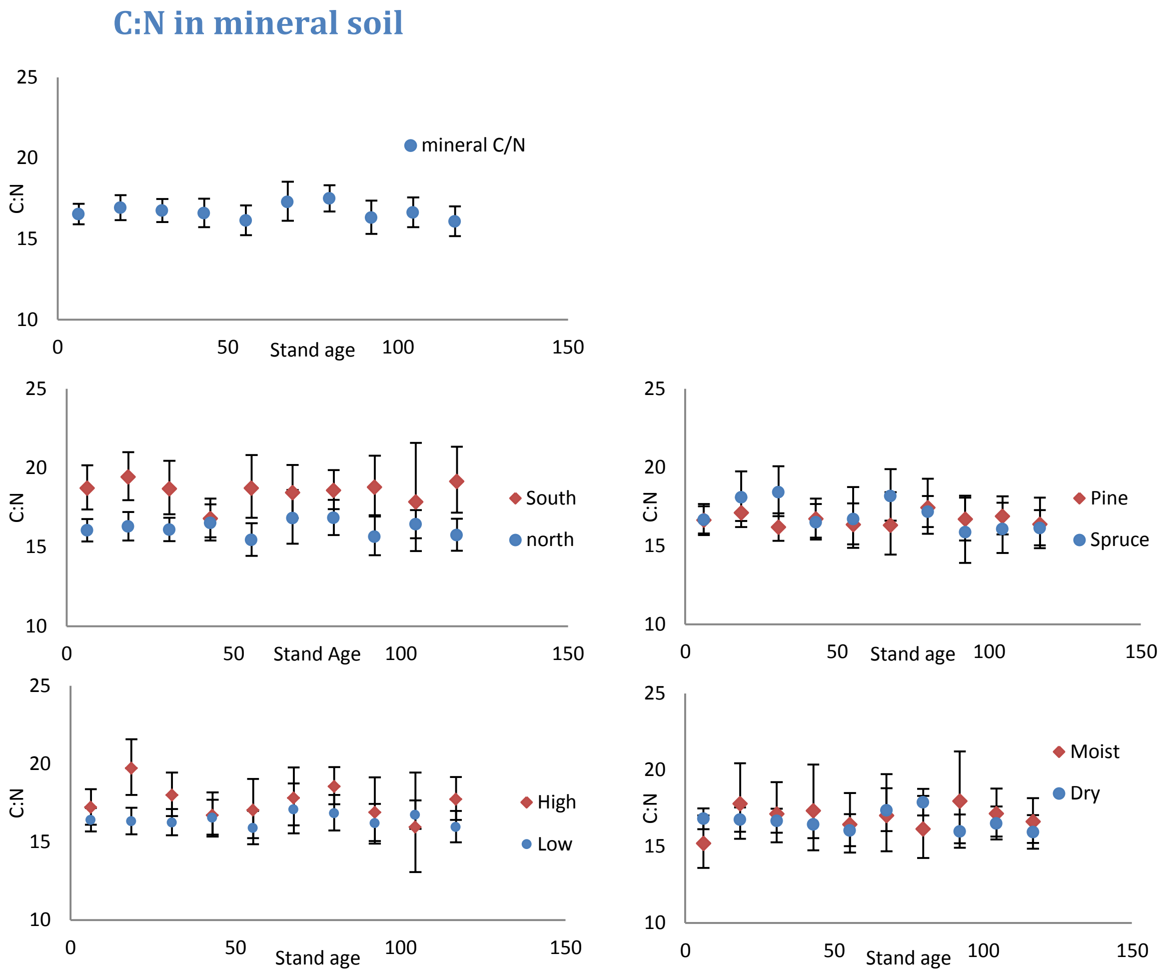

Figure 7. Carbon to nitrogen ratio over the stand age for the mineral soil. Mean values of C:N ratio in the mineral soil for each RA class, 95% confidence intervals, for the 9 groups over the stand age, namely; all data, North and South, Spruce and Pine, High SI and Low SI, Moist soils and Dry soils

Appendix III: Variables

List of Variables and abbreviations

Table 6. Short description of main data and variables used from the NFI and MI

variables	*Abb.*		units
Sampling Year		The year a plot was sampled	(years)
Latitude	*Lat*	Geographical coordinate specifying Northern position	degree
Longitude	*Lon*	Geographical coordinate specifying East-west position	degree
Limes Norrlandicus		indicator of climatic zone separation between boreal and temperate forests	class
Areal Factor	*AF*	describes the total area that a tract represents	-
Stand age		The average age of trees in each sampling plot	(years)
Site Index	*SI*	Indicator of the productivity of each site in correlation to the growth after a certain period	-
Least cutting age	*LCA*		(years)
Relative age	*RA*	Estimated as: (Stand age)/(1.1*LCA)	-
soil moisture		Separates in different classes the degree to a sit is moist as of the depth of the groundwater table from the surface of the area.	
Humus amount		Amount of humus measured from each plot	kg
Humus form		Classification of humus type as mor, mull or peat in 7 classes	-
SOC in O horizon	*C_org*	Estimate of humus quantity multiplied by the concentration of C that was measured in each plot	$kg{\cdot}m^{-2}$
N in O horizon	*N_org*	Estimate of humus quantity multiplied by the concentration of N that was measured in each plot	$kg{\cdot}m^{-2}$
Carbon in mineral soil	*C_min*	Estimation of C in the mineral soil	$kg{\cdot}m^{-2}$
N in mineral soil	*N_min*	Estimation of N in the mineral soil	$kg{\cdot}m^{-2}$
carbon to Nitrogen ratio	*C:N*	The ratio between C and N in each plot	-
Total volume		The total volume of living biomass in each sampling plot	$kg{\cdot}ha^{-1}$
N stem		Volume of the tree stand	$kg{\cdot}ha^{-1}$
N branch		Volume of the tree branches	$kg{\cdot}ha^{-1}$
N root		Volume of the tree roots	$kg{\cdot}ha^{-1}$
N needle		Volume of tree needles	$kg{\cdot}ha^{-1}$
Total N		Sum of N in the O horizon and Biomass N from the trees	$kg{\cdot}ha^{-2}$
Pine		Proportion of Pine trees in each sampling plot (*Pinus sylvestris* + *Pinus contorta*)	-
Spruce		Proportion of Spruce trees in each sampling plot	-
broadleaf		Proportion of deciduous trees in each sampling plot	-
mixed		Sampling plots with no species exceeding 60% of the basal area	-