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Nitrogen pools and C:N ratios in well-drained Nordic forest soils related to climate and soil texture

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Relationships between soil nitrogen (N) pools, climate, and soil-texture class in well-drained Nordic forest soils may be used for upscaling of regional N budgets. Total soil N pools and C:N ratios were studied in forest soils in Fennoscandia and Denmark (55–70°N, 5–27°E) in boreal pine and spruce forest, boreal mixed forest, and nemoral forest types (beech, oak, mixed). Total N pools in 198 forest soil profiles were calculated from horizon thickness, bulk density, stone content and nitrogen concentration and related to climate and soil texture through multiple linear regressions. The top 100 cm of the mineral soil and the organic layer were included. C:N ratios were calculated from C and N concentrations in 10-cm depth sections. Total soil N pools ranged from 0.05 to 1.65 kg N m^{-2} and were positively correlated with mean annual temperature (MAT) and mean annual precipitation (MAP). The range of mean annual temperatures was –2 °C to 8.4 °C, and the range of mean annual precipitations was 282 to 2270 mm y^{-1}. Soil N pools were highly variable and related to climate and soil texture class. The total soil N pools in coarse textured soils changed more with changing MAT and MAP than those in medium textured soils due to lower N pools in coarse soils in the northern part of the study area. C:N ratios were negatively correlated with temperature and precipitation in the uppermost mineral soil layers and the organic layer. C:N ratios of soil organic matter in the organic layer or top mineral soil are indicators of litter quality and degree of humification, but also reflect ecosystem N status in high N deposition areas.

Introduction

Nitrogen (N) cycling in forest ecosystems is studied for various reasons. Nitrogen availability is important to soil fertility and N cycling is altered by human activity (Galloway *et al.* 2004). Increasing atmospheric CO_2 concentrations, global warming and changes in precipitation patterns are likely to affect N processes and N pools in forest ecosystems. Changes in fire frequency (volatilisation of N) and plant growth, redistribution of N from soil to biomass, and enhanced fixation of N_2 (Townsend and Rastetter 1996) may be results of changing growth conditions for temperate and boreal forest. This calls for detailed knowledge of the total soil N pool, the distribution within the soil profile, and the ratio of carbon to nitrogen (C:N ratio) in relation to soil forming factors, as changing growth conditions will affect N transformation processes in forest soils.

N in soils originates mainly from biological fixation of atmospheric N_2. Incorporation and transformation of organic matter is part of soil formation. Current N pools and C:N ratios are a result of soil development in the Holocene. Temperature, precipitation, and inherent soil properties such as parent material may have caused differences in N pool size through interaction with biota. If we can generalise the relationship of N pools and C:N ratios to soil forming factors, the extrapolation of results from process studies and N manipulation experiments will be facilitated.

Climate and vegetation changed throughout the Holocene in the Nordic countries (Bradshaw and Holmqvist 2000, Björse and Bradshaw 1998). The current distribution of nemoral, mixed boreo-nemoral, and boreal forest is a result of vegetation migration, climate constraints, and land use. Neither climate nor vegetation type can therefore be regarded as constant in an analysis of Holocene N accumulation. Current climate, however, gives the conditions for the present N cycling. Accumulated soil N in forest ecosystems could thus be analysed in a climosequence, while keeping relief, parent material, and time reasonably constant (Jenny 1980).

Soil texture is indicative of soil nutrient status, water holding capacity, soil structure, and cation exchange capacity in newly glaciated soils. Therefore, soil texture is often used as an explanatory variable in studies of soil C and/or soil N (e.g. Christensen 2000, Jobbágy and Jackson 2000, Callesen *et al*. 2003, Vejre *et al*. 2003), and of C and N mineralisation (e.g. Reich *et al*. 1997, Cote *et al*. 2000, Giardina *et al*. 2001). Further, soil texture is assessed in soil surveys and often available in soil databases, and hence suitable for upscaling.

The vertical distribution of the N pool and C:N ratios at corresponding depths play key roles for how soils respond to environmental changes e.g. fires or a warmer climate. The organic matter in deeper soil layers is older and more humified than organic matter in surface layers, and it is generally observed that C:N ratios decrease with soil depth (Oades 1988).

In a regional study with limited climatic variation, soil texture was shown to affect N accumulation: high N pools and low C:N ratios were found in fine textured soils, and lower N pools and higher C:N ratios in coarse textured soils (Vejre *et al*. 2003). In this study we examined the effect of climate. The aim of this study was to establish quantitative relationships between the total N pools and C:N ratios in forest soil profiles in relation to climate within Fennoscandia and Denmark using the concept of independent soil forming factors (Jenny 1980). The study area ranged from a northern cool-temperate humid climate to a northern boreal climate. It was hypothesised, that the soil N pool and the C:N ratios in well-drained mineral soils show patterns that are related to climate, soil texture and soil depth. For the study area we expected to find larger N pools with increasing temperatures and precipitation for given soil qualities defined by texture.

Materials and methods

Data compilation

Data on soil profiles at forested sites in Denmark, Finland, Norway and Sweden, described and sampled over 20 years from 1975 to 1995, were compiled from several investigations (Nordsoil: Nordic forest soil database; K. Raulund-Rasmussen & I. Callesen pers. comm., *see* Callesen *et al*. 2003, Vejre *et al*. 2003). Apart from SW Denmark, most of the study area was glaciated during the Weichsel glaciation that ended 10 000–15 000 years BP. Soils are consequently rather young, developed on glacial till, glaciofluvial, fluvial, or aeolian material of mainly granitic origin. Five sites were developed on basic igneous rock. In total, 198 forest soil profiles had determinations of total C and N, and soil texture analysed by genetic horizon to 100-cm soil depth. Location of the profiles and delineation of nemoral, boreo-nemoral and boreal forest are illustrated in Fig. 1. Included profiles have been described and sampled from a soil pit wall so as to be representative of the genetic horizon, using the basic principles of soil surveys, e.g. the FAO guidelines (1990), comprising horizon designations indicative of soil genesis, horizon thickness, colour, texture, and structure. Only freely drained soils (drainage class moderately well-drained or better; drainage class according to criteria set by Soil Survey Division Staff (1993)) were included, thus excluding waterlogged soils. Some sites in the southern part of the study area have a pre-history of deforestation and conversion to *Calluna* heathland or agriculture, reforestation taking place in the 19th century.

Soil samples (< 2 mm) were analysed for C and N by dry combustion and soil texture by combined sieving and sedimentation (K. Raulund-Rasmussen and I. Callesen unpubl. data). Pools of N in each distinct genetic horizon, including the O horizon, were calculated and summed to a depth of 100 cm as follows:

$$N_{\text{pool}} = \Sigma_{\text{soil layers}}(N_{\text{conc}}) \times (\text{bulk density}) \times (\text{soil volume}) \times (100 - \text{stone}\%/100) \quad (1)$$

where N_{conc} = N concentration of the soil layer (mg g^{-1}), bulk density is the density of the fine earth fraction (Mg m^{-3}), and soil volume is the volume of the studied soil layer per m^2 (i.e. m^3 to 1 meter mineral soil depth), The volume of boulders and stones larger than 2 cm (stone%) was evaluated by a rough assessment of the profile wall for the profile as a whole (143 profiles) or within horizons (55 profiles). Bulk densities were determined in 60% of the profiles. Missing bulk densities were calculated for each horizon using regression models with carbon content as predictor. Regression parameters may be found in Vejre *et al*. (2003). The N pools of genetic horizons were assigned to 10-cm sections in order to facilitate comparisons of the vertical distribution. C:N ratios were calculated from C and N pools in equivalent 10-cm depth sections. At low concentrations the relative measurement error increases for both C and N determinations, implying an increasing random error in C:N ratios. The relative measurement error for N determinations by dry combustion is around 3%, and the lower detection limit is often around 0.2 mg N g^{-1} (Burt 2004). This was accommodated by setting a lower limit of N concentration of 0.1 mg N g^{-1} for calculating the C:N ratio.

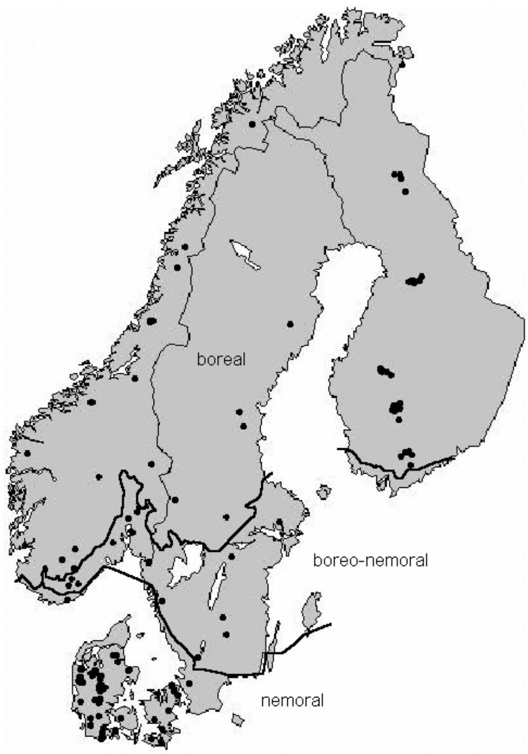

Fig. 1. Soil profile sampling locations. Vegetation zones nemoral, boreo-nemoral and boreal are delineated. Note that zonal alpine areas in mountainous regions transecting most of Norway from north to south and the northern boreal forest–tundra limit are not indicated. Redrawn from Påhlsson (1984).

A texture class was assigned to each profile based on texture data in horizons in the depth range 50–100 cm. Horizon depth weighted particle size distributions of clay (0–2 μm), fine silt (2–20 μm) and coarse silt + sand (20–2000 μm) were classified as coarse, medium or fine soil texture (Table 1). Calcareous soils were separated from the rest due to different chemical properties connected to the carbonate buffering. The sites were characterised by tree species, i.e. Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), common beech (*Fagus sylvatica*) or oak (*Quercus robur* or *Quercus petraea*), and 30 year averages of mean annual temperature (MAT) and mean annual precipitation (MAP) were obtained from the nearest national meteorological station. Among the 198 sites, MAT ranged from –2 to 8.4 °C and MAP ranged from 282 to 2270 mm.

Table 1. Number of sites (*n*), total N pools (kg N m^{-2} in 0–100 cm mineral soil depth + organic layer), C:N ratios, mean annual temperature (MAT), mean annual precipitation (MAP), and degree of latitude by soil texture class† or tree species. Spearman correlation coefficients, *r*, for total nitrogen pools with MAT (r_{NxMAT}), and MAP (r_{NxMAP}). * $p < 0.05$, ** $p < 0.01$, and *** $p < 0.001$.

	n	Total N (0–100 + O) (kg N m^{-2})		C:N (0–100 + O)		Mean MAT (°C)	$r_{N \times MAT}$	$r_{C:N \times MAT}$	Mean MAP (mm y^{-1})	r_{NxMAP}	$r_{C:N \times MAP}$	Latitude (°N)#
		Mean (SD)	Range	Mean (SD)	Range							
Soil texture class												
Coarse	85	0.48 (0.28)	0.05–1.25	26 (7)	11–49	5.6	0.57***	0.15	795	0.57***	0.04	58.6
Medium	89	0.51 (0.30)	0.09–1.60	24 (11)	11–42	4.3	0.54***	–0.28*	782	0.70***	–0.26*	60.5
Fine	20	0.68 (0.35)	0.28–1.65	17 (8)	7–39	6.9	0.27	–0.56*	701	0.18	0.27	56.8
Calcareous	4	1.12 (0.24)	0.91–1.46	12 (2)	11–14	8.4	–	–	602	–0.89		54.9
Tree species												
Pine	39	0.23 (0.18)	0.05–1.01	31 (16)	11–42	2.8	0.34*	–0.17	664	0.53**	0.19	62.2
Spruce	141	0.58 (0.29)	0.09–1.65	25 (10)	12–49	5.5	0.29***	0.10	825	0.53**	0.07	58.9
Beech and oak	18	0.68 (0.32)	0.28–1.46	17 (8)	7–39	8.0	0.71**	–0.47*	666	0.51*	0.39	55.5

† Note on texture class: Weighted average of 50–100 cm soil depth (mass % of clay, silt or fine sand multiplied with layer thickness/50 cm), < 2 mm fraction. Clay < 0.002 mm; fine silt 0.002–0.02 mm; coarse silt 0.02–0.063 mm; fine sand 0.063–0.2 mm. fine: > 10% clay; medium: < 5% clay and (> 5% fine silt or > 50% coarse silt + fine sand) or 5%–10% clay; coarse: others; calcareous: > 1% $CaCO_3$ in the depth range 0–100 cm.
# Latitude given with decimal degrees.

Regression analysis

Relationships between total N pool, MAT and MAP were explored by Spearman correlation coefficients within tree species and soil texture class (Table 1). In subsequent analyses, total N pool and MAP were log-transformed (base 10) to stabilise variances and overcome skewness. Relationships of total N pool (kg m^{-2}) with soil texture and climate were analysed in a general linear model using soil texture as class variable and MAT (°C) and MAP (mm y^{-1}) as continuous variables, interacting with soil texture class:

$$\log N_{\text{pool}} = \alpha_{\text{texture}} + \beta_{\text{MAT}} + \beta_{\text{texture} \times \text{MAT}} + \beta_{\log \text{MAP}} + \beta_{\text{texture} \times \log \text{MAP}} + e_i \quad (2)$$

The F-test for $\beta_{\text{texture} \times \text{MAT}}$ and $\beta_{\text{texture} \times \log \text{MAP}}$ indicate if the slope with climate depends on texture class (Weisberg 1985). Studentised residuals were scrutinised in residual plots for potential outliers. Equation 2 was applied in the analysis of the N pool in the organic layer and in each 10-cm section. C:N ratios in the organic layer and in the 10-cm sections were analysed in a model that included effects of soil texture class (coarse or medium), and the climate variables MAT and log MAP:

$$\text{C:N}_{\text{i}} = \alpha_{\text{texture}} + \beta_{\text{MAT}} + \beta_{\log \text{MAP}} + e_i \quad (3)$$

The simpler model was justified by low degrees of explanation in the more detailed model. The coefficients of determination ranged between 9% and 28%.

Total soil N pools and C:N ratios in 10-cm sections were calculated for a typical boreal and a typical nemoral climate within the region (MAT and MAP; 2 °C, 500 mm and 7.5 °C, 800 mm, respectively) using model parameters from Eq. 2 and Eq. 3, respectively. Significant differences were tested statistically by comparing means (CONTRAST statement for selected levels of the covariates using proc. GLM, SAS ver. 8.1). Estimates for total soil N pools were back-transformed from log-scale to original scale. Differences in total N pools and C:N ratios between soil texture classes coarse and medium were contrasted for these selected climates. The estimated C:N ratios of the organic layer were based on data from pine and spruce sites to eliminate the confounding effect of broadleaved species concentrated in the southern (nemoral) part of the study area. Confidence limits (α = 5%) were calculated as 1.96 × SE of the least squares mean. Analyses were performed in SAS ver. 8.1 using the procedures UNIVARIATE, CORR, and GLM (SAS 2000).

The total N pool, texture class, temperature and precipitation, and interactions between texture class were analysed. Temperature and precipitation were highly significant in F-test in ANOVA ($p < 0.0001$, F-test not shown), and the analysis was consequently split up by texture class. For the coarse and medium texture classes, temperature and precipitation were correlated up to $r \sim 0.39$ (Table 2), suggesting that collinearity could be a problem. Therefore an interaction term between temperature and precipitation, $\beta_{\text{MAT} \times \log \text{MAP}}$, was added and analysed for each texture class:

$$\log N_{\text{pool}} = \alpha + \beta_{\text{MAT}} + \beta_{\log \text{MAP}} + \beta_{\text{MAT} \times \log \text{MAP}} + e_i \quad (4)$$

The interaction term proved to be not significant ($p = 0.50$ for coarse and 0.40 for medium texture class). Thus collinearity between MAT and log MAP appeared not to be highly critical, although it may have affected the precision of parameter estimates.

Results

Total N pools

Total N pools to a depth of 100 cm mineral soil plus the organic layer ranged from 0.05 kg N m^{-2} to 1.65 kg N m^{-2} (Table 1). Total N pools were highest in calcareous soils, storing on average 1.12 kg N m^{-2}, and fine textured soils, storing on average 0.68 kg N m^{-2}, as compared with 0.51 kg N m^{-2} and 0.48 kg N m^{-2} in medium and coarse textured soils, respectively. Pine forest sites stored on average 0.23 kg N m^{-2}, spruce forest sites 0.58 kg N m^{-2}, and broadleaved forest 0.68 kg N m^{-2}. Pine sites were predominant in the north and broadleaved sites in the south, which was also indicated by mean latitude for tree species groups (Table 1).

Table 2. Regression of total nitrogen pools in 0–100 cm mineral soil + organic layer. Model: $\log N_{pool}$ (kg N m^{-2}) = $\alpha_{texture} + \beta_{texture}\text{MAT}$ (°C) + $\beta_{texture}\log\text{MAP}$ (mm y^{-1}) + e_i. Significantly different slopes are indicated with lowercase letters. Parameter estimates (intercept and slopes), standard errors of estimates, coefficient of determination, R^2, range of covariates and sample correlation, $r_{\text{MAT}\times\log\text{MAP}}$ (indicative of collinearity if > 0.7), from separate regressions for each soil texture class.

Soil texture class	n	α	SE	β_{MAT}	SE	$\beta_{\log\text{MAP}}$	SE	$p_{\text{MAT};\log\text{MAP}}$	R^2	MAT, (°C)	MAP (mm y^{-1})	$r_{\text{MAT}\times\log\text{MAP}}$
Coarse	85	–4.56	0.82	0.07^a	0.01	1.30^a	0.29	< 0.0001, < 0.0001	0.54	–0.6–8.1	516–1840	0.38***
Medium	89	–3.04	0.47	0.04^b	0.01	0.87^b	0.17	< 0.0001, < 0.0001	0.46	–2.0–7.7	282–2270	0.39***
Fine	20	n.s.		n.s.		2.01	0.69	0.76, 0.01	0.33	3.0–8.4	589–1180	–0.51*

n.s. = not significant. *F*-test, type I.

Correlation between N pools and climate

Significant, positive correlations between the total N pool (100 cm mineral soil plus the organic layer) and MAT and MAP were found within each texture class and tree species, except for fine textured and calcareous soils (Table 1). Significant correlations ranged from 0.34 to 0.7. Calcareous soils and fine textured soils were mainly located within the nemoral zone, whereas coarse and medium soils were more uniformly distributed across the studied area. In individual 10-cm mineral soil sections, climate (MAT and MAP) and soil texture class accounted for part of the variation in N pools. In coarse and medium texture classes, the N pools were positively correlated with temperature and precipitation down to a depth of 60 cm. The correlation coefficients with MAT and MAP decreased with depth from approx. 0.54–0.49 in the organic layer to 0.24–0.29 in depth section 50–60 cm.

Effect of climate and texture class in the regression analysis

The increase in total N pools with temperature and precipitation was stronger for coarse-textured soils than for medium-textured soils, i.e. β_{MAT} and $\beta_{\log\text{MAP}}$ differed by texture class ($p < 0.001$) (Table 2). In fine-textured soils, temperature had no influence on total N pools, but an increase with precipitation was significant ($p < 0.01$).

Prediction of N pools for fixed climates and soil texture class

Predicted total N pools for the range of temperature and precipitation analysed (Fig. 2) are visualised by estimated lines of equal total N pools from 0.1 kg N m^{-2} to 0.7 kg N m^{-2} for coarse and medium soil texture. Medium-textured soils stored more N at low temperature and precipitation than coarse-textured soils ($p < 0.0001$). This is illustrated by the large difference between the 0.1 and 0.3 kg N m^{-2} isolines at low temperature and precipitation and the small differences between the 0.7 kg N m^{-2} isolines at high temperature. The relative difference between soil

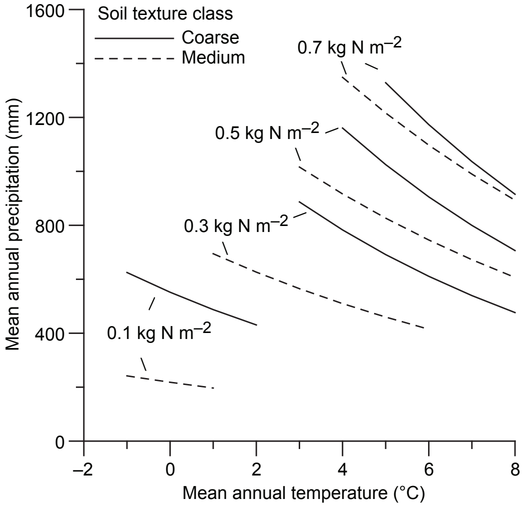

Fig. 2. Isolines for total soil N pools (kg N m^{-2}) in 0–100 cm mineral soil + the organic layer estimated from models in Table 2. MAP is here a function of MAT at constant soil N pool: 0.1, 0.3, 0.5, or 0.7 kg N m^{-2}. Example: Coarse texture, 0.7 kg N m^{-2} = –4.56 + 0.07 × MAT + 1.3log MAP is rearranged to MAP = $10^{(5.26 + 0.07\text{MAT})/1.3}$.

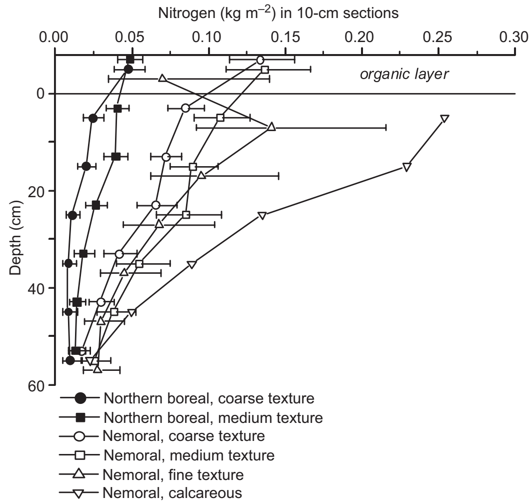

Fig. 3. Total soil N pools (kg N m^{-2} 10 cm^{-1}) in 10-cm sections calculated for two selected combinations of temperature and precipitation (2 °C, 500 mm y^{-1} and 7.5 °C, 800 mm y^{-1}) according to Eq. 1. Estimates are back-transformed from log scale to original scale. Error bars are 95% confidence limits calculated as ±1.96 SE of the least squares mean and back transformed. Organic layer N pools are restricted to pine and spruce sites, and not shown for the predominantly broadleaved stands on fine textured soils.

texture classes narrowed with increasing temperature and precipitation. In the nemoral climate zone, there was no difference between coarse and medium soils ($p = 0.29$).

Vertical distribution of N pools and C:N ratios in a boreal and a nemoral climate

Equation 2 was used to calculate the N pools for two combinations of MAT and MAP, a boreal (MAT 2 °C, MAP 500 mm) and a nemoral climate (MAT 7.5 °C, MAP 800 mm) for the texture classes coarse and medium (Fig. 3). Generally, the N pools decreased with soil depth (Fig. 3). For comparison, the mean values of fine and calcareous classes are included in the figure. These profiles were mostly situated in the nemoral zone. The difference in N pools between the boreal and the nemoral climate diminished with increasing soil depth (Fig. 3).

Effect of texture class on total N pool and C:N ratio

The N pools differed significantly between the texture classes coarse and medium in mineral soil sections between 0–40 cm in the boreal climate. The estimate for medium soil texture was consistently, but not significantly, higher than coarse soil texture in the nemoral climate. When the four texture classes were compared for the nemoral climate the N pools decreased in the order calcareous > fine > medium > coarse for the upper 0–30 cm mineral soil, calcareous fine textured soils and fine textured soils being significantly different from coarse textured soils.

The average C:N ratios in the upper 100 cm mineral soil + the organic layer were weakly negatively correlated with temperature ($r \sim -0.18$, $p = 0.01$). For the texture class medium ($r_{\text{MAT}} \sim -0.3$, $p = 0.01$ and $r_{\log\text{MAP}} \sim -0.3$, $p = 0.02$), and fine ($r_{\text{MAT}} \sim -0.56$, $p = 0.01$) the C:N ratio decreased with increasing temperature and precipitation (Table 1). On a data subset with mean annual temperature above 7 °C ($n = 114$), the C:N ratio of the upper 30 cm mineral soil + the organic layer was 28 in coarse-textured soils, which was significantly higher than the values of

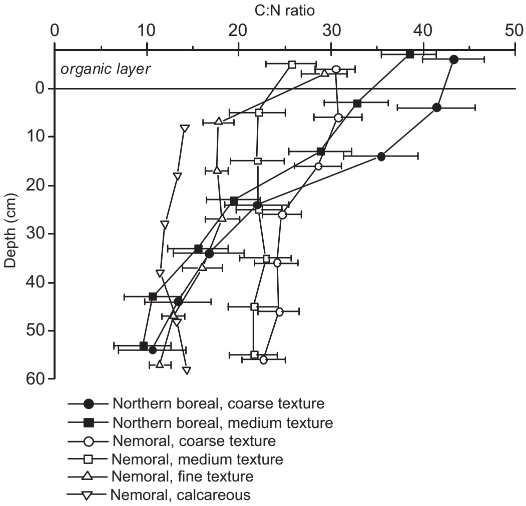

Fig. 4. C:N ratios in 10-cm sections, texture classes coarse and medium, calculated for two selected combinations of temperature and precipitation (2 °C, 500 mm y^{-1} and 7.5 °C, 800 mm y^{-1}) according to Eq. 2. Error bars are 95% confidence limits calculated as 1.96 × SE of the least squares mean. Soil texture classes refer to soil depth 50–100 cm.

21 in medium, 17 in fine, and 12 in calcareous soils ($p < 0.05$).

C:N ratios in the organic layer and mineral soil sections were related to climate and soil texture class, but differently, depending on soil depth (Fig. 4). The analysis of C:N ratios in O horizons in Fig. 4 include only Norway spruce and Scots pine stands in order to avoid confounding the effects of tree species and soil texture, i.e. broadleaved species on fine textured soils versus conifers on coarse textured soils. The model for C:N ratios in 10 cm depth sections (Eq. 2, *F*-test not shown) was significant in all sections, except the 20–30 cm section. Adjusting for climate effects by estimating C:N ratios at temperature 2 °C and precipitation 500 mm y^{-1} (typical for a boreal site), and at 7.5 °C and 800 mm y^{-1} (representing a nemoral site), gave estimates that are shown in Fig. 4. In the boreal climate, C:N ratios declined sharply from 38 and 43 in the organic layer to 11 and 12 at a mineral soil depth of 50–60 cm. The decline in C:N ratio with soil depth in the nemoral climate was less pronounced. Calcareous soils had the lowest C:N ratios followed by fine texture, medium texture and coarse texture classes.

C:N ratios were higher in the organic layer of coarse soils as compared with medium soils ($p = 0.0014$), in the 0–10 cm section ($p < 0.0001$), and in the 10–20 cm section ($p < 0.0001$). Below 20 cm soil depth there were no significant differences between the C:N ratios of the coarse and medium texture classes.

Discussion

Comparison with estimates of total soil N in literature in similar biomes

Our soil N pool estimates were comparable with the estimated total soil N pools in a tree species trial with conifers in southwestern Sweden. At a mean annual temperature of 6.4 °C and 1040 mm annual precipitation, Eriksson and Rosen (1994) estimated 0.5–0.65 kg N m^{-2} to 95 cm soil depth and including the O horizon. Post *et al*. (1985) examined N pools and C:N ratios at global scale in a large database of soil profiles under natural vegetation in relation to climate (Holdridge life zones) and reported 0.63 kg N m^{-2} to 1 m soil depth for boreal dry bush, 1.0 kg N m^{-2} for boreal moist forest, and 0.63 kg N m^{-2} for cool temperate forest. The figure for cool temperate forest is similar to our findings, and the increase in soil N with increasing precipitation within broad temperature regimes, e.g. the boreal biomes, is in line with our result.

Effect of drainage class on N pools

The N pool for boreal forest in Post *et al*. (1985) is 3–5 times the magnitude of our estimates (Fig. 2). Interestingly, our correlation with temperature across vegetation zones is thereby opposite to the global study by Post (1985). The positive temperature relationship found in our regional data set may be due to the focus on well-drained soils. Investigation of the influence of climate and soil quality on N accumulation is blurred, as effects of relief, drainage, temperature, and precipitation interact. In the present study, the effect of drainage was reduced by choosing well-drained sites.

Effect of soil age and fire

The age of the studied profiles potentially span more than 10 000 years. The trend in soil N could thus be influenced by soil age as well, since time and climate may be confounded in a systematic way, soil age decreasing with decreasing temperature and precipitation. However, very young soils may be found throughout the study area, following e.g. land heave and wind erosion. Our results suggest that northern soils have a potential for increased N storage with age and that this may be further stimulated by a warmer and wetter future climate (Fig. 2).

N pools at all soil depths were higher in the nemoral climate as compared with those in the boreal climate, irrespective of the soil texture class. In the humus layer (O horizon) it is established that recurring forest fires in Nordic boreal forests (Lehtonen and Kolström 2000, Wardle *et al.* 1997) have caused volatilization of litter and humus N, preventing accumulation of N. The effect of fire on soil humus pools depends on many factors including fire frequency, fire intensity, and site quality with respect to nutrient and moisture regimes. Fires may stimulate cycling of N and thus production on richer sites, if mineralised N and other nutrients are taken up by vegetation. Strong fires on sandy soils may give long-lasting loss of soil surface humus and nitrogen, leading to site impoverishment (Tamm 1950) and hence very low soil N pools. Wild fires have been suppressed within the last century leading to humus build-up, probably increasing N pools in boreal forests (Wardle *et al.* 1997). Even so, wild fires may have caused very low soil N values in some of the boreal forest soils studied.

Nitrogen deposition

Nitrogen deposition estimates were available at 137 sites, interpolated from national maps from the late 1980s and early 1990s. Total N deposition ranged from background levels (1–3 kg ha^{-1} y^{-1}), over intermediate (3–10 kg ha^{-1} y^{-1}) to elevated deposition (15–40 kg ha^{-1} y^{-1}). N deposition was also closely correlated with temperature ($r \sim 0.84$). Our study could not separate the effects of N deposition from the effects of the temperature and precipitation gradient, when analysing relationships between total soil N pools, and C:N ratios in the O horizon. Soil C:N ratio may also be influenced by previous cultivation, known to give sustained influence on N transformation in soils (Andersson *et al.* 2002). A fair share of the sites in Denmark and southern Sweden had been used for agriculture prior to reforestation in the 19th century.

Indicators of soil fertility and soil N status

Total N pool, C:N ratios, and N mineralisation indices have all been proposed as indicators of soil fertility in forest soil quality assessments (Schoenholtz *et al.* 2000). Based on regional studies, total soil N (Prescott *et al.* 2000), C:N ratios in the forest floor or mineral soil (Rehfuess 1999), or N mineralisation indices like gross, net or potential mineralisation (Kabzems and Klinka 1987, Andersson *et al.* 2002) have been proposed. However, links between the total N pools, C:N ratios and N mineralisation are not fully understood, and links to tree growth are ambiguous and influenced by elevated N deposition in some areas. Soil C:N ratio, used as a N availability indicator, and yield class of Norway spruce stands were not correlated parameters in Austrian monitoring data (Jandl and Herzberger 2001). On the other hand, Reich *et al.* (1997) found good correlation between annual net N mineralisation, soil texture and aboveground NPP in 50 hardwood and conifer stands in North America, and also a positive correlation with the mean annual temperature. Previous agricultural use contributed to higher total N flux at currently forested sites in Sweden in comparison with sites with a long forest record (Andersson *et al.* 2002). These somewhat contradictory examples indicate that analyses of state and processes in forest ecosystem N cycling should include soil and site characteristics such as climate and subsoil texture, but also previous land use and current and previous N deposition.

Our analysis suggests that climate (MAT and MAP) and texture class should be included as independent variables in analyses of N storage, C:N ratios and transformation of N. This way, bias in compiled data sets could be accounted for as attempted here.

Evaluation of the dataset and the calculation method

Differences in calculation method of bulk density estimates, sampling strategy in soil horizons, ± inclusion of organic layer, etc. contribute to unexplained variance, but in a random manner, which should not greatly change the relationships of N and C:N with climate found in the present study. More soil profiles from the cold, humid climate (e.g. a temperature of 1–2 °C and 1000–1500 mm annual precipitation, Fig. 2) corresponding to boreal wet forest (cf. Post *et al.* 1985), would have been desirable. However, our intention of studying well-drained mineral soils would then have been violated, as soil profiles in such climates would tend to be poorly drained and thus organic due to water-logging. The present data set is well described and consistent with respect to calculation methods, which supports the validity of the relationships found between N and climate within the Nordic countries.

The results of our analysis show that estimates of total soil N pools should be sorted according to climate and texture classes before comparisons are made between regions. Global or regional estimates should be based on stratified sampling of soil profiles by drainage class and texture classes, and account for regional relationships with temperature and precipitation. Our analyses indicate that N pools in well-drained forest soils increase and C:N ratios decrease with increasing temperature and precipitation in the organic layer and in the top mineral soil. These layers contain the largest proportion of soil N. The C:N ratios in poorly drained and peaty soils in arctic and alpine vegetation are lower than our estimates for well-drained forest soils (Ping *et al.* 1998). Correlation with climate, especially temperature, across vegetation zones should consequently take the drainage class of soils into account, and separate waterlogged soils from well-drained soils.

Errors in the estimates

Errors in the estimates may be calculated from errors in parameter estimates (Table 2). Predicted estimates of 0.54 kg N m^{-2} (95% CL = 0.48–0.62 kg N m^{-2}) for medium textured soils in the nemoral climate and 0.25 kg N m^{-2} (95% CL = 0.21–0.29 kg N m^{-2}) for similar soils in the boreal climate indicate a contribution from other factors than climate and soil texture to variation in soil N pools. Evaluation of soil stoniness, prediction error of bulk density, horizon borders, sampling error, and analytical error yield perhaps a 30% error in the total soil N estimates (Murillo 1994). The use of predicted bulk densities did not bias the estimates, but a relative 10%–20% error was added to the cumulative error of the N pool estimate (Callesen *et al.* 2003). The contributions from these sources are further discussed in Callesen *et al.* (2003) and Vejre *et al.* (2003). C:N ratios are based on concentrations and only sensitive to sampling error and analytical error. It may not be correct to calculate N pools to soil depth 100 cm, as N concentrations are close to detection limits in the lower layers. Although being very low, N pools in the northern part of the boreal zone (Fig. 3) may have been overestimated, as sample concentrations were extrapolated to a depth of 100 cm when the C horizon was deeper than 60 cm. In the northern part of the study area, the C horizon starts at a shallower depth than in the southern part, and concentrations (and pools) are lower (Fig. 3). Even the calculation of C:N ratios to depth 60 cm may be inappropriate use of the data. Most N is found above 30 cm soil depth, which is the main zone of biological activity. However, as indicated in Figs. 3–4, different levels of C:N ratios may be found in deeper layers as well, depending on climate and texture.

Conclusions

Total soil N pools are positively correlated with mean annual temperature and mean annual precipitation within well-drained soils in Fennoscandia and Denmark. Medium textured soils have higher N pools than coarse textured soils throughout the study region. As a consequence, relationships with soil texture, soil depth and climate should be accounted for when using the C:N ratio as an indicator of e.g. soil fertility or ecosystem N status. The use of C:N ratios as an indicator of soil fertility or N status in response to N deposition should clearly state to what soil depth the estimates refer to. Further studies should include the compilation of datasets in similar climates but with no confounding effect of N deposition. The variability in soil N pools indicates a large capacity for N storage in nemoral climates. With global warming, boreal areas may experience increasing soil N pools due to the improved growth environment. This development may be enhanced by increasing human activity and hence higher N deposition at northern latitudes.

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