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Topographical influences on soil properties in boreal forests

Jan Seibert [a,*], Johan Stendahl [b], Rasmus Sørensen [c]

[a] *Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden*
[b] *Department of Forest Soils, Swedish University of Agricultural Sciences, Sweden*
[c] *Department of Environmental Assessment, Swedish University of Agricultural Sciences, Sweden*

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Abstract

Topography is a major factor controlling both hydrological and soil processes at the landscape scale. This is well-known qualitatively in that topography, along with parent material, climate, biota, and time, is one of the fundamental soil forming factors. The topographic influence is also apparent in the soil catena concept. Digital elevation models (DEMs) and topographic indices calculated from these DEMs allow the relationship between topography and soil characteristics to be measured quantitatively as well. In this study we use data from the Swedish National Forest Soil Inventory, which is a long-term inventory of permanent sample plots from the Swedish National Forest Inventory. It includes a description of soil types and soil horizons as well as sampling of organic and mineral soil horizons for subsequent chemical analyses. We focused on Podzols and Histosols, which provided 4000 sample plots distributed over almost all of Sweden. Plot locations were determined accurately by GPS, which allowed the overlaying of plot data and the DEM. Topographic indices such as the topographic wetness index, TWI ($\ln(a/\tan\beta)$), were computed from gridded digital elevation data for all sample plots. We found several significant correlations between topographic indices and soil properties. The thickness of the organic layer increased with TWI and the thickness of the leached E-horizon increased with upslope area. Soil pH in the organic layer increased with TWI, while the C–N ratio decreased. Soil pH in the organic layer was also found to be higher for south facing slopes than for north facing slopes. The ratio between the divalent base cation (Ca and Mg) and the monovalent base cation (K and Na) concentrations in the O-horizon increased with TWI. These correlations confirmed the importance of topography on soil properties, although there was considerable scatter, which could be attributed to heterogeneity in the large data set.

Keywords: Topography; Soil survey; Topographic wetness index; Soil properties; Spatial variation

1. Introduction

Can the relationships between topography and soil properties found at the catchment scale also be observed at larger scales? We address this question by correlating field data from 4000 sites located throughout Sweden with topographic indices.

Spatial information about soil properties is usually a limiting factor for both land management and the application of spatially distributed models (Park and Vlek, 2002). Information from soil maps is usually low resolution and the values of soil attributes are assumed to be uniform although there is often great variation within soil units (Zhu et al., 1997). Thus there is much interest in relating different properties of the soil and habitat to readily available data such as elevation data. Elevation data can then be used to generate digital maps of soil properties or soil types (Behrens et al., 2005).

Together with parent material, climate, biota, and time, topography is one of the five fundamental elements of the soil forming factor theory (Amundsen et al., 1994; Jenny, 1941). Likewise, topography is central to the catena concept for soil development (Hook and Burke, 2000), which is characterized by leaching and redistribution of elements and soil material along hill slopes. The effect of topography is more pronounced on young and rolling soils than on old and level soils (Birkeland, 1999; Fisher and Binkley, 2000). The direction of the slope (i.e. the aspect) influences the amount and intensity of solar radiation to which a location is exposed and subsequently the temperature regime, which affects soil biological and chemical processes as

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* Corresponding author. Tel.: +46 8 6747876.
E-mail address: Jan.Seibert@natgeo.su.se (J. Seibert).

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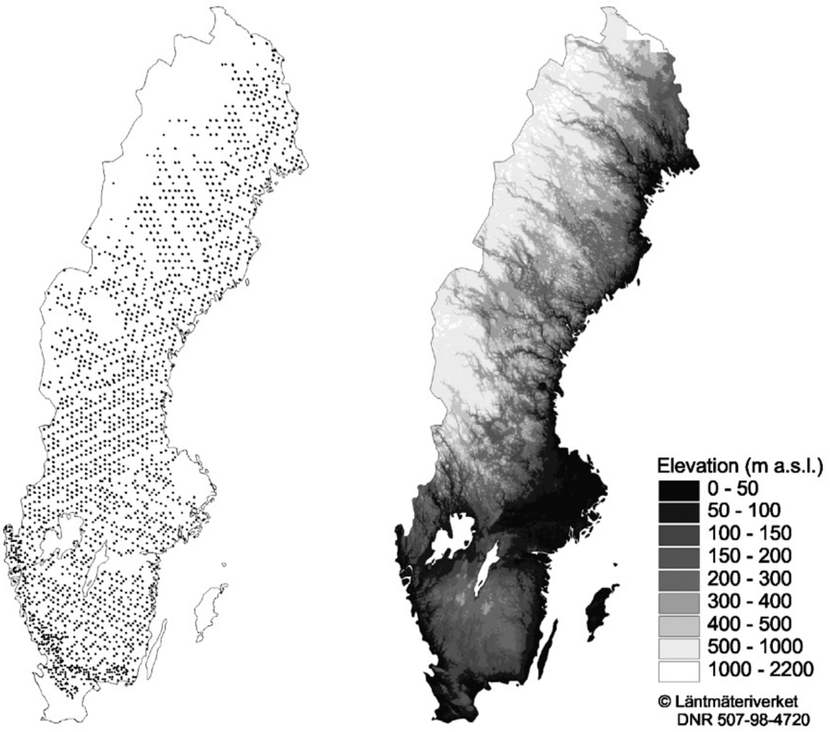

Fig. 1. Location of Swedish Forest Soil Inventory sampling points used in the study.

well as evaporation. The local slope determines not only the intensity of such processes as erosion and sediment redistribution, but also local drainage capacity. However, the most important effect of topography on soils in, for instance, boreal regions is its influence on water flow patterns at the landscape level. Topographical features such as curvature, slope, and upslope area influence the hydrological conditions of a location and generate different soil moisture conditions and flow patterns.

Table 1
Descriptive statistics of the various soil properties (TA = total acidity; BS = base saturation)

Horizon	Variable	*N*	Mean	Median	Lower quartile	Upper quartile	Percentile 10%	Percentile 90%
O	Thickness (cm)	4011	30.2	10	6	46	4	99
O	pH(H_2O)	4011	3.97	3.86	3.64	4.17	3.49	4.61
O	N (%)	4011	1.33	1.25	1.03	1.54	0.84	1.96
O	C (%)	4011	39.9	42.8	35.8	46.1	27.2	48.0
O	C–N ratio	4011	32.2	31.1	25.5	37.6	20.4	44.7
O	S (%)	4011	0.17	0.13	0.07	0.22	0.05	0.34
O	Al (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	2004	10.43	6.73	3.04	13.18	1.26	24.82
O	Ca (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	2004	64.0	48.1	31.2	73.0	19.6	118.9
O	K (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	2004	15.4	14.3	9.1	20.4	5.3	26.5
O	Mg (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	2004	16.8	14.3	9.8	20.5	6.9	29.3
O	Na (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	2004	4.01	3.29	2.12	4.93	1.39	7.29
O	TA (mekv $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	2004	720.4	731.6	561.1	880.8	396.1	1012.4
O	BS (%)	2004	81.8	87.4	74.3	95.2	55.3	98.6
E	Thickness (cm)	4011	10.6	8	4	14	2	22
B	pH(H_2O)	1325	4.79	4.78	4.59	4.99	4.40	5.17
B	N (%)	1325	0.12	0.09	0.06	0.15	0.04	0.21
B	C (%)	1325	2.46	2.00	1.18	3.22	0.71	4.59
B	C–N ratio	1325	20.3	20.2	16.8	23.7	13.6	26.8
B	S (%)	1325	0.02	0.02	0.00	0.03	0.00	0.06
B	Al (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	1325	6.82	5.54	2.91	9.12	1.61	13.33
B	Ca (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	1325	2.21	0.72	0.33	1.69	0.16	4.10
B	K (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	1325	0.54	0.44	0.28	0.65	0.19	0.98
B	Mg (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	1325	0.60	0.27	0.15	0.52	0.09	1.13
B	Na (mmol $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	1325	0.50	0.40	0.26	0.62	0.17	0.88
B	TA (mekv $\mathrm{kg}^{-1}_{\mathrm{dm}}$)	1325	72.4	64.0	41.7	93.1	29.0	123.8
B	BS (%)	1325	22.9	15.8	9.4	28.3	6.2	50.9

Topography is an independent soil forming factor and its contribution to soil formation can be considered on its own (Jenny, 1941).

An attempt to integrate topographical information in order to capture the hydrological variation was made by Beven and Kirkby (1979) by introducing the topographic wetness index (TWI), ln(a/tanβ), where a is the specific upslope area and tanβ is the local slope. According to the TWI concept, the soil moisture and ground water level of a location are the result of the accumulated upslope area, a, and the drainage expressed as slope, tanβ. TWI has been used in several studies to spatially estimate hydrological, physical, and chemical properties of soils (Welsch et al., 2001; Western et al., 1999; Whelan and Gandolfi, 2002).

Topographical influence on soil moisture conditions was studied at the Tarrawarra catchment in Australia, where Western et al. (1999) found that terrain, combined with the potential solar radiation index, explained 22–61% of the variation in soil moisture. In a later study Western et al. (2004) found that topography explained between 0 and 40% of the spatial variability of soil moisture. In that study the temporal variation of soil moisture was 10 times greater than the spatial variation. Other soil properties such as soil chemistry are less variable in time and can be considered as integrated measures of the soil moisture conditions.

Wilson et al. (2004) found that topography explained between 26 and 64% of soil moisture variation. Slope and slope position were found to be useful for estimating soil water retention at locations from several areas in the USA (Rawls and Pachepsky, 2002), and components of the TWI were used to estimate the distribution of mires in the Swedish landscape (Rodhe and Seibert, 1999). Brubaker et al. (1993) observed downslope increases of the amount of sand and silt parallel to decreases of clay and organic material content at their site in Nebraska, USA.

The indirect influence of topography through hydrology on soil chemical properties has been investigated internationally. Brubaker et al. (1993) observed increases in pH, $CaCO_3$, Ca and Mg, as well as base saturation downslope. Along the same gradient they found a decrease in cation exchange capacity and K_{avail}. McKenzie and Ryan (1999) found climate, terrain, and parent material to explain as much as 78% of total P variation and 54% of total C variation in a catchment in southeastern Australia. Zak et al. (1991) used slope position and aspect to estimate N-cycling rates in a Minnesota prairie, USA, but found small variations within the subtle topography. Whelan and Gandolfi (2002) sought correlation between TWI and soil organic carbon in their attempt to estimate denitrification near Devon, UK, but found poor correlations. Chen et al. (1997) found aspect and slope to be controlling factors for soil pH ($r=0.22$ and $r=-0.50$, respectively) in a mountainous area of eastern Taiwan. In the Catskill watershed in New York, USA, Johnson et al. (2000) studied the correlation between different terrain attributes and soil chemical parameters, pH, effective cation exchange capacity, exchangeable bases, total C and N, and the C–N-ratio. They were able to explain 4–25% of the variation and found much higher correlations among the soil chemical factors. Also in New York, USA, Welsch et al. (2001) found a high positive correlation ($r=0.56$) between TWI and nitrate.

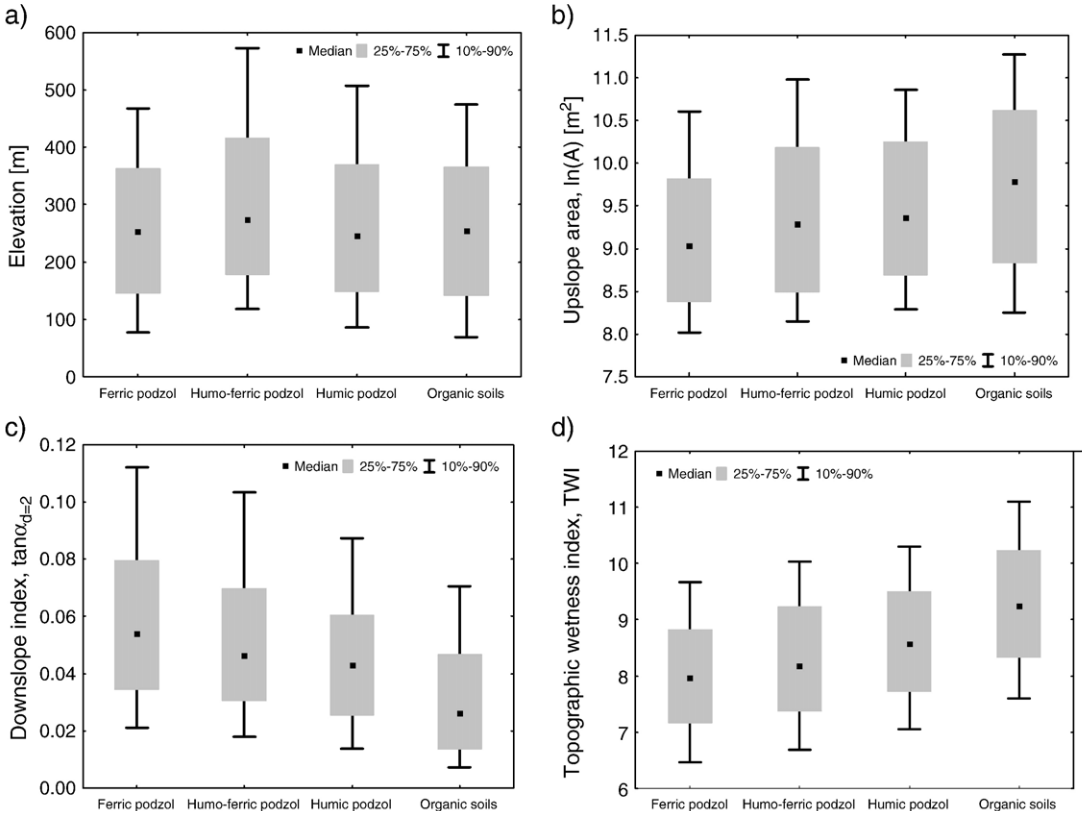

Fig. 2. Values of different topographic indices for the four different soil types, a) elevation [m a.s.l.], b) upslope area, ln(A), A in [m^2], c) downslope index, tan$\alpha_{d=2}$, d) topographic wetness index, TWI.

A strong relationship has been observed between topographical position, soil chemistry, vegetation composition, and forest productivity in young boreal forest soils, due to the downslope transport of water and nutrients (Fisher and Binkley, 2000). Knowledge of this relationship is not new; the Swedish site index assessment system, for example, includes lateral water flow estimates as a parameter (Hägglund and Lundmark, 1977). The influences on soil chemistry involve downslope increases in soil pH, base saturation, total nitrogen stock, and nitrate release (Giesler et al., 1998). Topography is also central to many ecological characteristics through its influence on both soil moisture and soil chemistry. Zinko et al. (2005), for instance, found strong correlations between TWI and vascular plant species richness.

Most previous studies were limited to the catchment scale and used data from smaller areas. Our investigation, on the other hand, was based on a national forest soil inventory that covers all of Sweden outside the mountain range. We focus on the influence of topography on properties for different conditions such as climate, parent material, and vegetation type. There is an obvious climatic gradient within Sweden that in turn influences the biota. Swedish forest soils are generally young and developed on rather homogenous till material of similar granitic origin, which may indicate that the influence of topography on soil properties is stronger than other soil forming factors such as time and parent material. Further, the influence of aspect is largest at latitude 40–60°N (Birkeland, 1999), which corresponds to the location of the investigated region.

2. Material and methods

2.1. Swedish survey of forest soils

This study was based on the Swedish National Forest Soil Inventory (NFSI; http://www-ris.slu.se), which runs parallel to the Swedish National Forest Inventory (NFI) (Ranneby et al., 1987) and covers all of non-mountainous Sweden, except for arable land and urban areas. In total, around 23,500 permanent 10 m radius plots are sampled and described in terms of forest and soil conditions in 10 year cycles. Each year's plots cover all of Sweden and represent a stratified random sample. For this study, data from the second NFSI (1993–2002) was used, although we were limited to data from 1996–2002 since only these included GPS coordinates. Regions with bedrock and soil types other than the granitoid bedrock with till parent material that is common to much of Sweden were excluded from the study (Fig. 1). The number of data points used in this study varied from around 1300 to 4000 points depending on the soil variable of interest. The soil chemical variables used in this study (Table 1) were analyzed on the fine fraction (<2 mm) after drying and grinding the samples. The total content of C, N, and S was analyzed after dry combustion using an element analyzer (LECO CNS-1000) on 0.03–0.5 g soil material depending on organic matter content. Exchangeable base cations were extracted using 1 M ammonium acetate, while a 1 M KCl solution was used for exchangeable Al. The extracts were analyzed using

Table 2
Spearman rank correlation coefficients for different variables (bold: $p<0.01$; TA = total acidity; BS = base saturation)

Horizon	Variable	Elevation	Upslope area, ln(A)	Downslope index, $\tan\alpha_{d=2}$	Topographic wetness index, TWI, $\ln(a/\tan\alpha_{d=2})$
O	Thickness (cm)	**−0.05**	**0.22**	**−0.43**	**0.39**
O	pH(H_2O)	**0.07**	**0.19**	0.02	**0.14**
O	N (%)	**−0.11**	**0.11**	**−0.19**	**0.18**
O	C (%)	**0.10**	0.00	**−0.17**	**0.10**
O	C–N ratio	**0.20**	**−0.10**	**0.10**	**−0.13**
O	S (%)	**−0.07**	**0.07**	**−0.19**	**0.15**
O	Al (mmol kg^{-1}_{dm})	**−0.18**	**−0.07**	**−0.07**	−0.03
O	Ca (mmol kg^{-1}_{dm})	**0.09**	**0.19**	0.00	**0.14**
O	K (mmol kg^{-1}_{dm})	**0.26**	**−0.06**	**0.34**	**−0.20**
O	Mg (mmol kg^{-1}_{dm})	**−0.03**	**0.15**	**−0.13**	**0.19**
O	Na (mmol kg^{-1}_{dm})	**−0.13**	0.04	**−0.25**	**0.17**
O	(Ca + Mg)/(K + Na)	**−0.09**	**0.19**	**−0.19**	**0.24**
O	TA (meq kg^{-1}_{dm})	**−0.10**	**−0.06**	**−0.12**	0.03
O	BS (%)	**0.17**	**0.11**	0.05	**0.08**
E	Thickness (cm)	**0.18**	**0.12**	**0.06**	**0.08**
B	pH(H_2O)	**0.16**	**0.11**	0.06	**0.09**
B	N (%)	0.05	−0.06	0.04	**−0.07**
B	C (%)	0.05	**−0.07**	0.01	**−0.08**
B	C–N ratio	0.04	−0.05	−0.04	−0.06
B	S (%)	**0.08**	−0.06	0.04	−0.06
B	Al (mmol kg^{-1}_{dm})	−0.07	**−0.09**	−0.02	**−0.08**
B	Ca (mmol kg^{-1}_{dm})	−0.03	**0.15**	0.05	**0.12**
B	K (mmol kg^{-1}_{dm})	0.03	**−0.08**	**0.12**	**−0.12**
B	Mg (mmol kg^{-1}_{dm})	**−0.10**	**0.10**	0.04	**0.08**
B	Na (mmol kg^{-1}_{dm})	−0.06	−0.03	0.01	−0.01
B	(Ca + Mg)/(K + Na)	−0.06	**0.18**	0.01	**0.17**
B	TA (meq kg^{-1}_{dm})	0.03	**−0.08**	0.02	−0.07
B	BS (%)	0.05	**0.14**	**0.09**	**0.10**

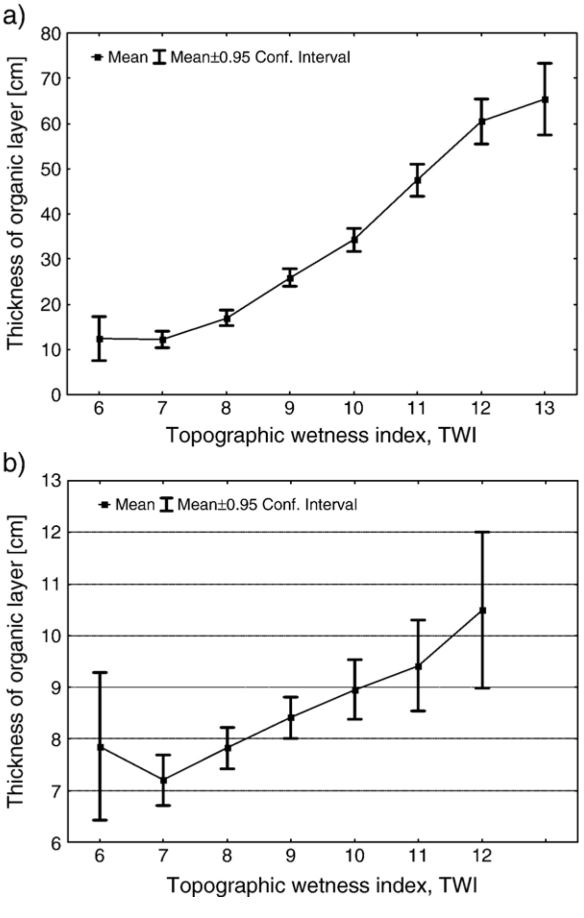

Fig. 3. Thickness of the organic layer against TWI, a) all locations, b) locations with a thickness greater than 50 cm were excluded (since only a few locations were remaining in the largest TWI class, these were added to the TWI = 12 class).

ICP equipment (ISA Jobin Yvon JY24). Total acidity (TA) was analyzed by extraction with 1 M ammonium acetate solution buffered at pH 7 followed by titration with NaOH. The pH was analyzed in water suspension. The soil variables used in this study and their descriptive statistics are listed in Table 1).

2.2. Calculation of topographic indices

The computation of topographic indices was based on the 50 by 50 m^2 grid DEM for Sweden. A smaller DEM was extracted from the DEM of Sweden for each sample site for computational purposes. These DEMs were chosen so that the sample site was located in the center of a 10 by 10 km^2 square and, thus, were large enough by far to reliably represent the surrounding area of the sampling site and to avoid any edge effects. The smaller DEMs were then used to compute topographic indices for each sampling site.

The topographic wetness index (TWI) developed by Beven and Kirkby (1979) within the runoff model TOPMODEL is one of the most widely applied topographic indices. The topographic wetness index $\ln(a/\tan\beta)$ is computed from the specific upslope area (a) (i.e., the upslope area (A) per unit contour length), which indicates the amount of water flowing towards a certain location; and the local slope ($\tan\beta$), which is a measure of the drainage from a place. This index can be calculated from gridded elevation data using various algorithms that differ mainly in the way the upslope area is computed (Quinn et al., 1995; Tarboton, 1997; Wolock and McCabe, 1995). Tarboton (1997) extended the single-direction algorithm to consider that the steepest gradient might not follow one of the eight cardinal or diagonal directions. Quinn et al. (1991) suggested a multiple-flow-direction algorithm, which tends to give more realistic spatial patterns than the single-direction algorithm, where the flow is concentrated in distinct lines. On the other hand, the multiple-flow-directions algorithm has been criticised as being overly dispersive. In this study we used the algorithm proposed by Seibert and McGlynn (2007), which combines the approaches of Quinn et al. (1991) and Tarboton (1997). The idea of this algorithm is to distribute the accumulated upslope area among all downslope directions using a weighting based on the gradients.

Our flow algorithm differed further from other flow accumulation algorithms in the following two ways. Streams were assumed to start when accumulated area exceeded a certain threshold (in this study set to 100,000 m^2). The accumulated area of a 'stream cell' was routed downslope as 'stream area' and not considered in the calculation of a in any downslope cell because the basic assumptions underlying the TWI do not hold when there is a stream. Furthermore, we treated cells without any adjacent downslope cell, i.e. depressions, differently than in most algorithms, where these so called 'sinks' are 'filled' before the index is calculated. Instead we considered depressions as real topographic features and continued the search for downslope cells using all cells which were located 2, 3,… cells away, until at least one downslope cell was found and the area was routed to this/these cell(s) (Rodhe and Seibert, 1999).

Hjerdt et al. (2004) recently suggested a downslope index as an alternative to the local slope. This index is calculated as $\tan\alpha_d = d/L_d$ where L_d is the distance to the nearest cell having a height of d length units (here set to 2 m) below the cell. The slope of the groundwater table and, thus, the drainage from a certain location might be better estimated by this downslope index than by the local gradient, because the downslope topography is accounted for. In this study we replace the local gradient with this downslope index, i.e., the TWI was calculated as $\ln(a/\tan\alpha_d)$.

In addition to TWI we used the values of lna and $\tan\alpha_d$ for each sample site separately. For all these indices we interpolated

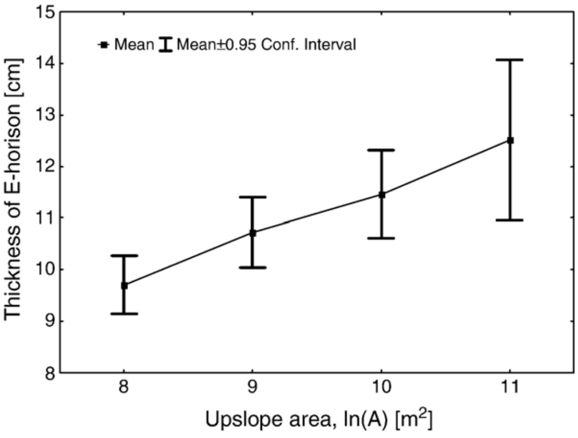

Fig. 4. Thickness of the E-horizon against upslope area, $\ln(A)$, A in [m^2].

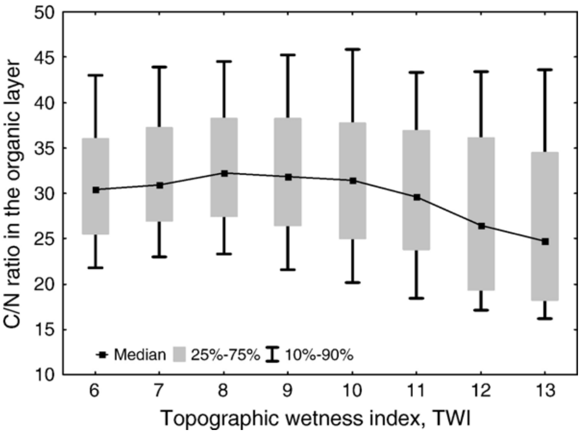

Fig. 5. C–N ratio in the organic layer for different TWI-classes (medians and percentiles).

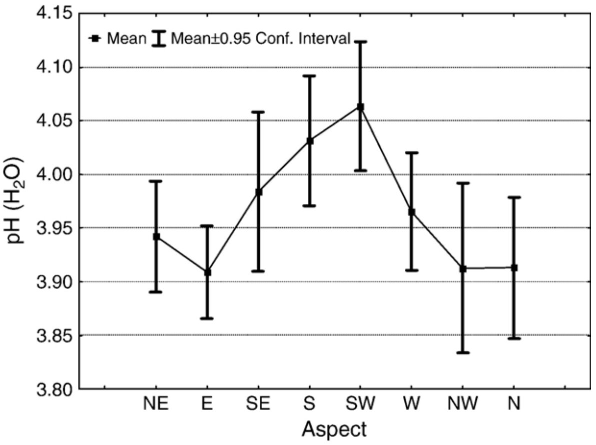

Fig. 7. Variation of pH with aspect in the organic layer. Only locations where the slope to the steepest direction, tanβ, was greater than 0.05 were included.

the value for a certain site from the values of the four surrounding grid cells using inverse distance weighing, where distance was defined as the distance between the sample site and the midpoints of the grid cells. In addition to the topographic index we also computed the aspect. Here we used the value of the grid cell in which the sample site was located. In the further analysis of aspect only plots where the local slope was larger than 0.05 were used.

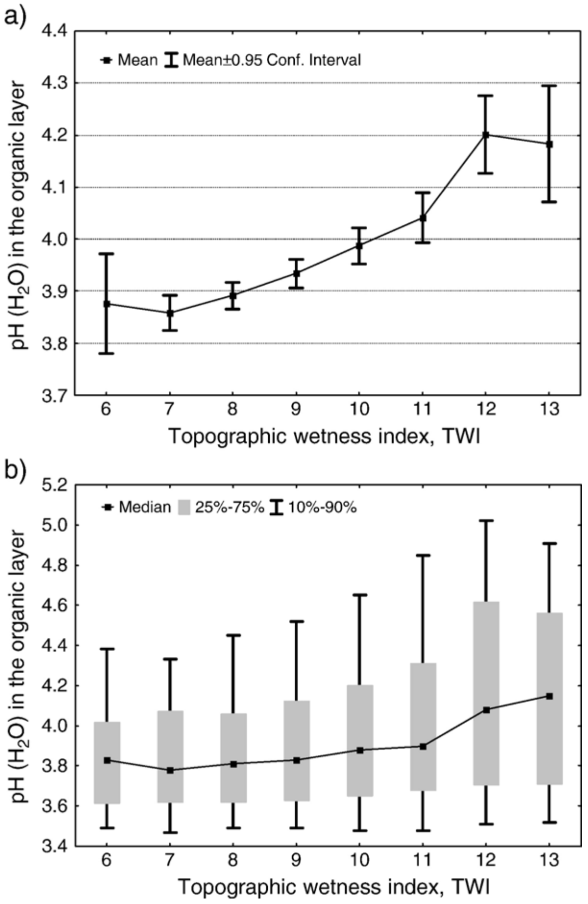

Fig. 6. Soil pH (H_2O) in the organic layer for different TWI-classes, a) mean values and confidence intervals, b) medians and percentiles.

2.3. Topographic indices and soil properties

The selected soil properties from the NFSI were compared with topographic indices as follows: The topographic indices (elevation, upslope area, slope, TWI, and aspect) were compared with the field data in several ways. First, the distribution of topographic indices was evaluated for the different soil classes. Second, correlation coefficients between topographic indices and measured soil properties were computed. Here Spearman rank correlation was used as a more robust measure of correlation than the Pearson correlation; in the latter variables are assumed to come from normal distributions and a linear relationship is presumed. Finally, the distributions of the various soil properties for different classes of topographic indices were compared.

Troedsson (1997) suggested a broad division of Sweden into 13 soil regions according to variation of climate, bedrock geology, soil parent material genesis and in some cases also topography and land use. We tested the correlations between topographic

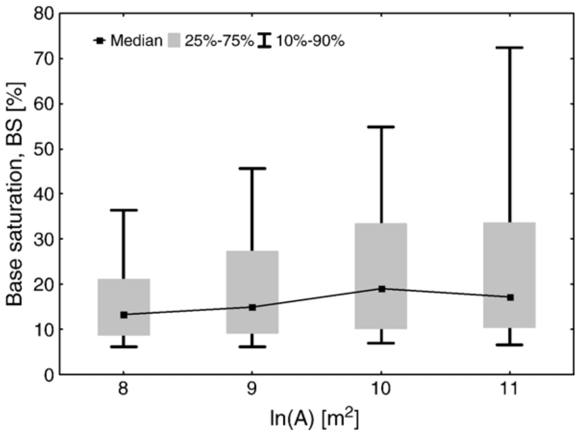

Fig. 8. Base saturation [%] in the B-horizon for different ln(A)-classes (medians and percentiles); the upslope area A is given in [m^2].

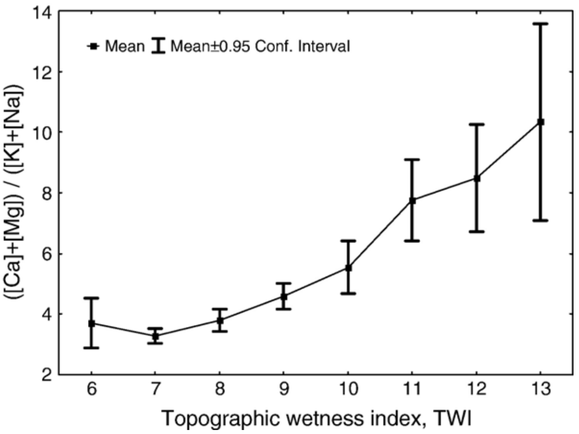

Fig. 9. Ratio between the concentrations of the divalent cations (Ca and Mg) and the monovalent cations (K and Na) in the O-horizon for TWI-classes (means and confidence intervals).

indices and soil properties also for these different regions within Sweden to evaluate how robust the correlations were. The number of plots in each soil region varied from 60 to 800.

3. Results

The different soil types had clearly different distributions of topographic index values, although there was a large overlap (Fig. 2). For a sequence from ferric to humic Podzols and finally to Histosols, there was a clear increase in average upslope area and a decrease in slope values. Consequently, the TWI also increased along the same sequence.

There was no clear relationship between soil type and elevation. We found several significant correlations between topographic indices and soil properties (Table 2), although not all correlations were strong. For the O-horizon, all soil properties were significantly correlated to one or more of the topographical indices. For the B-horizon, the correlations were generally weaker than for the O-horizon and only non-significant correlations were found for the C–N ratio and exchangeable Na.

The variable that correlated most strongly with topographical indices was O-horizon thickness (i.e. with TWI, $r=0.38$) (Fig. 3a). When soils with a humus layer thicker than 50 cm were excluded, the relationship was still strong although the absolute increase in thickness with TWI value decreased (Fig. 3b). The thickness of the leached E-horizon also increased with upslope area (Fig. 4) and with elevation (Table 2).

Total C and N content in the O-horizon increased with TWI, which seemed to be related mainly to the negative correlation with local slope. The C–N ratio decreased with increasing TWI (Fig. 5), which was caused primarily by an increase of total N with TWI. For the B horizon there was a weak correlation between topography and total C and N content.

The O-horizon pH increased with TWI (Table 2, $r=0.11$) and upslope area ($r=0.20$) and there was a significant difference in the mean values for the TWI classes (Fig. 6a). On the other hand, there was large scatter as illustrated by the box plot (Fig. 6b). The variation in pH increased with TWI (Fig. 6b).

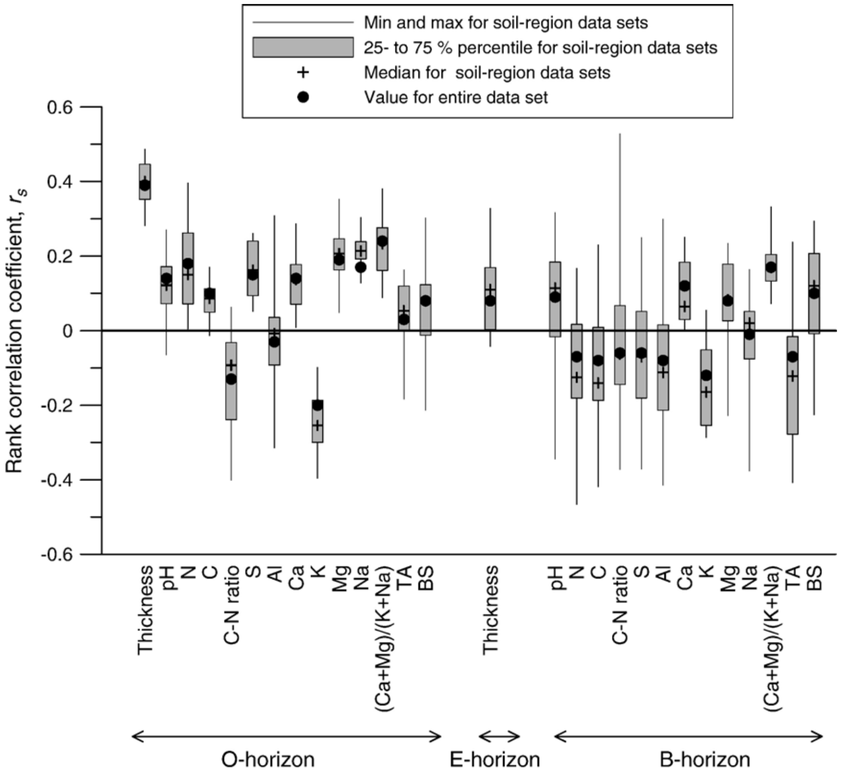

Fig. 10. Range and median of the rank correlation coefficients for TWI and the various soil properties for the 13 different soil regions. The values which were obtained using the entire data set are shown by the black circles.

Aspect also had an influence on pH in the organic layer with slightly, but significantly, higher values for south-facing than for north-facing sites (Fig. 7).

The B-horizon pH relationships were similar to those for the O-horizon, but much weaker. As could be expected from the pH variations, base saturation increased slightly with TWI (Fig. 8). The distribution of base-saturation values for different ln$a$ classes showed a clear increase in the upper percentiles, i.e. high base saturation was more frequent at sites where ln$a$ was large. Only weak correlations were observed for total acidity.

For both O- and B-horizons, Ca and Mg were similarly correlated to the topographical indices, with positive relationships to upslope area and TWI, and only weak or non-existing relationships to slope (Table 2). For K and Na, weak correlations were found with upslope area and stronger correlations with slope (Table 2). Unlike the other base cations, K exhibited a negative correlation to TWI. The ratio between concentrations of the divalent base cations (Ca and Mg) and the monovalent base cations (K and Na) in the O-horizon increased with TWI (Fig. 9). Al had only weak correlations with the topographical indices.

In general the correlation coefficients computed for the sampling plots within the 13 soil regions individually followed the correlation coefficients for all of Sweden for TWI (Fig. 10). Especially for those properties which were more correlated with TWI these correlations were also found in almost all soil regions. For upslope area and slope the pattern was similar. For elevation the correlation coefficients from the regional division were more different and correlations were generally higher for all of Sweden.

4. Discussion

Different soil types are developed under different conditions. In the sequence from ferric to humic Podzols and finally Histosols, it was evident that topography had an influence on soil formation (Fig. 2), most likely in this case through hydrological processes. The elevation had no influence on soil type formation. Our results confirm and quantify the well known observation that ferric Podzols are formed in dry locations while Histosol formation depends on high water availability (Brady and Weil, 2001). We also observed the gradient between these two extremes.

Similarly, O-horizon thickness varied positively with the TWI, i.e. higher soil moisture content or water availability gave rise to higher organic content (Fig. 3). The thickness of the leached E-horizon increased with upslope area. Leaching intensity depended on the amount of water passing through the E-horizon and the upslope area is a relative measure of lateral flow.

Correlations between topography and soil chemistry were generally stronger for the O-horizon than for the B-horizon, indicating that the organic layer is more exposed to topographic controls. This may also indicate that the soil chemistry is not only directly influenced by hydrological conditions, but also indirectly through different types of vegetation.

Johnson et al. (2000) also found increased C and N with TWI ($r=0.19$ and $r=0.17$, respectively) in New York, USA; and Welsch et al. (2001) observed positive correlations of TWI with nitrate ($r=0.56$) in the same area. The increase of C at higher water availability is probably due to higher primary production. However, unlike in our study, Johnson et al. found no significant correlation between TWI and C–N ratio in the organic layer. Sariyildiz et al. (2005) found leaf decomposition to increase down slope on south facing slopes. For north facing slopes the top and the bottom had higher decomposition rates than intermediately situated sites. This observation was made for Turkish mountain regions vegetated by fir, pine, beech, and oak.

Several studies have found a downslope increase of pH, but have not quantified it against topography (Brubaker et al., 1993; Chen et al., 1997; Giesler et al., 1998; Valentine and Binkley, 1992). Johnson et al. (2000) found hardly any correlation in the O-horizon between TWI and pH ($r=0.01$), but some negative correlation in the B-horizon ($r=-0.17$). Our correlations show an increase of pH with specific upslope area and thus TWI, which can partly be explained by a similar pattern for the base saturation. Base cations are thought to be dissolved by percolating soil water and taken up by plant roots as they move down slope. When plant residues decompose the chemical elements are partly mineralized, thus raising the pH.

The pH of the organic layer was also influenced by aspect, with higher pH in the more exposed directions. A similar pattern has also been observed by Johnson et al. (2000). Greater sun exposure can mean a higher mineralization rate and thus a higher concentration of base cations. A higher mean temperature and larger diurnal temperature variations might also increase the weathering rate. We observed a correlation between TWI and the ratio between divalent and monovalent base cations. This can be explained by a stronger adsorption of divalent base cations to soil particles at increasing soil moisture content (Eriksson et al., 2005). Therefore, the monovalent cations are leached from the system to a larger degree when a plot is exposed to larger water fluxes.

Despite several significant trends shown by the data, there was also an obvious scatter. This could be expected because the survey covers different climatic and geologic regions as well as a range of different site conditions. Forest vegetation and harvesting history also differ widely among the sites. These kind of large scale environmental databases are mainly intended to be summarized at a regional or national level. When used at plot level there will be a large degree of variability due to small scale spatial variation. This was especially the case for the mineral soil data which was collected from a single soil pit for each plot, whereas the humus samples were bulked from several cores. The observed relationships are expected to become stronger if a larger sampling support would be used for each plot. Obviously the coarse resolution of the DEM (50 m) is another limitation in this study because small-scale topographic features are not recognised, but this is the only data currently available for all of Sweden. More detailed elevation data available in the future might help to improve correlations between topographic indices and soil properties. One additional reason for noise might be errors in the GPS coordinates of the sample sites, although this error is probably small compared to the error introduced by the coarse resolution DEM that was used.

One issue with the large dataset used in this study is that even weak correlations often are statistically significant. On the other hand, due to the large variability of environmental conditions high correlations coefficients can not be expected and the correlations found may still have a physical meaning. The computation of correlations coefficients for the 13 soil regions indicated that the correlations for TWI, upslope area and downslope index were rather robust. The most strongly correlated properties found for all of Sweden also were clearly correlated in almost all of the 13 regions. This was not the case for elevations where regional correlations generally were lower than the correlation for all of Sweden. This can be explained by a strong elevation gradient across Sweden, whereas the other topographic indices varied more at the landscape scale and have less large-scale variability.

In several of the diagrams a tendency can be seen that confidence intervals increased for higher TWI values, indicating higher variations among sites with high TWI-values. One explanation might be a greater within-cell variation of wetness conditions for cells with high TWI values (Zinko et al., 2005). It is important to consider the intercorrelation of the topographic indices. Obviously TWI is correlated to both upslope area and slope. Furthermore, slopes tend to be steeper ($r_s = 0.19$) in areas with higher elevation while areas with a large upslope area tend to have gentler slopes ($r_s = -0.14$).

5. Concluding remarks

Despite the expected scatter due to heterogeneity in the data set, which included data from regions with differing climates, geology, and forest management history, it was possible to find correlations between topographic indices and soil characteristics. These correlations between TWI and pH for the data set covering all of Sweden agreed with correlations found at smaller scales. The value of these results is the larger generality than that of studies using smaller study sites. The use of topography as a source of information in environmental management will increase in the future, especially as the availability of high resolution elevation data increases.

Our study indicates the potential of topography as a proxy for soil properties but also the need for further studies. The considerable scatter observed in our study might be reduced by elevation data with a higher resolution. Multi-variant approaches might help considering the heterogeneity in the data set which we used by including other variables than topography into the analyses. New data sets covering smaller, and more homogenous, areas with spatially intense observations might be another approach to quantify the importance of topography on soil properties, especially if topographic indices are considered when designing the spatial distribution of sample plots for soil measurements.

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