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Organic Carbon Stocks in Swedish Podzol Soils in Relation to Soil Hydrology and Other Site Characteristics

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Site characteristics influence soil organic carbon (SOC) stocks. In Podzols under Swedish forest land, SOC stocks were related to latitude, altitude, soil hydrological class categorized by mean groundwater level, mean annual precipitation, temperature sum during the growing season, total annual nitrogen (N) deposition and site capacity. SOC stocks were determined for the O-horizon and for total soil (O-horizon + mineral soil to a depth of 50 cm). Data from the Swedish National Forest Soil Inventory 1993–2001 were used (1477 field plots). The O-horizon was sampled with a core sampler and carbon (C) stocks were determined. For the mineral soil layers the SOC stock was calculated based on the SOC concentrations, bulk density and content of rock fragments. The results showed that the overall mean SOC stock was 2.8 and 8.2 kg C m^{-2} for O-horizon and total soil, respectively. Soil hydrological class strongly affected SOC stocks, which increased from on average 6.7 kg C m^{-2} at dry sites to 9.7 kg C m^{-2} at slightly moist sites. Corresponding values for the O-horizon were 2.0 to 4.4 kg C m^{-2}. The correlation coefficients for the linear relationship between SOC stock and site characteristics were highest for N deposition, which explained up to 25% of variation, and latitude, which explained up to 20% of variation. Altitude had the lowest degree of explanation.

Keywords soil organic carbon, forest land, soil hydrological class, N deposition, latitude, site capacity, mean annual precipitation, temperature sum, altitude
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1 Introduction

Soil organic carbon (SOC) is the largest terrestrial carbon pool (Janzen 2004), and plays an important role in the global carbon cycle. Small changes in the global SOC pool may affect the global carbon budget and the atmospheric CO_2 concentration. However, estimates of the global SOC pool in the top 1 m of soil are somewhat uncertain and vary between 1500 and 2000 Pg (Post et al. 1982, Eswaran et al. 1993, Batjes 1996, IPCC 2000). To improve these global estimates, but also national SOC estimates, more SOC surveys of different kinds are needed. These surveys can be based on a national scale, but can also be focused on different biomes (Dixon et al. 1994), climate zones, land uses, vegetation groups or soil groups (Batjes 1996). Assessments of SOC stocks within and among soil types are important in understanding causes and effects of climate or land use changes on the ecosystem CO_2 balance. Podzols defined according to the World Reference Base for Soil Resources (WRB) soil classification system (FAO 1998) cover approximately 485 million hectares world-wide and they are extensive in Scandinavia, north-west Russia and Canada (Driessen et al. 2001). In Sweden, Podzols cover approximately 13.7 M ha or 60.4% of the forest land area. The estimation of SOC pools in Swedish Podzols is consequently an important task in the national assessment of carbon pools.

Factors that govern soil processes, SOC sequestration and the development of soil properties over time include climate, parent material, topography and biota (Shaw 1930, Jenny 1941). These factors are crucial in both soil science and ecosystems ecology (Amundson et al. 1994), and influence the rate of net primary production and the components of decomposition, including heterotrophic respiration and soil organic matter stabilization. Several papers report the impact on SOC pools of temperature (Liski and Westman 1997, Callesen et al. 2003), precipitation and soil moisture (Batjes 1996), parent material (Nichols 1984, Oades 1988, Spain 1990, Sollins et al. 1996, Torn et al. 1997) and biota (Wedin 1995, Binkley and Giardina 1998, Burke et al. 1998). Topography is clearly confounded with microclimate and parent material (Hook and Burke 2000), biota and availability of groundwater. Land use can have a huge impact on soil carbon stocks (Davidson and Ackerman 1993, Paustian et al. 1998, Phillips et al. 1998, Miller et al. 2004). Management measures such as ploughing, fertilization, fire suppression and harvesting have also been shown to influence soil carbon stocks (Olsson et al. 1996, Nykvist 2000, Johnson and Curtis 2001, Bhatti et al. 2002, Guo and Gifford 2002, Vellinga et al. 2004).

In Sweden, the National Forest Soil Inventory (NFSI) provides possibilities for testing the relationship between site factors and SOC stocks for forest land on a regional/national scale. The NFSI covers all forest land, which is the most predominant land cover in Sweden with around 23 M ha, corresponding to ~55% of the land area. The NFSI is coordinated with the Swedish NFI (Swedish Forest Inventory) and is carried out on permanent plots in a repeated inventory where the same plot is investigated at 10-year intervals. The second repetition, i.e. the third inventory, is currently underway (2003–2012).

The objective of this study was to evaluate the relationship between forest site characteristics and the SOC stock in the O-horizon and the total SOC stock including the O-horizon and mineral soil down to a depth of 50 cm in Swedish Podzols. Site characteristics used in this study were latitude, altitude, soil hydrological class categorized by the mean groundwater level, mean annual precipitation (MAP), temperature sum during the growing season, total annual N deposition and site capacity (annual mean production of stem wood during the rotation period, $m^3\ ha^{-1}\ yr^{-1}$). The hypothesis was that site properties such as soil hydrology and temperature sum would be positively correlated with SOC stocks, while latitude would be negatively correlated. In addition, N deposition and forest yield, were expected to show a positive dependency on SOC stock. However, these factors also show intercorrelations. The aim of this Swedish study was to contribute to the overall understanding of SOC conditions.

2 Materials and Methods

2.1 The National Forest Soil Inventory

The NFSI comprises about 23 500 permanent sample plots in a stratified national grid system (denser in the southern part of the country) that are re-analysed within a 10-year cycle. All the plots have been described previously as regards land use, location and general site characteristics (Olsson 1999). The site characteristics evaluated were soil hydrological class, site capacity, latitude, temperature, N deposition and precipitation. The soil hydrological class was categorized into four groups according to mean depth to the groundwater table during the growing season; 1) dry sites with groundwater deeper than 2 m, 2) fresh sites with groundwater level between 1 and 2 m below soil surface, 3) slightly moist sites with groundwater level ca. 0.5 to 1 m below soil surface, and 4) moist sites with the groundwater level not deeper than 0.5 m. However, the moist sites generally do not have Podzols and the few moist sites with Podzols that occurred were thus excluded from the dataset and not further evaluated. The remaining three moisture classes were grouped into two classes: dry + fresh and slightly moist. Temperature was expressed as the cumulative temperature sum during the growing season (°C d), i.e. the cumulative mean day temperature for each consecutive day from spring to autumn when temperature exceeded + 5°C. Temperature sums were calculated as a function of latitude and altitude according to Odin et al. (1983). Mean annual precipitation (1961–90, in mm) and N deposition (1999–2002, in kg N ha^{-1} yr^{-1}) were taken from the observation net by the Swedish Meteorological and Hydrological Institute (SMHI 2004). The precipitation data were categorized into 100 mm classes.

This study is based on the survey period 1993–2001 and restricted to Podzols on forest land with production exceeding 1 m^3 ha^{-1} yr^{-1}). Most are on loamy sandy to sandy glacial tills and sand deposits based on granitic or gneissic mineralogy. The tree layer is dominated by Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.), with some downy birch (*Betula pubescens* Ehrh.) and silver birch (*Betula pendula* Roth). The bottom layer and field layer are dominated by mosses and dwarf shrubs such as *Vaccinium myrtillus* L. and *Vaccinium vitis idaea* L. Data were available for 1477 inventory plots to calculate SOC stocks in both the O-horizon and in the mineral soil down to 50 cm depth. These 1477 plots were evenly distributed over the country (Fig. 1) between latitudes 55.5°N and 68.1°N, and with altitudes from 10–780 m a.s.l. (mean: 257 m), on Podzols in dry, fresh and slightly moist hydrological conditions.

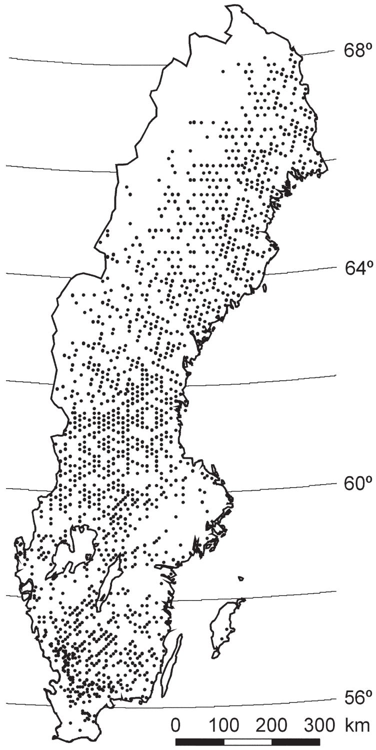

Fig. 1. Distribution of NFSI plots categorized as forest land, Podzol and dry, fresh or slightly moist hydrology used in this study for determination of total soil organic carbon stocks in the O-horizon and mineral soil 0–50 cm.

Samples were taken from the O-horizon (with the litter layer removed) and from three levels in the mineral soil; 1) the upper 0–5 cm of the B-horizon (B5), 2) 45–55 cm below ground surface (M50) and 3) 55–65 cm from the top of the mineral soil (M60) (Fig. 2). The O-horizon samples were taken volumetrically with a core

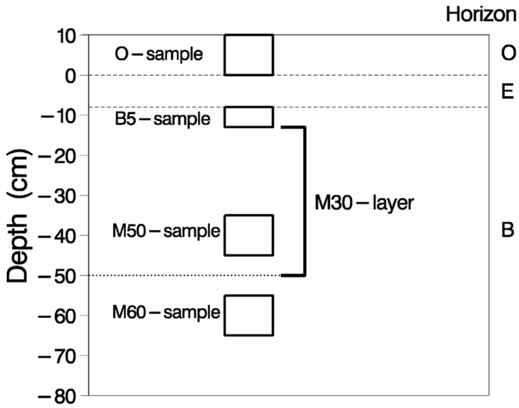

Fig. 2. Sampling strategy for Podzol profiles within the Swedish National Forest Soil Inventory, 1993–2002. In this example the thickness of the O- and E-horizon is 10 and 8 cm, respectively. The M30-layer represents the mineral soil layer between the B5-layer and 50 cm depth in the mineral soil, where the organic carbon (OC) concentration was calculated (linear regression) from OC concentrations in B5, M50 and M60.

sampler with a diameter of 10 cm. On average 3 core samples were taken per plot and bulked to one composite sample. The mineral soil samples were not taken volumetrically.

In the laboratory the samples were homogenized, sieved and dried to constant weight at 35°C. Total organic carbon in the soil material <2 mm was analysed with a LECO CNS-1000 analyser. Fine (0–1 mm) live and dead roots were included in the soil samples. The SOC data refer to fine soil material. The sampling procedure used resulted in a slight systematic underestimation of SOC due to non-representative sampling of large and hard organic residues, e.g. dead undecomposed roots and twigs >5 cm. This underestimation was approximated to ~15%.

The carbon concentrations in samples from B5, M50 and M60 were used in a linear regression to estimate the C-concentrations in a layer (M30) between B5 and 50 cm depth in the mineral soil (Fig. 2). Carbon concentration in the E-horizon was estimated using a function developed with data from an earlier NFSI (1983–1987):

$$Cconc_E = 7.0448 + (0.1758 \times Cconc_B) - (0.9047 \times pH(H_2O)_B) - (0.1077 \times d_E) + (0.0019 \times d_E^2) \quad (1)$$

$n = 949, \quad R^2 = 0.214$

where $Cconc_E$ is the estimate of SOC concentration (% of d.w.) in the E-horizon, $Cconc_B$ is SOC concentration (% of d.w.) in the B5-layer, $pH(H_2O)_B$ is pH (H_2O) in the B5-layer, and d_E is the depth of the E-horizon (cm).

2.2 Calculation of Stocks

Soil organic carbon (SOC) stocks were calculated for both O-horizon and total soil. The latter was defined as the O-horizon plus mineral soil 0–50 cm and calculated as the sum of stocks in O- and E-horizon, plus the B5-layer (top 5 cm of the B-horizon) and the M30-layer.

For each of the mineral soil layers the SOC stock was calculated according to:

$$Cstock = Cconc \times BD \times d \times (100 - Vstone)/100 \quad (2)$$

where Cstock is the SOC stock in kg C m^{-2}, Cconc is the SOC concentration in % of d.w., BD is the bulk density in kg m^{-3}, d is the depth of layer in m, and Vstone is the proportion of rock fragments >2 mm in % of volume.

Bulk density for the O-horizon was measured based on the volume determined from sampling, and for mineral soil layers estimated by a function from Nilsson and Lundin (2006):

$$BD = 1.546 \times e^{-0.313 \times \sqrt{Cconc}} + 0.0021 \times d \quad (3)$$

$n = 678, \quad R^2 = 0.764$

where BD is the bulk density in g cm^{-3}, Cconc is the SOC concentration in % of d.w., and d is the depth below O-horizon (cm).

The stone and boulder contents were estimated based on data of the occurrence of stones and boulders at the soil surface within the NFSI. The following categories are used in the NFSI: 1) glacial till with large boulders, 2) glacial till rich in boulders, 3) glacial till with moderate occurrence of stones and boulders, and 4) soils with low content of stones and boulders. Based on empirical data and a study by Eriksson and

Holmgren (1996), we set the volume content of rock fragments >2 mm in the first and second categories to 50%, in the third to 30% and in the fourth to 0%. The spatial variation in stones and boulder distribution is great and according to data by Eriksson and Holmgren (1996) the standard deviation is around 40% of the mean.

Arithmetic mean values with 95% confidence interval and coefficient of variation (CV: standard deviation in % of mean) were calculated. For the calculated data on total SOC in O-horizon plus mineral soil between 0–50 cm depth, the estimated variation in bulk density and coarse material was included, with CV 30% and 40% respectively. The CV for the bulk density was based on Nilsson and Lundin (2006), and the CV for coarse material was taken from a study by Eriksson and Holmgren (1996). The total variability was calculated as the combined variability for plot, bulk density and content of coarse material according to the IPCC Good Practice Guidance for LULCF (Penman et al. 2003):

$$CVtot = (CVcalc^2 + CVbd^2 + CVcoarse^2)^{1/2} \quad (4)$$

where CV is the coefficent of variation, CVtot is the total CV, CVcalc is the calculated CV from plot data, CVbd is the CV for bulk density, and CVcoarse is the CV for coarse material (>2 mm).

The 95% confidence interval for the SOC stocks was based on CVtot, mean values and number of observations.

A regression analysis was made between the SOC stock and site factors, which included a t-test of difference in slope between the two moisture groups. Prior to the analysis the variables were tested for normality, but there was no need for transformation of the data. Pearson correlation coefficients were calculated between SOC stocks and large-scale climate and site variables.

3 Results

3.1 Carbon Concentrations and Stocks

The thickness of the O-horizon was slightly larger for fresh sites than for dry (+23%), while for the slightly moist class the O-horizon was considerably thicker, more than double that at dry sites (+121%) (Table 1). This pattern was also seen in the amount of organic matter in the O-horizon. The carbon concentration in the O-horizon did not vary greatly with moisture class, while it was significantly higher in the mineral soil layer M50 for slightly moist sites compared with drier sites. For the other layers there was a tendency for increasing concentrations going from dry to slightly moist conditions (Table 1). It was also observed that the carbon concentration in the mineral soil decreased significantly with depth.

The mean total SOC stock (O-horizon plus the mineral soil to 50 cm depth) was 8.2 kg C m^{-2}, with a 95% confidence interval of ±0.3 kg C m^{-2}. The standard deviation was 3.75 kg C m^{-2}, which corresponds to a CV (coefficient of variation) of 46% of the mean. The O-horizon mean SOC stock was 2.8 kg C m^{-2} with a 95% confidence interval of ±0.1 kg C m^{-2}, corresponding to 35% of the total SOC stock. The CV for the O-horizon was 89%.

3.2 Impact of Soil Hydrological Class

There was a strong soil moisture impact on SOC stocks. The stock in the O-horizon increased significantly ($p < 0.01$) from dry to fresh (+19%), and strongly from dry to slightly moist conditions (+113%) (Fig. 3). There was a similar pattern for the total SOC stock (Fig. 3), with a significant increase from dry to fresh (+15%) and a strong increase from dry to slightly moist conditions (+41%). Similar results were found when the plots were split up into two groups; those from southern Sweden (55.5–60.9°N), and those from northern Sweden (61–68.1°N).

The higher SOC stocks, both for the O-horizon and the total stock, in fresh moisture conditions compared with dry might be related to higher site capacity and higher litter supply in the former due

Table 1. Descriptive statistics for variables measured in the Swedish National Forest Soils Inventory for Podzol soils. n = number of sites, $CL_{95\%}$ = 95 percent confidence limits, CV (%) = coefficient of variation expressed as a percentage.

Subset	Variable	n	Mean	$CL_{95\%}$ Lower	$CL_{95\%}$ Upper	CV (%)
All data	O-horiz. thickness (cm)	2143	8.2	7.94	8.42	70
	O-horiz. substance amount (kg m^{-2})	2143	7.5	7.18	7.86	107
	$C_{conc.}$ O (%)	2143	38.9	38.5	39.3	22
	$C_{conc.}$ B5 (%)	2050	2.2	2.15	2.29	70
	$C_{conc.}$ M50 (%)	1875	0.9	0.82	0.92	120
	$C_{conc.}$ M60 (%)	1629	0.5	0.48	0.55	141
Dry sites	O-horiz. thickness (cm)	144	5.6	5.07	6.13	57
	O-horiz. substance amount (kg m^{-2})	144	5.0	4.36	5.67	79
	$C_{conc.}$ O (%)	144	38.5	37.0	39.9	22
	$C_{conc.}$ B5 (%)	137	2.0	1.75	2.25	74
	$C_{conc.}$ M50 (%)	116	0.6	0.46	0.77	133
	$C_{conc.}$ M60 (%)	106	0.5	0.31	0.59	157
Fresh sites	O-horiz. thickness (cm)	1457	6.9	6.66	7.09	62
	O-horiz. substance amount (kg m^{-2})	1457	6.2	5.90	6.53	99
	$C_{conc.}$ O (%)	1457	38.6	38.2	39.1	23
	$C_{conc.}$ B5 (%)	1420	2.3	2.19	2.35	67
	$C_{conc.}$ M50 (%)	1303	0.8	0.78	0.89	124
	$C_{conc.}$ M60 (%)	1176	0.5	0.46	0.55	146
Slightly moist sites	O-horiz. thickness (cm)	539	12.4	11.8	13.1	60
	O-horiz. substance amount (kg m^{-2})	539	11.8	10.8	12.7	96
	$C_{conc.}$ O (%)	539	39.7	39.1	40.4	20
	$C_{conc.}$ B5 (%)	488	2.1	1.98	2.27	78
	$C_{conc.}$ M50 (%)	453	1.0	0.94	1.14	104
	$C_{conc.}$ M60 (%)	342	0.6	0.49	0.63	119

to better water availability in the tree rooting zone. An increase in site capacity of 17% (4.8–5.7 m^3 ha^{-1} yr^{-1}) was found going from dry to fresh conditions, which was close to the 18% increase in total SOC stock. Any difference in SOC decomposition rate in the upper soil layers for dry and fresh sites was expected to be relatively small because the moisture content in these layers is not strongly influenced by groundwater, at least in loamy sandy or sandy soil mineral material. The higher SOC stocks at slightly moist conditions compared with fresh conditions was entirely due to more SOC in the O-horizon, as there was no significant difference in the SOC stock of the mineral soil 0–50 cm. However, the higher values at slightly moist conditions could not be explained by differences in site capacity because the production rate was lower at the slightly moist sites (5.3 versus 5.7 m^3 ha^{-1} yr^{-1}, i.e. –7%).

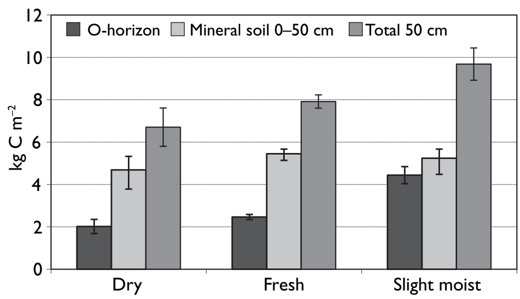

Fig. 3. SOC stocks, average and 95% confidence interval, for O-horizon and total soil (O-horizon plus mineral soil 0–50 cm) at sites with dry (n = 104), fresh (n = 1082) and slightly moist conditions (n = 291).

Table 2. Intercept and slope coefficient (y = a + bx) and R^2 value for the linear relationship between SOC stocks in Podzols at dry + fresh sites (a1, b1) and slightly moist sites (a2, b2). n = 1186 for dry + fresh sites and n = 291 for slightly moist sites. Statistical t-test of the difference in slope coefficient (* = p<0.05, ** = p<0.01, *** = p<0.001 and n.s. = not significant).

	Dry + fresh sites (n = 1186)			Slightly moist sites (n = 291)			Difference in slope
	a1	b1	R^2	a2	b2	R^2	b1 vs. b2
			Latitude, °N				
Total	36.73	–0.469	0.20	45.56	–0.582	0.19	***
O-horizon	14.80	–0.201	0.11	31.50	–0.439	0.18	***
Mineral soil	21.93	–0.269	0.13	14.06	–0.143	0.03	***
			Altitude, m a.s.l.				
Total	9.04	–4.74E-03	0.04	10.98	–5.14E-03	0.02	n.s.
O-horizon	3.35	–3.58E-03	0.07	6.00	–6.31E-03	0.06	***
Mineral soil	5.69	–1.16E-03	0.00	4.98	1.17E-03	0.00	***
			Temperature sum, °C d				
Total	2.40	5.16E-03	0.16	2.10	7.22E-03	0.16	***
O-horizon	–0.33	2.63E-03	0.13	–1.83	5.95E-03	0.18	***
Mineral soil	2.73	2.53E-03	0.08	3.94	1.27E-03	0.01	***
			Mean annual precipitation, mm				
Total	–0.151	1.14E-02	0.19	–0.344	1.43E-02	0.16	***
O-horizon	–0.115	3.64E-03	0.06	–2.205	9.47E-03	0.12	***
Mineral soil	–0.037	7.77E-03	0.17	1.861	4.87E-03	0.05	***
			N deposition, kg N $ha^{-1}yr^{-1}$				
Total	5.08	0.433	0.25	6.24	0.541	0.21	***
O-horizon	1.26	0.185	0.13	1.85	0.403	0.20	***
Mineral soil	3.82	0.248	0.16	4.39	0.137	0.04	***
			Site capacity, m^3 ha^{-1} yr^{-1}				
Total	5.05	0.490	0.17	6.81	0.544	0.12	n.s.
O-horizon	1.26	0.208	0.09	2.19	0.422	0.12	***
Mineral soil	5.04	0.061	0.01	4.63	0.121	0.02	**

3.3 SOC Gradients in Relation to Site Conditions

For Swedish Podzols on forest land with dry and fresh conditions, the total SOC stock decreased with latitude (Table 2) from ~10 kg C m^{-2} in the south to ~6 kg C m^{-2} in the north. In a similar way, the SOC in the O-horizon at dry and fresh sites declined from 3.5 kg C m^{-2} in the south to ~2 kg C m^{-2} in the north. For slightly moist sites, the decrease in SOC stocks with increasing latitude was stronger for the O-horizon than for the mineral soil 0–50 cm. For dry and fresh sites, on the other hand, the decrease was slightly stronger in the mineral soil (Table 2). For altitude, the correlation with SOC was negligible.

Of all site factors studied, atmospheric N deposition showed the strongest positive correlation with the total SOC stock as well as for the O-horizon and the mineral soil 0–50 cm alone. This was observed for both dry + fresh sites and slightly moist sites (Table 2). The N deposition was positively correlated with temperature sum and MAP (Table 3) and showed a strong exponential decline with latitude (Fig. 4), from over 15 kg N ha^{-1} yr^{-1} in the very south to 2 kg N ha^{-1} yr^{-1} in the north.

For dry and fresh sites and slightly moist sites, the total SOC stock was positively correlated with MAP, estimated in classes (Table 2). However, at dry and fresh sites this seemed to be dependent mainly on the accumulation of SOC in the mineral soil, whereas at slightly moist sites the accumulation of SOC took place mainly in the O-horizon. Thus, the R^2 values were low for the O-horizon at the dry and fresh sites, and for the mineral soil

Table 3. Correlation matrix for the independent variables (latitude, altitude, temperature sum during the growing season (°C d), mean annual precipitation (MAP, mm), N deposition (kg N ha^{-1} yr^{-1}) and site capacity (m^3 ha^{-1} yr^{-1}), including max and min values.

	Latitude	Altitude	Temp. sum	MAP	N dep.	Site capac.
Max-min	55.6–68.1	10–780	490–1650	500–1200	2.1–18.9	1.0–16.0
Latitude		+ 0.16	– 0.79	– 0.35	– 0.74	+ 0.65
Altitude	+ 0.16		– 0.57	0.00	– 0.26	– 0.31
Temp. sum	– 0.79	– 0.57		+ 0.17	+ 0.69	+ 0.68
MAP	– 0.35	0.00	+ 0.17		+ 0.49	+ 0.26
N dep.	– 0.74	– 0.26	+ 0.69	+ 0.49		+ 0.68
Site capac.	– 0.65	– 0.31	+ 0.68	+ 0.26	+ 0.68	

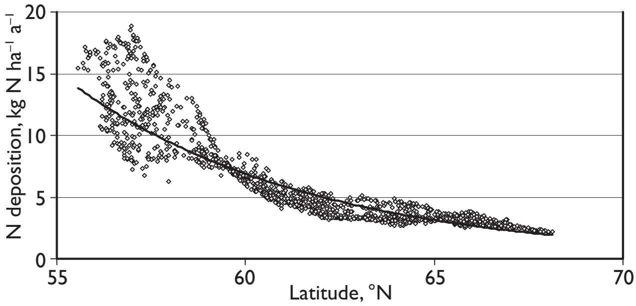

Fig. 4. Annual total atmospheric N deposition in relation to latitude (lat) for the sites investigated. N deposition= $86216e^{-0.1573 \times lat}$ (R^2 = 0.88, n = 1186). N deposition data taken from the Swedish Meteorological and Hydrological Institute.

0–50 cm at the slightly moist sites. The MAP was positively correlated with N deposition and site capacity (Table 3).

At dry and fresh sites, there was a positive dependency between the site capacity and total SOC stock (Table 2). Site capacity was positively correlated with N deposition, temperature sum and MAP (Table 3).

There was a positive dependency between temperature sum and total SOC stock, as well as O-horizon stock, both on dry + fresh sites and slightly moist sites (Table 2). However, when plots in southern Sweden (< 61°N) and northern Sweden (> 61°N) were analysed separately, there were only very weak positive or no dependencies with temperature sum, with R^2 = 0.07 and < 0.01, respectively. The positive dependency between temperature sum and SOC stock was weaker than that for N deposition (Table 2).

4 Discussion

The mean SOC stock in the O-horizon in this study, 2.8 kg C m^{-2}, was lower than corresponding values in well-drained Podzols in Denmark (3.5 kg C m^{-2}, Vejre et al. 2003) and in Norwegian mineral forest soils (~5 kg C m^{-2}, de Wit and Kvindesland 1999), but higher than those measured in mineral forest soils in Finland (1.9 kg C m^{-2}, Liski and Westman 1995, 1997). Values reported for SOC stocks in the O-horizon of boreal and temperate forests range from 0.8 to 8.3 kg C m^{-2}, with most values in the range 1–4 kg C m^{-2} (Vogt et al. 1986, Grigal and Ohmann 1992, Homann et al. 1995, Simmons et al. 1996, Bhatti et al. 2002, Callesen et al. 2003, Kulmatiski et al. 2004, Lettens et al. 2004).

In terms of soil hydrological class, the total SOC stock (O-horizon plus the mineral soil to 50 cm depth) was higher at slightly moist sites than at dry and fresh sites. However, this difference was exclusively due to the difference in SOC stock at the O-horizon (Fig. 3). Possible explanations for the higher stocks at slightly moist sites are that decomposition losses are lower due to occasional water saturation, that production of litter from the field layer is higher, or that the litter quality is different (Swift et al. 1979, Aerts 1997, Trumbore and Harden 1997, Davidson et al. 1998, Ju and Chen 2005, Muukonen and Mäkipää 2006, Tagesson and Lindroth 2007, Bonifacio et al. 2008, Eglin et al. 2008, Jungkunst et al. 2008). Other studies have shown that a higher groundwater level usually results in higher SOC stocks (e.g. Tan et al. 2004). The deviating pattern in the O-horizon and in the mineral soil may be caused by the distribution of root litter. Field data from the Lustra programme (Berggren Kleja et al. 2008) show that 0–2 mm root biomass in the O-horizon is higher at moist sites than at fresh and dry sites, whereas the root biomass in the mineral soil 0–50 cm is lower at moist sites.

A comparison of the national gradient for total SOC stock at dry and fresh sites with that at slightly moist sites showed that the slope coefficient was positive and significantly higher at the slightly moist sites for N deposition, MAP and temperature sum. It was negative and significantly lower at slightly moist sites for latitude and altitude (Table 2). The same pattern was found for SOC in the O-horizon, whereas the mineral soil 0–50 cm showed a different pattern, with significantly lower correlation to N deposition and MAP at slightly moist sites compared with dry and fresh sites (Table 2). This suggests that the change in SOC stocks in relation to site factors takes place in both the O-horizon and the mineral soil for dry and fresh sites, but mainly in the O-horizon for slightly moist sites.

In this study, SOC stocks increased with increasing MAP and temperature sum and decreased with increasing latitude (Table 2). A SOC pool increase with MAP is consistent with data on the global scale (Post et al. 1982, Jobbágy and Jackson 2000). However, as regards temperature, those authors showed that on a global scale, SOC stocks usually increase with decreasing mean annual temperature (MAT). As MAT usually declines with increasing latitude, a positive correlation would also exist between latitude and SOC pools (Harrison et al. 1995, Zhou et al. 2003). This pattern deviates from gradients on the regional scale presented in this paper. At such regional or local scales the dependency between SOC stocks and MAP, MAT and latitude can thus be the reverse of those on the global scale. Factors such as land cover (e.g. vegetation composition) and soil chemical, physical (especially texture) and biological properties may influence the SOC pools at regional and local scales (Post et al. 1982, Burke et al. 1989, Schimel et al. 1994, Homann et al. 1995, Kulmatiski et al. 2004, Tan et al. 2004). An increase in SOC stocks with increased MAT has also been reported for well-drained Nordic forest soils by Callesen et al. (2003). They expressed SOC stocks to 50 cm depth in these soils as a function of MAT and MAP. If MAT and MAP are set to 7°C and 700 mm respectively in southern Sweden, and 3°C and 700 mm respectively in northern Sweden, the regression by Callesen et al. (2003) would give 9.6 kg C m^{-2} in the south and 5.6 kg m^{-2} in the north, figures that correspond well with the 9.9 and 6.3 kg C m^{-2} found in this study. As Sweden has an elongated form, relatively flat topography and geographical orientation in a near north-south direction, a strong negative correlation exists between latitude and MAT. This explains the latitudinal impact on SOC stocks (Table 3). The decrease in SOC stocks towards the north is also consistent with data from high latitude transects by McGuire et al. (2002). They compiled data from five transects in Siberia, Alaska, Canada and Scandinavia within the range 52–80°N and found that soil mineral carbon stocks declined substantially towards the north. However, the organic layer showed a more complex pattern.

One possible explanation for the increasing SOC accumulation in the mineral soil at dry and fresh sites and in the O-horizon at slightly moist sites with higher MAP may be the combined effect of MAP and N on fine-root litter supplies. This is consistent with observations on fine root distribution reported by Berggren Kleja et al. (2008).

The increase in SOC stocks with decreasing latitude in Sweden seems to extend further south. Vejre et al. (2003) showed that the SOC pool in 34 well-drained Podzols in Denmark, with latitudes between approximately 55–57°N, was 14.6 kg C m^{-2} in the O-horizon + 0–100 cm mineral soil.

As the SOC stock to 0–50 cm depth is roughly 70–85% of the total stock down to 100 cm depth in forest soils (Grigal and Ohmann 1992, Jobbágy and Jackson 2000, Krogh et al. 2003), a value of 14.6 kg C m^{-2} down to 100 cm depth corresponds to a total SOC stock (O-horizon plus 0–50 cm mineral soil) of about 12 kg C m^{-2} in. This value is about 14% higher than our value (10.5 kg C m^{-2}) obtained at latitude 56°N from the linear relationship between latitude and total SOC stock of dry and fresh sites (Table 2).

Possible explanations for the increase in SOC stocks towards southern Sweden include the quantity and quality of different tree species and field layers, different temperature conditions and site production capacity, and different atmospheric N deposition and land management. We excluded the impact of moisture as an explanation because we compared sites with similar moisture conditions. Stands with Norway spruce (*Picea abies*) have more SOC than stands with Scots pine (*Pinus sylvestris*), according to Liski and Westman (1995, 1997). They also found that the SOC stock for Norway spruce and Scots pine sites increased by the same amount with increasing temperature sum from northern to southern Finland. As there are more pine trees than spruce trees in northern Sweden and vice versa in southern Sweden, the latitudinal distribution of tree species may contribute to the latitudinal gradient in SOC stocks. However, there could also be a historical perspective in the sense that southern Sweden has been forested for a longer time than northern Sweden.

Among other factors that may influence SOC stocks, the nitrogen factor is usually important.

Inorganic N can affect SOC accumulation in many ways, both direct and indirect (Hyvönen et al. 2007). First, it increases photosynthesis rates and thereby the amount of organic matter supplied to the soil. According to a literature review by Nadelhoffer (2000), it is likely that N deposition stimulates fine-root turnover and production. Second, it decreases rates of decomposition losses during the later stages of decomposition and can thereby result in a long-term accumulation of organic matter in the soil. Martikainen et al. (1989), Nohrstedt et al. (1989) and Arnebrant et al. (1996), among others, showed lower CO_2 release after application of N fertilizer. This has been explained as a result of the dynamics between the decomposers and the substrate chemistry (Ågren et al. 2001). Data reported by Knops and Tilman (2000) suggest that the rate of carbon accumulation is controlled by the rate of N accumulation, which in turn depends on atmospheric N deposition. The current trend with decreasing N deposition might, in coming years, lead to lower carbon sequestration in Swedish forest soils, especially in southern Sweden, where the current N deposition is rather high.

The much higher SOC stocks in southern Sweden may be explained by the high N inputs in this region in particular, i.e. note the exponential function for N deposition (Fig. 4). Likewise, the relatively small differences in SOC stocks between central and northern Sweden can be interpreted as a result of low N inputs in these regions. However, it should be kept in mind that observations of reduced decomposition rates as a result of N input usually refer to experiments with high N dosages (> 100 kg N ha^{-1} yr^{-1}), whereas atmospheric N deposition in Sweden is much lower.

Compared with the temperature sum, N deposition had a larger positive effect on SOC stocks (Table 2). This indicates that temperature does not have unambiguous influence on carbon stocks, in contrast to N deposition. This is also consistent with Berggren Kleja et al. (2008), who concluded that the turnover time of soil organic matter at two cooler northern sites was faster than that at a southern site. They suggested that lower access to inorganic N forms in the north results in higher decomposition rates of soil organic matter and that this effect seems to overshadow the effect of temperature. This is also in agreement with a review on N impact by Hyvönen et al. (2007).

The reasons for the positive dependency between site capacity and total C stocks to 50 cm depth at dry and fresh sites are complex. On one hand, higher site capacity might result in a higher amount of litter being supplied to the soil, as indicated by biomass functions based on stem diameter (Marklund 1988, Lehtonen et al. 2004) and by field data from the sites within the Swedish Lustra programme (Berggren Kleja et al. 2008). As N deposition, temperature sum and MAP have a positive relationship with SOC stocks (Table 2), site capacity also ought to have a positive correlation with SOC stocks. In addition, sites with high site capacity also often have dense stands, which could lead to forest floor conditions (e.g. relatively low temperatures and throughfall amounts) that might hamper the decomposition of organic matter. However, sites with above-normal forest yield are often located on soils with relatively high biological activity in the soil, and this usually results in high decomposition of organic matter.

5 Conclusions

The overall mean value for total SOC to 50 cm depth, i.e. O-horizon plus mineral soil 0–50 cm, in Podzols in Sweden was found to be 8.2 kg C m^{-2}, of which the O-horizon SOC comprised 35%. This estimate is the most comprehensive and accurate made so far, being based on nation-wide random sampling. On a national scale the spatial variability within the Podzols was fairly large, with a coefficient of variation of 46% for total SOC to 50 cm depth, and 89% for SOC in the O-horizon. This is attributable to the wide range of site conditions in the fairly elongated country of Sweden. On a local scale, soil hydrological class had the strongest influence on SOC stocks. On the national scale, the SOC stocks were linearly correlated in the order N deposition > latitude > MAP > site capacity > temperature sum > altitude. Increasing values of N deposition, MAP, site capacity and temperature sum had a positive effect on SOC stocks, while increasing latitude and altitude seemed to decrease SOC. However, interpretation of the impact of N deposition, MAP, site capacity and temperature sum is difficult because these factors are all strongly negatively correlated with latitude and are also strongly interrelated. This is due to the fairly flat topography, elongated form and geographical position of Sweden.

Our results suggest that annual N deposition and MAP at slightly moist sites mainly favour SOC accumulation in the O-horizon, whereas at dry sites they favour SOC accumulation in both O-horizon and mineral soil. This may be due to the fact that slightly moist sites respond to N and temperature by increasing fine-root litter mainly in the O-horizon and that they have lower decomposition losses due to occasional water saturation. In a climate change perspective, it seems that higher temperatures and wetter conditions could favour carbon sequestration in the soil.

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