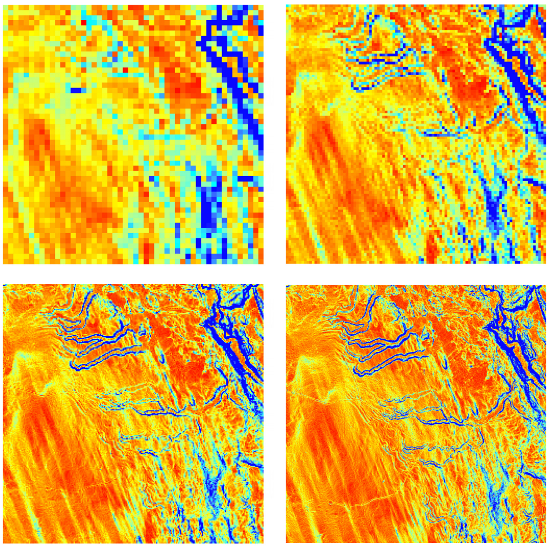
Topographical influence on soil chemistry

Licentiate thesis
by
Rasmus Sørensen



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Abstract

Topography is one of the five basic soil forming factors together with parent material, climate, biota and time, and therefore a major controlling factor on the soil properties. Topography can be quantified numerically by topographic indices, calculated based on a digital elevation model (DEM). The topographic wetness index (TWI) is a measure of the hydrological condition of a site, determined by a combined measure of upslope area and slope. TWI is a useful estimator of hydrological, pedological and biological properties at the landscape scale.

In this licentiate thesis the TWI was studied, partly as a predictor of variations in soil properties, and partly for its dependency on the used calculation method and the resolution of the underlying DEM. Several methods for calculating the TWI were tested against field measurements. No single best method was found; instead an optimal method specific to the estimated property of interest was found most effective. Correlations between TWI and soil properties were observed both for 25 km2 study sites and at a larger scale based on data from the National Inventory of Forest Soils for all of Sweden. While clear patterns were observed for several soil properties, there was also a considerable scatter in the correlations. These studies were based on DEMs with resolutions of 20 and 50 meters. In an additional study, a DEM with a grid resolution of 5 meters, derived from LIDAR data, was resampled to generate DEMs of different resolutions, which were used to test the effects of different resolutions on the TWI calculations. The distribution of TWI was scale dependent and a lot of the variation of TWI based on the 5 m resolution DEM was lost at 10 meter resolution.

Terrain analysis can be used to predict hydrological, pedological and biological properties at a spatial resolution impossible to achieve through field work. By choosing an appropriate DEM resolution and adjusting the calculation methods for specific purposes, the usefulness of the TWI could be refined allowing its application over a large spatial range.

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Appendix

Papers I – III

This licentiate thesis is a summary of the following papers. In the following text the papers will be referred to by their Roman Numerals.

I. Sørensen, R., Zinko, U. & Seibert, J. 2006. On the calculation of the topographic wetness index: evaluation of different methods based on field observations. *Hydrology and Earth System Sciences*, **10**:1-12.

II. Seibert, J., Stendahl, J. & Sørensen, R. Topographical influences on soil properties in boreal forest soils. (Manuscript)

III. Sørensen, R. & Seibert, J. Effects of DEM resolution on the calculation of topographical indices. (Manuscript)

Introduction

Water is both the most important solute and the most mobile component in soils and is therefore the main redistributing agent of elements in this medium. Understanding the hydrology is thus a key to understanding the spatial variation of important soil properties.

Soil forming factors

Hydrological modelling is usually based on the assumption that a limited number of parameters can predict the spatial variation of hydrological properties at landscape scale. The parameters used for prediction are the major factors influencing the hydrological conditions; including time series of precipitation, evapotranspiration, solar radiation, and relatively constant factors like soil transmissivity and, not least, topography. From one or more of these factors several studies have made predictions of, for example; the variation of hydrology (Rodhe & Seibert, 1999b; Western *et al.*, 1999), soil chemistry (Johnson, Méndez & Lawrence, 2000) and landscape biology (Moore, Norton & Williams, 1993; Zinko *et al.*, 2005).These factors can all be found in the soil forming factor theory, which states that any soil is a function of the influence of the five soil forming factors: Parent material, Climate, Topography, Biota and Time (Brady & Weil, 2001).

Parent material

The properties of the parent material (i.e. the composition of the initial mineral depositions) are primarily grain size and thus particle surface area, particle size distribution, porosity, hardness and chemical composition. A higher surface area of the soil particles means higher weathering rate. The porosity, particle size and distribution are all important for the physical stability of the soil, and for the hydraulic conductivity in the soil. The mineral composition of the soil influences the composition of weathering products in the soil solution.

Climate

Climate (or abiotic factors) refer to precipitation quantity and form (rain or snow), precipitation distribution over the seasons (temperature at which the precipitation is dominant), temperature, solar radiation, wind exposure etc. Soil chemical and biological processes are strongly influenced by temperature. At higher mean temperatures soils develop faster and the uptake of nutrients by plants goes faster. Temperature also affects the content of organic material. Water is the agent in which chemical processes take place; water is also responsible for transporting weathering products and particles. This means that the combination of temperature and soil water content influence the rates of weathering and nutrition uptake by plants. However, plants are of course also sensitive to high temperature and high amount of water, and so the relationships between growth and water supply or temperature have been found to be unimodal.

Topography

Water flow is driven mainly by gravity, and so the topography is essential for determining the distribution of water within a catchment. The quantity of water that passes a location in the landscape is dependent on the position on the slope and the curvature of the landscape, and the waters velocity is dependent on the steepness of the hill slope. The direction of the slope, i.e. aspect, is important for the angle and amount of solar radiation that reaches the soil surface and vegetation.

Biota

Soil is a composite of both a mineral component (silt/sand/gravel) and also an organic component. To be termed soil, organic material must be present, and the proportion of this organic material can vary, with peats consisting solely of organic material.. Organic material is added to the soil from litter fall, root exudates and decaying organic material. Organic material releases nutrients (anions & cations) that living organism subsequently take up again from the soil during growth. Organic acids from decaying biotic material together with soil CO_2 from roots increase the weathering rate of soil minerals in the unsaturated zone.

Biota also contributes to the soil porosity through channels from roots and earth living heterothophs. Microorganisms decompose organic material to make available nutrients for the vegetation. Bioturbation, i.e. the vertical mixing of organic and mineral soil, is a result of soil organism activity.

Time

All soil forming factors have a kinetic component, and thus soil formation is strongly influenced by the amount of time the soil has been exposed to transformation. (Brady & Weil, 2001).

The Topographic Wetness Index

Within Swedish boreal forest the factors Parent material, Climate and Time can be assumed relatively homogenous. Vegetation has been found to be strongly dependent on water availability and thus topography (Moore, Norton & Williams, 1993; Zinko*, et al.*, 2005). This is the theory behind the expected and observed influence of topography on soil properties. The topographical factor in hydrological modelling is often expressed in a topographic index. The most widely applied index is the topographic wetness index, TWI.

TWI was first introduced by Beven and Kirkby (1979) as part of the runoff model TOPMODEL. It is defined as $\ln(a/\tan\beta)$, where a is the specific upslope area and $\tan\beta$ is the slope of the ground surface. This means that locations with a large upslope area receive a high index value and are expected to have relatively higher water availability; as opposed to locations with a small upslope area that receive a small index value and are expected to have relatively lower water availability. Likewise, steep locations receive a lower index value and are expected to be better drained than gently sloped locations, which receive a higher index value (Fig.1).

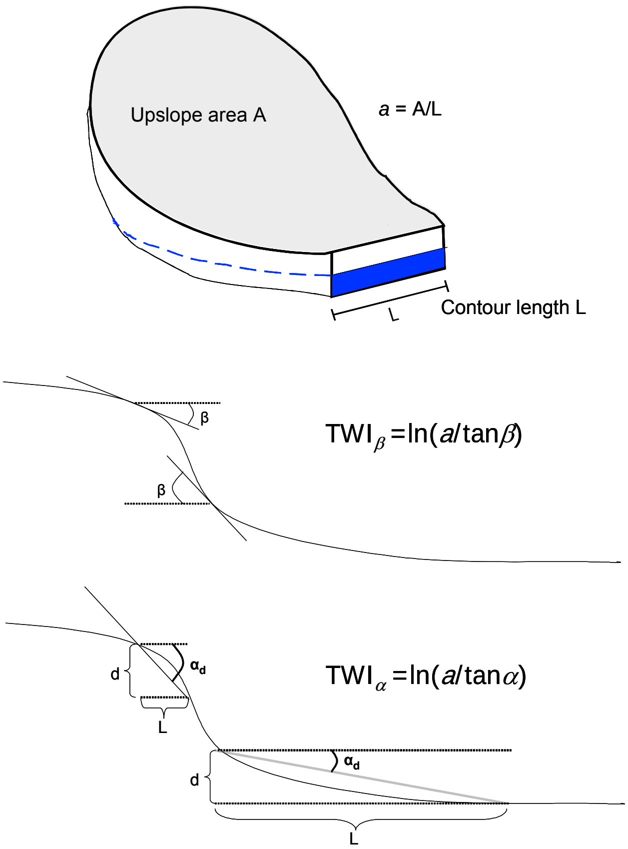

Fig. 1. The components of the TWI; specific upslope area a, local slope index (tanβ) and downslope index (tanα=d/L).

Consequently, TWI is a relative measure of the hydrological conditions of a given site in the landscape.

Several assumptions are underlying the derivation of the TWI. The slope of the ground surface is assumed to represent the slope of the groundwater table. The soil hydraulic conductivity and the precipitation are both expected to be uniform over the studied landscape. Finally, the natural logarithm in the expression of TWI represents an assumed decrease of transmissivity with depth (Rodhe & Seibert, 1999b). All these assumptions can be relaxed, but this requires additional information such as the spatial variation of hydraulic conductivities, which usually is not available. Within Swedish boreal forested landscapes, however, the assumptions are generally fulfilled (Rodhe & Seibert, 1999b).

A downslope index has recently been suggested by Hjerdt et al. (2004) as 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 d length units below the cell. By taking downslope topography into account 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 (Fig 1).

TWI is calculated from digital elevation models (DEMs) usually organized in raster grids. The DEM grid size is commonly in the range of 20 – 100 meters, and is important for the accuracy of the results derived from the DEM. One of the major advantages of DEM derived indices is that they provide estimates of landscape properties without the need for field sampling.

TWI has been used in several studies to spatially estimate both hydrological, physical and chemical properties of soils (Welsch *et al.*, 2001; Western*, et al.*, 1999; Whelan & Gandolfi, 2002).

Topographical influence on soil moisture conditions was studied in the catchment of Tarrawarra, Australia, where Western et al. (1999) found terrain, combined with the potential solar radiation index, to explain between 22-61% of the variation. This was supported by Wilson et al. (2004) who were able to explain between 26 and 64%. Slope and slope position were found useful for estimating soil water retention at locations from several areas in the USA (Rawls & Pachepsky, 2002), and components of the TWI were used for estimating the distribution of mires in the landscape in Sweden (Rodhe & Seibert, 1999a). 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 was investigated by Brubaker et al (1993), who observed an increase of pH, $CaCO_3$, extractable Ca, Mg, and Ca, as well as base saturation downslope. Along the same gradient they found a decrease 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 for estimating N-cycling rates in a prairie area of Minnesota, 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 in the area of 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 mountain area of eastern Taiwan. In the Catskill watershed in New York, USA, Johnson et al. (2000) studied 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.

In young boreal forest soils there is a strong relation between topographical position, soil chemistry, vegetation composition and forest productivity, due to the transport of water and nutrients downslope (Fischer and Binkley, 2000). This relationship has long been pointed out and lateral water flow has e.g. been included as an indicator in the Swedish site index assessment system (Hägglund & Lundmark, 1977). The influence on soil chemistry involve downslope increases in soil pH, base saturation total nitrogen stock and nitrate release (Giesler, Hogberg & Hogberg, 1998). The topography is also central for many ecological characteristics through the influence of both soil moisture and soil chemistry, which have also been subject to studies. E.g. Zinko et al. (2005) found strong correlations between TWI and vascular plant species richness.

Objectives

Several studies have demonstrated the usefulness of the TWI, which is increasingly used to estimate landscape features such as hydrological variables (e.g. (Band *et al.*, 1993; Rodhe & Seibert, 1999b; Western*, et al.*, 1999; Whelan & Gandolfi, 2002), and variables indirectly influenced by hydrology, such as soil chemistry (Band*, et al.*, 1993; Johnson, Méndez & Lawrence, 2000; Welsch*, et al.*, 2001; Whelan & Gandolfi, 2002), and plant species richness (Holmgren, 1994; Moore, Norton & Williams, 1993; White & Running, 1994; Zinko*, et al.*, 2005).

The purpose of this thesis is to contribute to the understanding of

- the influence of topography on soil properties in Swedish boreal forest (papers I & II)
- the influence of different calculation methods as well as DEMs of different resolution on the computed TWI maps (papers I & III)

Paper I

In previous studies in Swedish boreal forest the TWI explained 30-52% of the variation in plant species richness, 58-71% of ground water variation and 50–71% of soil pH variation (Zinko*, et al.*, 2005). The TWI in these correlations was calculated by standard methods. However, the calculation of the TWI can be varied depending on different assumption of ground water flow path and mechanisms controlling drainage. Therefore, an optimization of the TWI calculation method could provide the opportunity to improve the correlations between TWI and soil parameters.

In this study we compared a number of calculation methods for TWI and evaluated them in terms of their correlation with vascular plant species richness, soil pH, groundwater level, soil moisture, and a constructed wetness degree. The TWI was calculated by varying six parameters affecting the distribution of accumulated area among downslope cells and by varying the way the slope was calculated. All possible combinations of these parameters were calculated for two separate boreal forest sites in northern Sweden, in which previous studies had observed high predictive power for the TWI.

We did not find a single calculation method that performed best for all measured variables; rather the optimal method seemed to be variable and site specific. It was possible to identify some general characteristics of the optimal method for different groups of measured variables. The results provide guiding principles for choosing the best method for estimating species richness, soil pH, groundwater level, and soil moisture by the TWI derived from digital elevation models.

Paper II

With the key assumption that the soil forming factors parent material, climate and time are homogenous, this paper raises the question: is there any consistency in the relationship between TWI and soil parameters when moving beyond catchment scale?

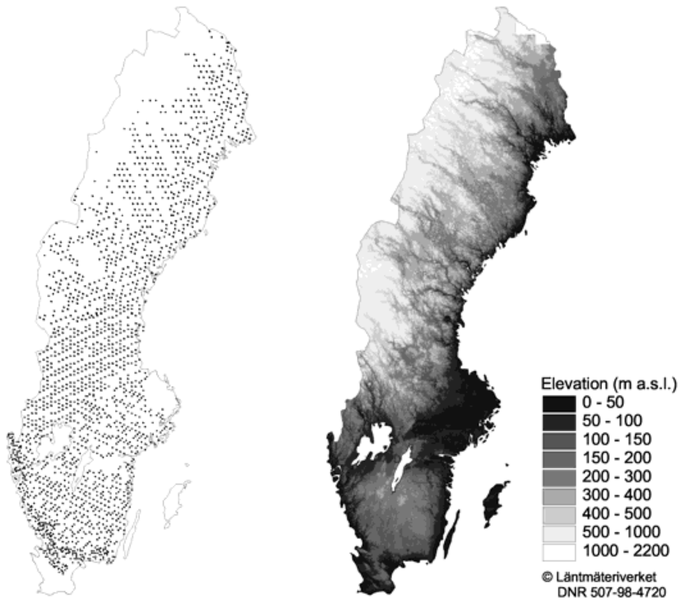

Fig. 2. Location of sampling points from the Swedish Forest Soil Inventory used in the study.

In this study we used data from 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). The survey is a long-term inventory of permanent sample plots. The survey includes a description of soil types and soil horizons and sampling of organic and mineral soil horizons for subsequent chemical analyses.

In this study we selected podzols and organic soils which resulted in 4 000 sample plots distributed over almost all of Sweden (Fig. 2).The positions of the plots were determined accurately by GPS, which allowed the overlaying of plot data and the DEM. TWI was computed from gridded digital elevation data for all sample plots.

There were several statistically significant correlations ($n=1325$ to 4011, $p<0.01$, $r^2=0.01$ to 0.14) between topographical indices and soil properties. These included a positive correlation between the thickness of the organic layer and the TWI and an increase in the thickness of the bleached E-horizon with increased upslope area. Soil pH in the organic layer increased with TWI (Fig. 3), whereas the C/N-ratio decreased; soil pH in the organic layer was also found to be higher for south facing slopes compared to north facing slopes. The ratio between the concentrations of the divalent base cations (Ca and Mg) and the monovalent base cations (K and Na) in the O-horizon also increased with TWI.

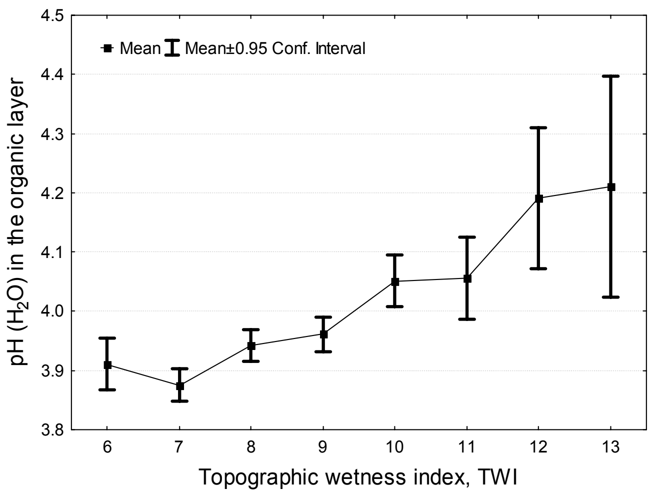

Fig. 3. Soil $pH_{(H2O)}$ in the organic layer for different TWI-classes.

These correlations confirmed the importance of topography on soil properties, although there was a considerable scatter, which could be attributed to the heterogeneity in this large data set.

Due to size of the data set used in this study the data were far from homogeneous. The sample sites varied among other things in climate, geology and vegetation history. Therefore, the scatter observed in the correlations was expected. Despite the scatter, the observed correlations were all significant (p<0.01), and demonstrated the importance of topography in predicting soil properties.

Paper III

The DEMs used for calculation of TWI in paper I and II had resolutions of 20 by 20 m^2 and 50 by 50 m^2. Zinko et al. (2005) considered that the variation within high TWI grid cells was so high that a finer grid (than their 20 by 20 m^2) would increase the accuracy of the correlation between TWI and landscape parameters.

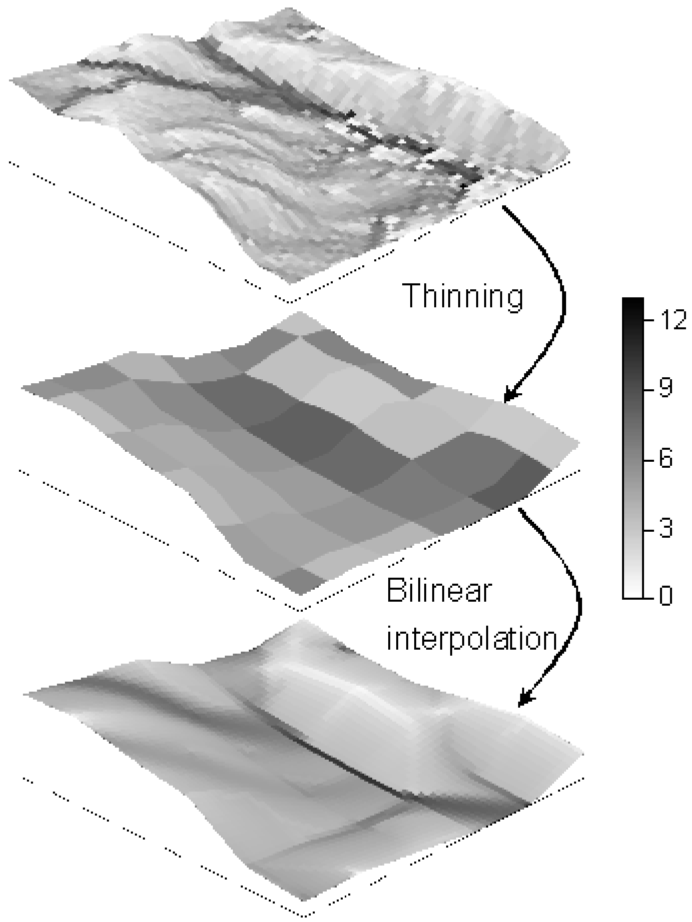

Fig. 4. Example from the maps of the specific upslope area, ln(a), for the original 5 m resolution DEM (above), a 50 m resolution DEM generated by thinning (middle), and a high resolution low information content DEM processed by bilinear interpolation back to 5 m resolution (below)(500 by 500 m^2 window).

For this paper, access was obtained to LIDAR (LIght Detection And Ranging) data over a boreal forest area. From the LIDAR data a DEM of 5 by 5 m^2 grid size was extracted. On basis of this DEM another 3 DEMs were extracted by thinning to resolutions of 10, 25 and 50 m grid sizes in order to study the effect of lower grid size and information content. These thinned DEMs were then transformed back to a grid resolution of 5 m using bilinear interpolation to isolate the effect of information content from the effect of grid size (Fig. 4). For all seven DEMs distribution functions were compared in accordance with previous studies. Additionally a cell by cell correlation was made for the original and the three interpolated DEMs; and the original and the three lower resolution DEMs were compared for each area of 50 by 50 meters. In addition to the traditional tanβ slope an alternative slope measure was tested, tanα, that considers the drainage conditions rather than the local slope. Similar to previous studies, we observed that higher resolution and information content gave lower estimates of the specific upstream area, and a narrower slope distribution. The cell by cell correlation among low grid size DEMs showed a decrease in correlation to r=0.70 and r=0.41for 10 m and 25 m resolution, respectively. The variation of TWI also decreased dramatically with increasing grid size. The observed effects were somewhat lower for the tanα and the interpolated DEMs than for the tanβ and the lower resolution DEMs. Our results show that simply interpolating the DEMs to a higher resolution (i.e. a smaller grid size) might give more similar TWI distribution, but quite different patterns can be obtained compared with the TWI computed from the original 5 m DEM. The optimal resolution should represent the important topographic features for a certain variable of interest. Using a finer resolution might in some cases actually weaken rather than improve correlations with topographic indices.

Concluding remarks

For terrain analysis to be a useful predictive tool, the topographical features used in modelling must be correlated with the landscape properties of interest. If this condition is met then the terrain analysis can be used to predict hydrological, pedological and biological properties at a spatial resolution impossible to achieve through field work. Currently the TWI is used by some Swedish public authorities when selecting potential locations for nature reserves for the protection of species richness of vascular plants.

We have shown that by selecting an appropriate DEM resolution and adjusting the calculation methods for specific purposes, the usefulness of the TWI could be refined and be applied over a rather large spatial range. A better understanding of the hydrological processes behind the redistribution of chemical elements in the soil would help further refinement of the TWI. Currently under evaluation is a proposal for a DEM, finer than today's 50 m resolution, covering all of Sweden, if completed this would significantly increase the applicability of TWI and other indices.

A further step in the application of TWI to a larger spatial range would be to utilise the large dataset of the Swedish National Survey of Forest Soils and Vegetation in relating landscape properties to topographic indices, e.g. by adding information about other known parameters, such as soil type or climate (i.e. other soil forming factors) in order to minimize the high level of noise in the correlations.

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On the calculation of the topographic wetness index: evaluation of different methods based on field observations

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Abstract. The topographic wetness index (TWI, ln(a/tanβ)), which combines local upslope contributing area and slope, is commonly used to quantify topographic control on hydrological processes. Methods of computing this index differ primarily in the way the upslope contributing area is calculated. In this study we compared a number of calculation methods for TWI and evaluated them in terms of their correlation with the following measured variables: vascular plant species richness, soil pH, groundwater level, soil moisture, and a constructed wetness degree. The TWI was calculated by varying six parameters affecting the distribution of accumulated area among downslope cells and by varying the way the slope was calculated. All possible combinations of these parameters were calculated for two separate boreal forest sites in northern Sweden. We did not find a calculation method that performed best for all measured variables; rather the best methods seemed to be variable and site specific. However, we were able to identify some general characteristics of the best methods for different groups of measured variables. The results provide guiding principles for choosing the best method for estimating species richness, soil pH, groundwater level, and soil moisture by the TWI derived from digital elevation models.

1 Introduction

Topography is a first-order control on spatial variation of hydrological conditions. It affects the spatial distribution of soil moisture, and groundwater flow often follows surface topography (Burt and Butcher, 1986; Seibert et al., 1997; Rodhe and Seibert, 1999; Zinko et al., 2005). Topographic indices have therefore been used to describe spatial soil moisture patterns (Burt and Butcher, 1986; Moore et al., 1991). The spatial distribution of groundwater levels influences soil processes and will in turn affect the properties of the soil (e.g. Zinko et al., 2005; Sariyildiz et al., 2005; Band et al., 1993; Florinsky et al., 2004; Whelan and Gandolfi, 2002).

The topographic wetness index (TWI) was developed by Beven and Kirkby (1979) within the runoff model TOPMODEL. It is defined as ln(a/tanβ) where a is the local upslope area draining through a certain point per unit contour length and tanβ is the local slope. The TWI has been used to study spatial scale effects on hydrological processes (Beven et al., 1988; Famiglietti and Wood, 1991; Sivapalan and Wood, 1987; Siviapalan et al., 1990) and to identify hydrological flow paths for geochemical modelling (Robson et al., 1992) as well as to characterize biological processes such as annual net primary production (White and Running, 1994), vegetation patterns (Moore et al., 1993; Zinko et al., 2005), and forest site quality (Holmgren, 1994a).

Topography affects not only soil moisture, but also indirectly affects soil pH (Högberg et al., 1990; Giesler et al., 1998). Soil moisture and pH are important variables that influence distribution (Giesler et al., 1998) and species richness of vascular plants (Zinko et al., 2005; Gough et al., 2000; Pärtel, 2002; Grubb, 1987) in Fennoscandian boreal forests. Because of the links between topography and plant species richness, the TWI has been useful for predicting the spatial distribution of vascular plant species richness in the Swedish boreal forest (Zinko, 2004). In these studies the TWI explained 52% of the variation in plant species richness for a site with relatively higher average soil pH (HP-site) and 30% of the variation for a site with lower average soil pH (LP-site). In the same studies, TWI was also found to correlate well with depth to groundwater and soil pH. (LP; groundwater: Spearman's rank correlation r_s=0.58, $P<$0.001, n=46; soil pH: r_s=0.50, $P<$0.001, n=84; HP: groundwater level: r_s=0.71, $P<$0.001, n=45; soil pH: r_s=0.71, $P<$0.001, n=55).

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The TWI is usually calculated from gridded elevation data. Different algorithms are used for these calculations; the main differences are the way the accumulated upslope area is routed downwards, how creeks are represented, and which measure of slope is used (Quinn et al., 1995; Wolock and McCabe, 1995; Tarboton, 1997; Güntner et al., 2004). New algorithms have been evaluated primarily in terms of comparisons with other algorithms (e.g. Quinn, 1991; Holmgren, 1994a; Tarboton, 1997) or in terms of theoretical geometric correctness (Pan et al., 2004). Only a few studies have evaluated the TWI computation algorithms using spatially distributed field measurements. Güntner et al. (2004) compared different algorithms and modifications of the TWI with the spatial pattern of saturated areas. They concluded that the ability of the TWI to predict observed patterns of saturated areas was sensitive to the algorithms used for calculating upslope contributing area and slope gradient. Kim and Lee (2004) evaluated different calculation methods based on their ability to predict the observed stream network and found that a modification of the multidirectional flow accumulation algorithm suggested by Quinn et al. (1991) was needed to solve the problem of flow dispersion overestimation in near-stream cells.

In this study, we asked whether or not the correlation between TWI and a number of variables for which a correlation could be expected depends on the method used to calculate the TWI. Spatially distributed field observations of plant species richness, soil pH, groundwater level, and soil moisture were used to evaluate the different methods. Initial results indicated that different methods might provide differing results. Therefore, we sought to determine whether it was possible to find one single TWI computation method for estimating different field variables in boreal forest landscapes. We used data from Zinko (2004) for two boreal forest sites in northern Sweden that differed in average soil pH. In contrast to previous studies on the relationship between plant species richness and TWI (Zinko et al., 2005; Zinko, 2004), we started this study with the assumption that there actually should be a correlation between TWI and the different field variables. Therefore, a suitable computation algorithm for TWI should provide this correlation and the highest correlation coefficients would indicate the most suitable computation algorithm. Our study was restricted to calculations of TWI based on raster elevation data (20×20 m resolution). We also restricted the analysis to point-to-point comparisons because our field observations were not suitable for other comparison methods such as those described by Grayson et al. (2002) or Güntner et al. (2004).

The main questions we addressed for this paper were: (1) Do different calculation methods and modifications of TWI give different results in terms of correlation with measured variables of hydrology, soil chemistry, and vegetation? (2) Which combinations of calculation methods and parameters provide the most accurate results? (3) Is there one general method for TWI computation that provides near-optimal correlations for different areas and different measured variables of hydrology, soil chemistry, and vegetation?

2 Material and methods

2.1 TWI calculation methods and modifications

The raster DEM with a grid size of 20 by 20 m had been derived from aerial photography using a Zeiss PlaniComp analytic stereo instrument (accuracy of ±0.7 m). When calculating TWI from the DEM, different algorithms and modifications of the original "TOPMODEL" index (Beven and Kirkby, 1979) can be used. The variants of TWI differ in the ways that the upslope area a, creek cell representation, and slope are computed. The different calculation methods we tested are listed below.

2.1.1 Upslope area

Calculation of upslope area depends on the way the accumulated area of upstream cells is routed to downstream cells. Traditionally, the area from a cell has been transferred in the steepest downslope direction to one of the eight neighbouring cells. Quinn et al. (1991) introduced a multidirectional flow algorithm that allowed the area from one cell to be distributed among all neighbouring downslope cells, weighted according to the respective slopes. The distribution of area to each downslope cell was based on slope according to the term $\mathrm{F}_i=\tan\beta_i/\Sigma\tan\beta_i$. Quinn's multiple flow algorithm more accurately predicted flow paths in the upper part of the catchment while the single directional flow algorithm had higher predictive power in the lower parts (Quinn et al., 1991).

Holmgren (1994b) extended Quinn et al.'s (1991) distribution function by introducing an exponent h that controls the distribution among downslope directions according to $\tan\beta_i^h/\Sigma\tan\beta_i^h$, where $0\leq h\leq\infty$. A high exponent (h) means that more accumulated area will be distributed in the steepest direction, i.e. more similar to single directional flow. The lower the exponent the more equally the flow will be distributed among the downslope cells (for a more detailed description see Holmgren, 1994b, or Quinn et al., 1995). This exponent can thus be seen as a parameter that causes a gradual transition from single directional flow (infinite h; in practice values above $\sim$25) to multidirectional flow (h=1).

In the usual single-direction algorithm, the steepest direction into which the accumulated area is routed is restricted to the eight cardinal and diagonal directions. An alternative was proposed by Tarboton (1997), who calculated the steepest downslope direction based on triangular facets that allowed the steepest direction to be routed in any direction rather than being restricted to the eight cardinal and diagonal directions. The accumulated area is then routed to the two cardinal and diagonal directions that are closest to the steepest direction weighted according to their distance from this direction. This method was further developed by allowing multiple flow directions (Seibert, unpubl. manuscript). Around the midpoint, M, of any pixel, eight planar triangular facets were constructed with the midpoints, P_1 and P_2, of two adjacent neighbouring pixels. The slope direction of this plane (determined by M, P_1, and P_2) was computed for each facet. If the steepest slope direction was outside the 45° (π/4 radian) angle range of the particular triangular facet (i.e., not between the vectors pointing from M towards P_1 and P_2, respectively), the direction with the steeper gradient of the two directions towards P_1 or P_2, was used as the steepest direction. After computing the steepest direction for all eight triangular facets, those directions that had a steeper gradient than both of their adjacent facets were identified. These directions were interpreted as local outflows and the accumulated area was distributed among these directions. Similar to Quinn's multidirectional flow algorithm the h exponent was used to control the weighting of the different directions according to their respective slopes. We tested both Tarboton's and Quinn's approach with different values for the exponent, h, as mentioned above. Both of the algorithms were tested with seven values for h: 0.5, 1, 2, 4, 8, 16, and 32, for a total of 14 different combinations of flow distribution methods.

2.1.2 Creek representation

The basic assumptions of the TWI do not hold when there is a creek and, thus, creeks need to be considered explicitly. We assumed that creeks began when the accumulated area exceeded a certain creek initiation threshold area (*cta*). The accumulated area of a "creek cell" is usually routed downslope as "creek area" and not considered in the calculation of a in downslope cells. However, a key question is if the area below *cta* should be routed downwards and contribute to a (i.e., only the area exceeding *cta* is treated as creek area) or if all accumulated area should be routed downwards as creek area. We tested both variants (called *cta*-down) and 8 values for *cta*: 2.5, 5, 10, 15, 20, 30, 40, and 50 ha.

2.1.3 Slope

The local slope $\tan\beta$ might not always be a good representation of the groundwater table hydraulic gradient because downslope topography more than one cell distant is not considered. A new slope term, $\tan\alpha_d$ was introduced by Hjerdt et al. (2004) in response to this issue. In contrast to $\tan\beta$, which only considers the cell of interest and its neighbours, $\tan\alpha_d$ is defined as the slope to the closest point that is d meters below the cell of interest. Both slope estimates give similar results for small values of d, but the results differ for larger values of d (Hjerdt et al., 2004). The distance to this point can be computed as either beeline distance or distance along the flow path (i.e., always following the steepest downslope directions). In the following text this parameter is called slope distance. We tested both $\tan\beta$ and $\tan\alpha_d$, varying the latter with different vertical distances d: 2, 5, 10, 15, and 20 m (i.e., in total 6 slope variants). Both beeline and flow path distance were tested.

In summary, combinations of three binary (flow distribution, *cta*-down, slope distance) and three continuous (h, *cta*, d) calculation parameters were tested. For the continuous parameters we tested six to eight different values. A total of 2688 (=2·2·2·7·8·6) different TWI values were computed for each of the two forest sites.

We treated cells without any adjacent downslope cell, i.e., depressions, as real topographic features and not as errors in the elevation data. Therefore, instead of "filling" these depressions before the index was calculated, we continued the search for downslope cells using all cells located 2, 3, ... cells away until the nearest downslope cell was found; the area was routed to this/these cell(s) (Rodhe and Seibert, 1999). An initial test indicated that filling the sinks would not have significantly influenced the results of this study.

We did not compare the TWI values directly to the observed field data but used the mean value of a 3×3 cell window around the particular cell to minimize the effect of erroneously assigning a sample site to the wrong cell in the DEM.

2.2 Study sites and field measurements

The study was performed in two separate 25-km^2 boreal forest sites in northern Sweden: one site with low average soil pH (LP) in Åmsele, Västerbotten county (64°33′ N, 19°35′ E), and one site with high average soil pH (HP) 240 km to the southwest in Kälarne, Jämtland county (62°59′ N, 16°01′ E). The elevations of both sites vary between 220 and 400 m a.s.l. The bedrock is mainly granitic and the soil consists of glacial till with peat cover in the depressions. Yearly precipitation is about 600 mm at both sites. Mean temperature in January is −13°C and −10°C for the LP and HP sites respectively, and in July is +14°C for both sites (Raab and Vedin, 1995). Vegetation at both sites is dominated by boreal forest composed mainly of *Pinus sylvestris* and *Picea abies*; intensive silviculture has been conducted for over 50 years in these forests. The studied areas therefore include semi-natural forest, clear-cuts, and plantations of native and exotic (*Pinus contorta, Abies* sp.) tree species. For a more detailed description of the study sites see Zinko (2004). Study plots of 200 m^2 were distributed to the centre of the 400 m^2 grids of the digital elevation model used for calculating the topographical index. The study plots (88 plots in the LP site and 56 plots in the HP site) were randomly distributed within each site, but constrained so that the number of samples for different classes of TWI values was equal (i.e., high TWI values were sampled more frequently than would correspond to their occurrence in the landscape). The plots were located in the field by a GPS receiver. Marshlands without trees, lakes, and streams were not included in this study.

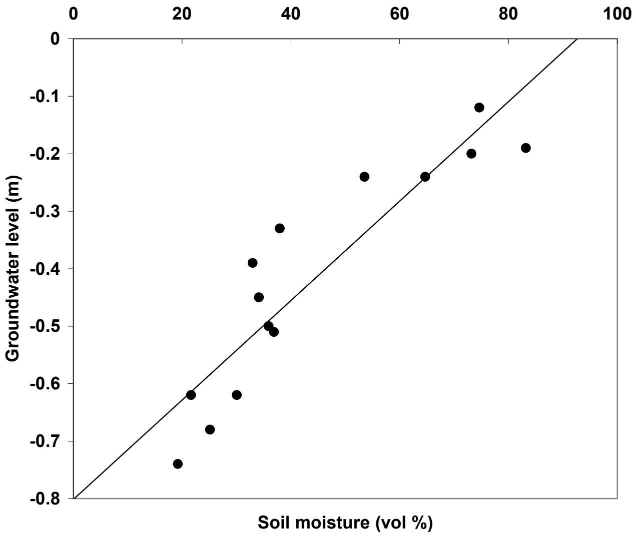

Fig. 1. Relationship between soil moisture (measured with TDR) and groundwater levels at the HP site in July 2002. Observations of both variables were available for 14 plots (r^2=0.823, P>0.001, n=14).

We catalogued all vascular plant species at the LP site in July 1999 and in July 2002 at the HP site. Soil sampling was conducted in 2002 and 2003 at the HP and LP sites, respectively. Cores of 2.5 (LP) and 5 (HP) cm diameter and up to 30 cm long were collected for soil pH measurement from the O-horizons at eight evenly distributed locations within 2 m of the plot centre. The eight soil samples were bulked to one single sample, air-dried, and analysed for soil pH (H2O, 1:25, soil:solution mass ratio).

Polyethylene tubes with an inner diameter of 9 mm were installed to a depth of 0.7 m as close as possible to the centre of the plots to measure ground water levels. At one plot in each study site, the presence of bedrock and boulders made it impossible to insert a tube. For the same reason not all tubes were inserted to 0.7 m. We excluded all plots at which groundwater levels were never recorded (38 plots in the LP site and 10 plots in the HP site). Groundwater levels were measured four times (once a month) between June and September 2001 at the LP site and twice during 2002 (July and October) at the HP site. We used the mean of the four groundwater level measurements at the LP site for the statistical analysis. Since summer and fall 2002 were dry, with groundwater levels below 0.7 m in many HP plots, we used only one occasion (October) of groundwater level measurements. For the wells for which groundwater levels could be observed in both months the levels were clearly correlated (r=0.69).

At the HP site, soil moisture in the upper 15 cm was measured with a Time Domain Reflectometry (TDR) instrument (TRIME FM3 manufactured by IMKO, Germany). The factory-set calibration curve that translates the dielectric constant of the soil into soil water content was used for all measurements. The soil water content of a plot was calculated as the mean value of the eight measurements, which were taken at about 2 m distance from the center towards all cardinal and diagonal directions. At soil water contents above ~50%, the measurements became unreliable and unrealistic soil water contents of up to 80–100% were returned for wet soils. While these values obviously are not correct, it was assumed that they still could be used as a relative measure to compare the wetness in the different plots. Very wet plots, in which the ground water was at or close to the ground surface and where the TDR measurements gave values of 100% for most points, were excluded from further soil moisture analyses. TDR measurements were performed in July and October 2002. Both measurements were highly correlated (r=0.90) and only the July measurements were used in this paper. Soil moisture and groundwater levels were measured for all plots during a 2–3 day period without precipitation so that the conditions could be assumed to be constant during the measurement period.

For the HP site, the July groundwater and soil moisture measurements were combined into a parameter called "degree of wetness", which allowed ranking of all locations according to soil moisture and groundwater observations. This was motivated by the fact that groundwater observations were not available for dry locations where the levels were more than 0.7 m below the surface; whereas the TDR measured soil moisture was unreliable for wet locations. The "degree of wetness" is an approach to combine soil moisture and groundwater data into one data series. In this way the two methods complemented each other and allowed ranking of all plots according to a single wetness variable. We performed a linear least square regression with groundwater level as the dependent variable and soil moisture as the predictor. Groundwater level could then be expressed as a function of soil moisture (Fig. 1). For plots (n=22) where only soil moisture content was measured in July a value based on this function was estimated. If only groundwater level was measured there was no modification (n=11). If both TDR and groundwater level were measured, the average of estimated and measured groundwater level was used (n=14), i.e., both types of hydrological data were represented and got the same weight. If neither moisture nor ground water level was measured, the location was excluded from the analysis (n=9). The degree of wetness computed in this way was then used to rank the plots according to wetness conditions and these ranks were used for the calculation of Spearman's rank correlations. While the relationship between soil moisture and groundwater is not linear we suppose that a linear approximation is acceptable within the ranges of our measurements for the ranking as described above.

The different variables obviously were correlated to some degree. The correlation coefficients varied from 0.28 to 0.87 (Table 1). With a weak correlation it is possible that different methods provide best results, although even with low correlations one single method could be best in all cases. In general, the correlation matrix suggests two groups of variables. Correlations between plant species richness and soil pH as well as groundwater levels and soil moisture were higher than correlations across these two groups of variables.

2.3 Data analysis

All correlation coefficients between the 2688 different TWI values and the measured variables (plant species richness, soil pH, groundwater level, soil moisture, and wetness degree (for the HP site)) for each site were calculated using Spearman's rank correlation. The results were examined in three ways:

(1) The highest correlation coefficient (HC) between each measured variable and each of the parameter values was identified. For each measured variable this was done by keeping one parameter fixed to a certain value but allowing the other parameters to vary. The variability of the HC within a parameter was then analysed.

(2) The 10% methods (best-10%) resulting in the highest correlations between TWI and measured variables were selected and distribution functions were compiled for each parameter. We also computed the overlap of the best-10% sets between the two study sites as well as for the different measured variables within each study site. The overlap was computed as the ratio between the number of methods found in both best-10% sets and the total number of methods in a best-10% set (269).

(3) Finally, we determined which calculation methods were most suitable for more than one variable. For each set of correlations between each measured variable and parameter value the differences (ΔC) between the highest correlation coefficient and all the other correlation coefficients were computed. The measured variables were divided into different groups and the mean differences $\overline{\Delta C}$ for all variables within a group were calculated. The calculation method with the lowest $\overline{\Delta C}$ was considered the most suitable TWI calculation method for this particular group of measured variables. The groups used in this analysis were: (i) all variables from both sites (to obtain an overall best calculation method), (ii) all parameters from the HP site, (iii) all variables from the LP site, (iv) different groups of the measured variables.

The first approach showed the best calculation method for each single measured variable alone, whereas the second approach provided information on how likely a good correlation was depending on a certain value for one single parameter. The two approaches, HC and best-10%, were used together to decide on the best methods for each measured variable and were expected to return similar results. The third approach gave a general perception of the processes influencing the groups of measured parameters.

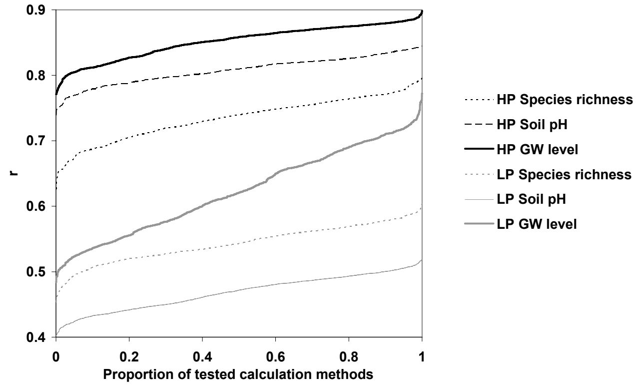

Fig. 2. Accumulated distributions of Spearman rank correlation coefficients, increasing from the poorest correlation (left side) to the best correlations (right side), obtained by using the 2688 different TWI values.

3 Results

The correlations between TWI values and measured variables varied considerably between the different calculation methods. The Spearman rank correlation between TWI and soil pH, for instance, varied between 0.40 and 0.52 for the LP site and between 0.74 and 0.84 for the HP site (Fig. 2). Among all variables at both sites the least accurate method gave correlations between 0.11 and 0.29 units lower than the best of the tested methods.

3.1 Single measured variables

Different calculation methods yielded the strongest correlations for the different single measured variables at the two study sites. Below we summarize the results for each parameter (see also Fig. 3 and Table 2).

3.1.1 Flow distribution

The modification of Tarboton's approach was superior for calculation of flow distribution (Table 2), except for pH and groundwater level at the HP site, where Quinn's method achieved a higher portion among the best-10% methods.

3.1.2 h_exponent

The h values of the best methods were evenly distributed for species richness for the LP site. For pH, higher h values dominated the best-10%, while lower $h$values gave better results for groundwater. The best of the highest correlations (HCs) for species richness and soil pH were similar among all parameter values, whereas the best HC for groundwater was with low h values (Fig. 3a). A slightly different pattern was observed at the HP site. For plant species richness and groundwater level, h=0.5 had the best-10% (Fig. 3d). A low h (h=2) also performed best for soil moisture. For

Table 1. Pearson correlation coefficients, r, among the measured variables for the HP-site (Table 1a) and for the LP-site (Table 1b).

1a.

HP – Kälarna	Spec rich	pH	GW level	TDR	Wetness degree
Spec rich	1				
pH	0.87	1			
GW level	0.48	0.66	1		
TDR	0.41	0.61	0.86	1	
Wetness degree	0.62	0.78	0.96	0.95	1

1b.

LP – Åmsele	Spec rich	pH	GW level
Spec rich	1		
pH	0.62	1	
GW level	0.32	0.28	1

soil pH and wetness degree the h=8 and 16, respectively, had slightly better best-10%. The best HCs were found using the three lowest h-exponent values (h=0.5, 1, or 2) for plant species richness, soil pH, and groundwater level while the highest value (h=32) gave the highest HCs for soil moisture and wetness degree (Fig. 3d).

3.1.3 cta

At the LP site, high *cta* values had the highest portion of the best-10% for species richness, whereas for pH and groundwater level, lower *cta* values had the highest portion (Fig. 3b). This also applied for the HCs. For the HP site, the groundwater level followed the same pattern, but for the rest of the measured variables the best-10% were evenly distributed and the HCs were similar (Fig. 3e).

3.1.4 cta-down

The decision as to whether or not the area corresponding to *cta* was routed downslope as groundwater flow did not influence the correlations. In both sites the portion of the best-10% was equally distributed between the two options (not shown).

3.1.5 Slope

For the LP site, $\tan\beta$ or $\tan\alpha_2$ had the largest portion of the best-10% for species richness, soil pH, and groundwater level (Fig. 3c). The highest HC was found when using $\tan\beta$ for all three measured variables. At the HP site $\tan\alpha_{20}$ gave best results both with respect to best-10% and HC for soil pH and species richness (Fig. 3f). According to the best-10% and HC, $\tan\alpha_2$ was found to be best for groundwater, whereas $\tan\beta$ was best for soil moisture and wetness degree.

3.1.6 Slope-distance

The downslope index computed with the beeline distance performed best for both plant species richness and soil pH at both sites (Table 2). In contrast, the distance following the flow path gave best results for the groundwater levels at both sites and soil moisture at the HP site (Table 2). The slope distance method did not affect the correlations with wetness degree at the HP site.

The large variation in best parameter values for the different measured variables indicates that there is no single best method. In general, there was also a relatively small overlap between the best-10% methods for the different measured variables and study sites (Table 3). At the HP site, there was significant overlap between the best methods for plant species number and soil pH as well as among the hydrological variables (although one has to consider that wetness degree was calculated from groundwater level and moisture). No overlap at all between any of the hydrological variables and species richness or soil pH was found at the HP site. There was significant overlap at the LP site among all three parameters (Table 3). There was overlap among the hydrological parameters and between the pH-methods for both sites together. There was also significant overlap between the pH at the HP site and the species richness and the pH at the LP site, but not between the species richness at both sites. However the species richness at the LP site overlapped with the soil moisture at the HP site.

3.2 Grouped measured variables

The overall best calculation method, evaluated by the portion among the best-10%, was found when using the modification of Tarboton's flow distribution, low values of h (h=1–2), the $\tan\beta$ slope, and *cta* values of 15 ha. Slope distance did not have any influence on the correlations (Fig. 4, Table 4), nor did the cta-down (not shown).

We identified two groups of measured variables that each had generally similar best-10% distributions, with plant species richness and soil pH in one group, and groundwater level, soil moisture, and wetness degree in the other. The calculation parameters performing best for the first group were Quinn's flow distribution method, h value of 2–8, $\tan\alpha_{15}$ slope and beeline slope distance, and *cta* values of 15–20 ha (Fig. 4, Table 4). For the group of hydrological variables, the best results were obtained with Tarboton's flow distribution, h value of 1–2, *cta* value of 10–20 ha, $\tan\beta$ slope, and flow path slope distance (Fig. 4, Table 4). The parameter cta-down did not have any influence on the correlations (not shown).

Grouping the variables by study site resulted in best performance for Tarboton's flow distribution and $\tan\beta$ slope for all measured variables in the HP site. The other parameters

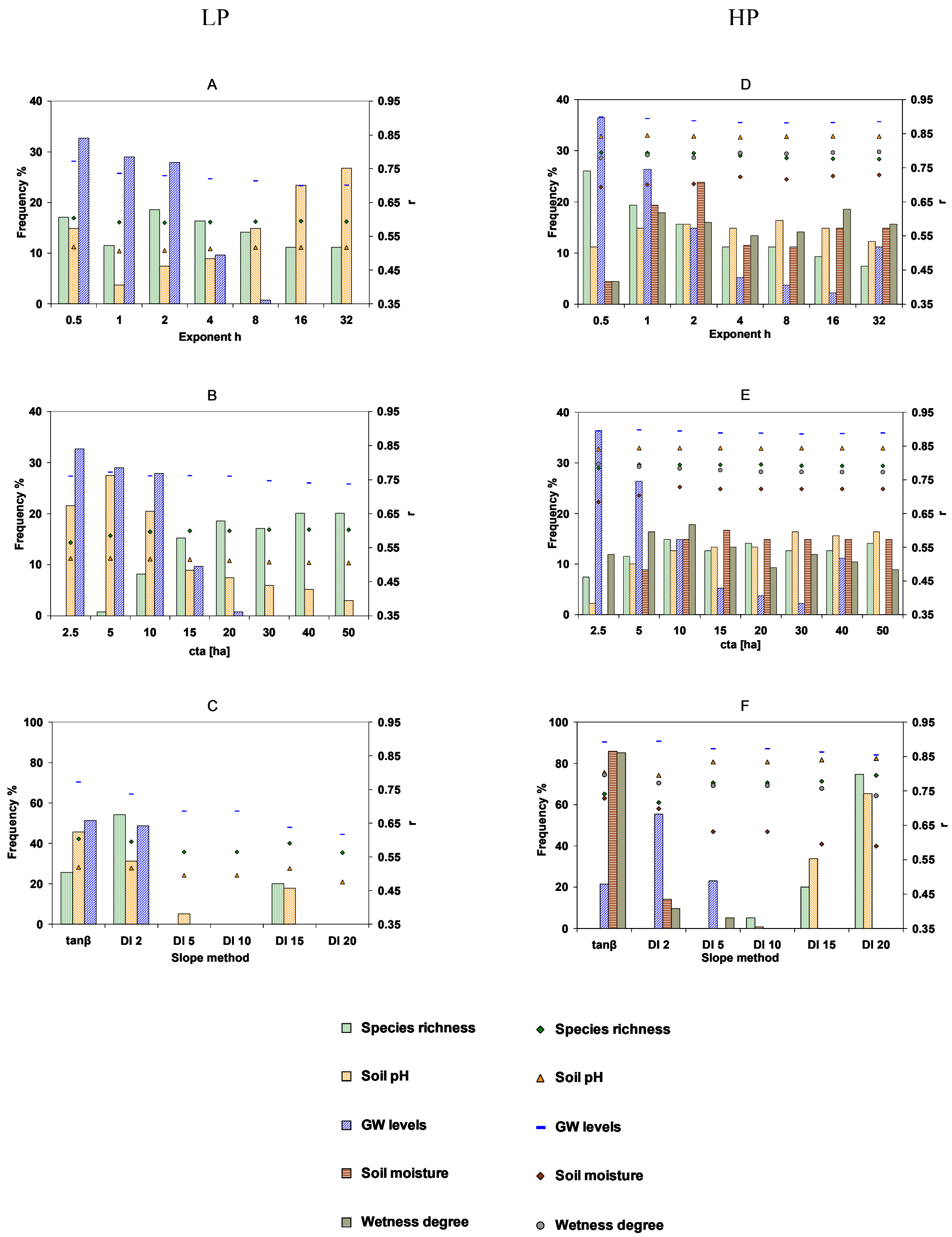

Fig. 3. Distributions for each measured variable of the best 10% calculation methods (bars) among different values of the exponent h, the slope method (including different values for the d in the downslope index), and the creek initiation area, *cta*. The highest correlation coefficients (HC) obtained using a certain parameter value are shown by symbols. The figures **(a–f)** show the distributions for the three different parameters in the two study areas: (a) h in the LP site. (b) cta in the LP site. (c) slope in the LP site. (d) h in the HP site. (e) cta in the HP site. (f) slope in the HP site. Note the different scale on the y-axis for the slope method.

exhibited no significant influence on correlations for this site, but h values of 0.5 and *cta* values of 2.5–5 gave lower correlations (Fig. 4, Table 4). In the LP site Tarboton's flow distribution, low values of h (0.5–2), *cta* values of 10–20, $\tan\alpha_{d2}$ slope, and the beeline distance yielded the best results (Fig. 4, Table 4). Cta-down did not have any effect on the results in any of the sites (not shown).

The best calculation methods when grouping the measured variables according to type or site resulted in correlation coefficients between the overall best calculation method and the best calculation method for each single measured variable (Table 5).

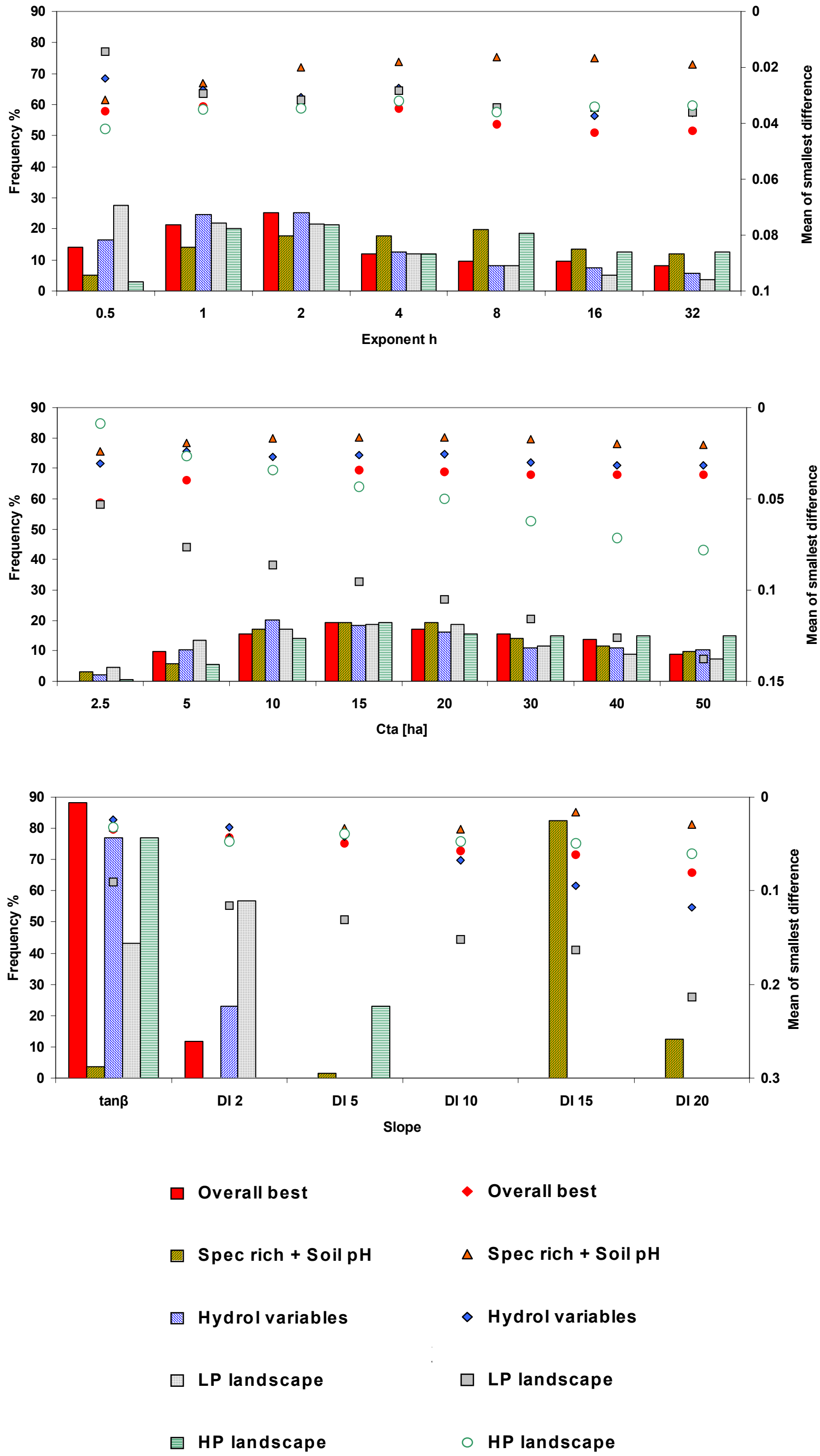

Fig. 4. Distribution of the best 10% calculation methods (bars) among different values of the exponent *h*, the slope method (including different values for the d in the downslope index), and the creek initiation area, *cta*, for different groups of measured variables. The symbols show how much correlation coefficients decrease when using the best method for a group instead of the best method for the individual variables. This was expressed as the mean of the differences between the highest correlation coefficients obtained for each individual variable and the highest correlation coefficients, which were obtained for the entire group for a certain parameter value.

Table 2. Distribution of the best 10% of all tested calculation methods (using different measured variables) for flow distribution and slope distance respectively. Note that there were only two options for each of these two parameters. As both options were tested equally often in all cases, the deviation from a 50-50 distribution indicates how important a certain choice is. The highest Spearman's rank correlation coefficients, r_s, which were obtained with a certain method, are given in brackets.

	LP site (Åmsele)			HP site (Kälarne)				
Flow distribution method	Species richness	pH	Ground-water	Species richness	pH	Ground-water	Soil moisture	Wetness degree
Tarboton	63	60	59	55	33	41	78	68
	(0.604)	(0.519)	(0.762)	(0.795)	(0.842)	(0.894)	(0.729)	(0.797)
Quinn	37	40	41	45	67	59	22	32
	(0.590)	(0.515)	(0.772)	(0.793)	(0.845)	(0.898)	(0.700)	(0.787)
Slope distance method (for tanα_d)								
Beeline	79	76	40	100	100	13	41	49
	(0.604)	(0.519)	(0.760)	(0.795)	(0.845)	(0.892)	(0.729)	(0.797)
Along flow path	21	24	60	0	0	87	59	51
	(0.589)	(0.510)	(0.772)	(0.771)	(0.829)	(0.898)	(0.729)	(0.797)

Table 3. Overlapping between the best 10% calculation methods for the different measured variables. The overlap was computed as the ratio between the number of methods found in both best-10% sets (of the measured variables to be compared) and the total number of methods in a best-10% set (n=269). For random drawings the overlapping ratio would be smaller than 0.071 with a probability of 0.05 and higher than 0.127 with a probability of 0.95.

		LP site (Åmsele)			HP site (Kälarne)				
		Species richness	pH	Ground-water	Species richness	pH	Ground-water	Soil moisture	Wetness degree
LP site (Åmsele)	Species richness	1	0.290	0.320	0	0.186	0.119	0.215	0.082
	pH		1	0.142	0.007	0.142	0.052	0.126	0.261
	Groundwater			1	0	0	0.424	0.379	0.254
HP site (Kälarne)	Species richness				1	0.677	0	0	0
	pH					1	0	0	0
	Groundwater						1	0.163	0.178
	Soil moisture							1	0.751
	Wetness degree								1

4 Discussion

Our results demonstrate that different methods of calculating the TWI indeed produce a high variation in correlation strengths between the various TWI values and the different measured variables. There was not one single method that was optimal for all variables and study sites. Overall, the overlap of the best-10% between either measured variables or study sites was rather small (Table 3). However, general characteristics for methods yielding the best-10% could be observed for certain groups of variables.

The correlation coefficients decreased with the generality of the calculation method. The best overall calculation method did not yield as strong correlations as the best calculation methods for each single measured variable. However, the latter calculation methods were only optimal for a particular variable and study site and are thus of more limited general applicability.

In our study, the modification of Tarboton's flow distribution method was in general superior to Quinn's distribution method. This was expected, since Quinn's method tends to overestimate flow dispersion and braiding, especially in near-stream areas (Kim and Lee, 2004). Pan et al. (2004) found the multiple flow direction to be geometrically more accurate than the single flow direction algorithm in idealized DEMs. Our empirical study also found that the multiple directional flow algorithms were superior to the single-directional algorithm in both Quinn's and Tarboton's methods. However,

Table 4. Distribution of the best 10% of all tested calculation methods (using different groups of measured variables) for flow distribution and slope distance respectively. Note that there were only two options for each of these two parameters. As both options were tested equally often in all cases, the deviation from a 50-50 distribution indicates how important a certain choice is. The mean of the difference between the very best correlation coefficient for each measured parameter and the group wise best correlation coefficient are given in brackets.

	Species richness and pH	Groundwater, soil moisture and wetness degree	LP (Åmsele) site	HP (Kälarne) site	All
Flow distribution method					
Tarboton	41	71	87	74	77
	(0.093)	(0.181)	(0.154)	(0.114)	(0.125)
Quinn	59	29	13	26	23
	(0.096)	(0.168)	(0.152)	(0.112)	(0.123)
Slope distance method (for $\tan\alpha_d$)					
Beeline	91	37	58	52	48
	(0.084)	(0.181)	(0.154)	(0.104)	(0.121)
Along flow path	9	63	42	48	52
	(0.096)	(0.169)	(0.149)	(0.114)	(0.125)

Table 5. Best Spearman rank correlation coefficients obtained for the single measured variables at each site and for different groups of variables. Correlation coefficients for correlations where the particular variable is included in the respective group are in bold.

		Best correlation for groups of variables				
	Best possible correlation for each variable	Species richness and pH	Groundwater, soil moisture and wetness degree	LP site (Åmsele)	HP site (Kälarne)	All
LP site (Åmsele)						
Species richness	**0.604**	**0.587**	0.556	**0.597**	0.570	**0.580**
pH	**0.519**	**0.505**	0.492	**0.513**	0.497	**0.498**
Groundwater	**0.772**	0.582	**0.772**	**0.743**	0.711	**0.722**
HP site (Kälarne)						
Species richness	**0.795**	**0.765**	0.667	0.716	**0.730**	**0.739**
pH	**0.845**	**0.840**	0.757	0.795	**0.798**	**0.802**
Groundwater	**0.898**	0.835	**0.886**	0.872	**0.862**	**0.871**
Soil moisture	**0.729**	0.582	**0.676**	0.674	**0.723**	**0.702**
Wetness degree	**0.797**	0.721	**0.765**	0.746	**0.792**	**0.772**

optimal values for h were larger than one in some cases, indicating that the usual multidirectional flow algorithm might sometimes result in too large a spreading of the accumulated area. Holmgren (1994b) suggests a value of h between 4 and 6 irrespective of DEM resolution. In our study the best correlations for the hydrological variables were mainly found with lower values of h (0.5–2). The value of h could depend on the steepness in the studied landscape. Our results combined with those of Güntner et al. (2004), who found h values of 8–10 to be most suitable in a mountainous catchment, suggest that h might decrease when going from mountainous (with steeper slopes) to hilly areas.

The best-10% differed in terms of slope calculation between the two groups of measured variables. For plant species richness and soil pH, a higher slope distance ($\tan\alpha_{d15}$) and the beeline distance should be used, while for the hydrological variables best results were obtained with $\tan\beta$ slope and slope distance calculated along the flow path. The difference in d indicates that downslope drainage conditions are more important for the plant species richness and soil pH than for groundwater level, soil moisture, and wetness degree. A possible explanation is that local slope influences the hydrological variables, while larger geomorphologic features are more important for species richness of vascular plants and soil pH. For example, a site on a plateau with relatively small upstream area but a low slope can be quite moist but have low soil pH and plant species richness. A higher value of d gives information about the downslope conditions, which can indicate where along a slope the site is situated. A gentle slope would be found in the lower parts of a hill, while a steeper slope would indicate that the point is situated in a recharge area. Groundwater recharge and discharge areas differ considerably in terms of soil pH and plant species richness, with both increasing towards discharge areas (Giesler et al., 1998; Zinko et al., 2005).

Güntner et al. (2004) found that a *cta* of 6–10 ha worked best for the TWI used to predict water-saturated areas. In our study *cta* values of 10 to 20 ha generally gave the best correlations for the measured hydrological variables. However, the *cta* did not have much influence on the strength of the correlations, which may be because most plots were located in non-creek cells regardless of the value of *cta*. Although Güntner et al. (2004) found a smaller value of *cta*, indicating that creeks start with less accumulated area, precipitation in their study catchment was roughly twice that in our sites. Kim and Lee (2004) found an optimal *cta* value of 20 ha for estimation of the creek network in their catchment in South Korea.

Correlation coefficients were in general higher at the HP site than at the LP site. This difference might be explained by the fact that the pH range in the HP area is greater than that of the LP area, meaning that there is more variation in pH to be explained by the TWI.

Grouping the variables helped to identify some guiding principles and allow speculating about physical explanations. For instance, higher values for d in the downslope index (i.e., an integration of the slope over a larger scale) gave better results for the correlation with soil pH and species richness, whereas the local slope worked better for soil moisture. One might argue that this could be because soil pH and species richness depend more on long-term lateral flow processes that redistribute weathering products within the catchment. In contrast the soil moisture at the surface reflects current conditions and is more sensitive to local topographical features.

5 Concluding remarks

This study was a first attempt to find a general calculation method for the TWI that would be valid for the spatial distribution of plant species richness, soil pH, groundwater level, and soil moisture in Fennoscandian boreal forest. We were not able to identify one single best method since different methods gave best correlations with the different measured variables. Although not as pronounced as for the different variables the best methods were also site specific. However, "compromise" methods that yielded best calculations for the different measured variables were identified. In general, the modified Tarboton's flow distribution performed better than Quinn's method, and a low h value yielded the best results. The local slope tan*ß* was found in most cases to be superior to the use of the $\tan\alpha_d$ slope. However, a higher d value and the beeline slope distance were best for estimating soil pH and species richness, while $\tan\beta$ and flow path slope distance were best for estimating the hydrological variables.

It might be useful to explore, if at least some data are available, the variety of calculation methods for the topographical index prior to performing estimates based on it. Our results also indicate the need to further refine the algorithms. Some calculation parameters could be variable in time or space. The value of *cta*, for instance, could vary with slope or season and the value of h could vary with soil type or slope. The species richness of vascular plants and the pH, however, are not expected to vary seasonally.

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Topographical influences on soil properties in boreal forest soils

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Abstract

Topography is a major controlling factor on hydrological processes at the landscape scale and, thus, also soil processes depend on topographic position. In a qualitative way this is well-known and topography is together with parent material, climate, biota and time one of the fundamental soil forming factor. The topographic influence is also apparent in the concept of soil catenas. Digital elevation models (DEMs) and topographic indices calculated based on these DEMs allow the study of the relation between topography and soil characteristics in a more quantitative way. In this study we use data from the Swedish National Forest Soil Inventory. The survey is a long-term inventory of permanent sample plots of the Swedish National Forest Inventory. The survey includes a description of soil types and soil horizons and sampling of organic and mineral soil horizons for subsequent chemical analyses. In this study we selected Podzols and Histosols, which resulted in 4 000 sample plots distributed over almost all of Sweden. The positions of the plots 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, whereas the C-N ratio decreased. Soil pH in the organic layer was also found to be higher for south facing slopes compared to north facing slopes. The ratio between the concentrations of the divalent base cations (Ca and Mg) and the monovalent base cations (K and Na) in the O-horizon increased with TWI. These correlations confirmed the importance of topography on soil properties, although there was a considerable scatter, which could be attributed to the heterogeneity in this large data set.

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1 Introduction

Can relationships between topography and soil properties, which have been found at the catchment scale, also be observed at larger scales? This is the question we address in this study, in which we correlate field data from 4000 sites located all over Sweden to topographic indices.

Spatial information of soil properties is usually a limiting factor for land management and in the application of spatially distributed models (Park and Vlek, 2002; Behrens et al., 2005). Soil information from soil maps is usually at too low resolution and the values of soil attributes are assumed uniform although often there is large variation within soil units (Zhu et al., 1997). Therefore there is a great interest in relating different properties of the soil and habitat to easily available data, such as elevation data. Elevation data can than 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 in 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 as opposed to 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 a location is exposed to and thus the temperature regime, which affects soil biological and chemical processes as well as evaporation. The local slope determines the intensity of slope processes such as erosion and sediment redistribution, but also local drainage capacity. However, the most important effect of topography on soils in e.g. boreal regions is through the 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 result in different soil moisture conditions and flow patterns. Topography is an independent soil forming factor and its contribution to soil formation can be considered on its own (Brady and Weil, 2001; Singer and Munns, 1999).

An attempt to integrate topographical information in order to capture the hydrological variation was made by Beven and Kirkby (1979) by introducing the Topographical Wetness Index (TWI) algorithm, $\ln(a/\tan\beta)$, where a is the specific upslope area and $\tan\beta$ is the local slope. According to the TWI concept the soil moisture and ground water level of a location is the result of the accumulated upslope area, a, and the drainage expressed as slope, $\tan\beta$. TWI has been used in several studies to spatially estimate both 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 in the catchment of Tarrawarra, Australia, where Western et al. (1999) found terrain, combined with the potential solar radiation index, to explain between 22-61% of the variation. In a following study Western et al. (2004) found topography to explain between 0 and 40% of the spatial variability of soil moisture. In the same 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 measure of the soil moisture conditions.

Wilson et al. (2004) were able to explain between 26 and 64%. Slope and slope position were found 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 for estimating the distribution of mires in the landscape in Sweden (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 an increase of pH, $CaCO_3$, extractable Ca, Mg, and Ca, as well as base saturation downslope. Along the same gradient they found a decrease 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 for estimating N-cycling rates in a prairie area of Minnesota, 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 in the area of 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 mountain area of eastern Taiwan. In the Catskill watershed in New York, USA, Johnson et al. (2000) studied 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.

In young boreal forest soils has been observed a strong relation between topographical position, soil chemistry, vegetation composition and forest productivity, due to the transport of water and nutrients downslope (Fischer and Binkley, 2000). This relationship has long been pointed out and lateral water flow has e.g. been included as an indicator in the Swedish site index assessment system (Hägglund and Lundmark, 1977). The influence 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 for many ecological characteristics through the influence of 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 regions. Our investigation, on the other hand, was based on a national inventory of forest soils, which covers all of Sweden outside the mountain range. It focuses on the influence of topography on properties for different conditions as regards climate, parent material and vegetation type. There is an obvious gradient in climate within Sweden, which in turn influences on the biota. Swedish forest soils are 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 compared to other soil forming factors such as time and parent material. Further, the influence of aspect is largest at latitude 40-60º N (Birkeland, 1999), which corresponds to the location of the investigation site.

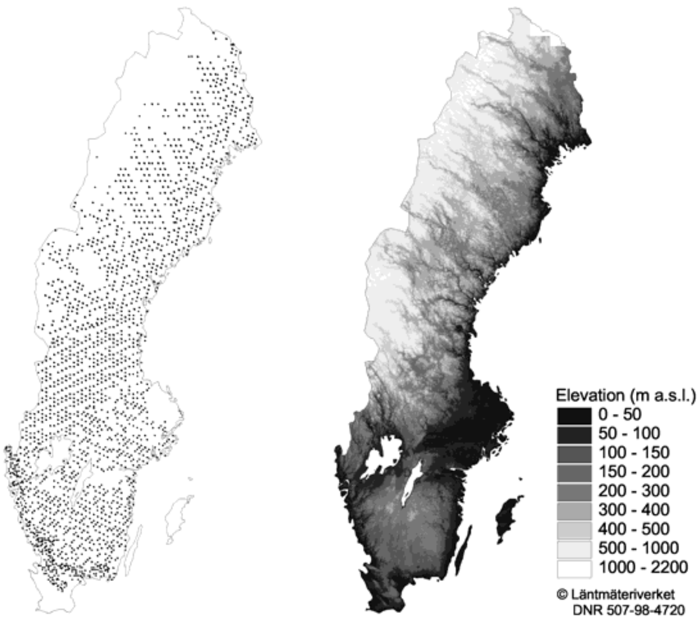

Figure 1. Location of sampling points from the Swedish Forest Soil Inventory used in the study.

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 Sweden outside the mountain range, except for arable land and urban areas. In total, ca 23 000 permanent plots of 10 m radius are sampled and/or described regarding forest and soil conditions recurrently every 10 year. 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 limited to data from 1996 until 2002 since only these included GPS positioned coordinates. Regions with bedrock and soil types others than granitoid bedrock with till parent material common to large part of Sweden were excluded from the study (Fig. 1). The number of data points used in this study varied from ca 1300 to 4000 points depending on the soil variable of interest. The soil chemical variables used in this study (Tab. 1) were analyzed on the fine fraction (< 2 mm) after drying and grinding the samples. The total content

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	C (%)	4011	39.9	42.8	35.8	46.1	27.2	48.0
O	N (%)	4011	1.33	1.25	1.03	1.54	0.84	1.96
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	pH(H_2O)	4011	3.97	3.86	3.64	4.17	3.49	4.61
O	Ca (mmol kg^{-1}_{dm})	2004	64.0	48.1	31.2	73.0	19.6	118.9
O	Mg (mmol kg^{-1}_{dm})	2004	16.8	14.3	9.8	20.5	6.9	29.3
O	K (mmol kg^{-1}_{dm})	2004	15.4	14.3	9.1	20.4	5.3	26.5
O	Na (mmol kg^{-1}_{dm})	2004	4.01	3.29	2.12	4.93	1.39	7.29
O	Al (mmol kg^{-1}_{dm})	2004	10.43	6.73	3.04	13.18	1.26	24.82
O	BS (%)	2004	81.8	87.4	74.3	95.2	55.3	98.6
O	TA (mekv kg^{-1}_{dm})	2004	720.4	731.6	561.1	880.8	396.1	1012.4
E	Thickness (cm)	4011	10.6	8	4	14	2	22
B	C (%)	1325	2.46	2.00	1.18	3.22	0.71	4.59
B	N (%)	1325	0.12	0.09	0.06	0.15	0.04	0.21
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	pH(H_2O)	1325	4.79	4.78	4.59	4.99	4.40	5.17
B	Ca (mmol kg^{-1}_{dm})	1325	2.21	0.72	0.33	1.69	0.16	4.10
B	Mg (mmol kg^{-1}_{dm})	1325	0.60	0.27	0.15	0.52	0.09	1.13
B	K (mmol kg^{-1}_{dm})	1325	0.54	0.44	0.28	0.65	0.19	0.98
B	Na (mmol kg^{-1}_{dm})	1325	0.50	0.40	0.26	0.62	0.17	0.88
B	Al (mmol kg^{-1}_{dm})	1325	6.82	5.54	2.91	9.12	1.61	13.33
B	BS (%)	1325	22.9	15.8	9.4	28.3	6.2	50.9
B	TA (mekv kg^{-1}_{dm})	1325	72.4	64.0	41.7	93.1	29.0	123.8

of C, N and S was analyzed after dry combustion using an element analyzer (LECO CNS-1000). Exchangeable base cations were extracted using ammonium acetate, whereas for exchangeable Al a KCl solution was used. The extracts were analyzed using ICP equipment (ISA Jobin Yvon JY24). Total acidity (TA) was analyzed by extraction with ammonium acetate solution buffered at pH 7 and subsequently determination of the total acidity by titration with NaOH. The pH was analyzed in water. The soil properties used in this study and their descriptive statistics are listed in Tab.1.

2.2 Calculation of topographic indices

The computation of topographic indices was based on the DEM for Sweden which is available at grid resolution of 50 by 50 m^2. For computational reasons a smaller DEM was extracted from the DEM of Sweden for each sample site. 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 by far large enough 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, which differ mainly in the way the upslope area is computed (Quinn et al., 1995; Tarboton, 1997; Wolock and McCabe, 1995). Multiple-flow-direction algorithms tend to give more realistically looking spatial pattern than single-direction algorithms, where the flow is concentrated to distinct lines. In this study we used the multiple-flow-direction algorithm proposed by Quinn et al. (1991). The idea of this algorithm is to distribute the accumulated upslope area among all downslope directions using a weighting based on the gradients.

The flow algorithm we used differed partly from the algorithms described by Quinn et al. (1991). Streams were assumed to start when the accumulated area exceeded a certain threshold area (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, which underlie 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).

A downslope index has recently been suggested by Hjerdt et al. (2004) as 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 d length units (here set to 2 m) below the cell. By taking downslope topography into account 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. In this study we replace the local gradient by this downslope index, i.e., the TWI was calculated as $\ln(a/\tan\alpha_d)$.

Additionally to TWI we used the values of $\ln a$ and $\tan\alpha_d$ for each sample site separately. For all these indices mean values of 3-by3 cell windows were used for each sample site, because the use of the value of only one grid cell is more sensitive to errors in the coordinates of the sample sites. In addition to the topographic index we also computed the aspect.

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. Firstly, the distribution of topographic indices was evaluated for the different soil classes. Secondly, correlations coefficients between topographic indices and measures soil properties were computed. Here Spearman rank correlation was used as a more robust measure of correlation than Pearson correlation, where 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.

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 going from ferric to humic Podzols and finally to Histosols, there was a clear increase in average upslope area and a decrease in slope values.

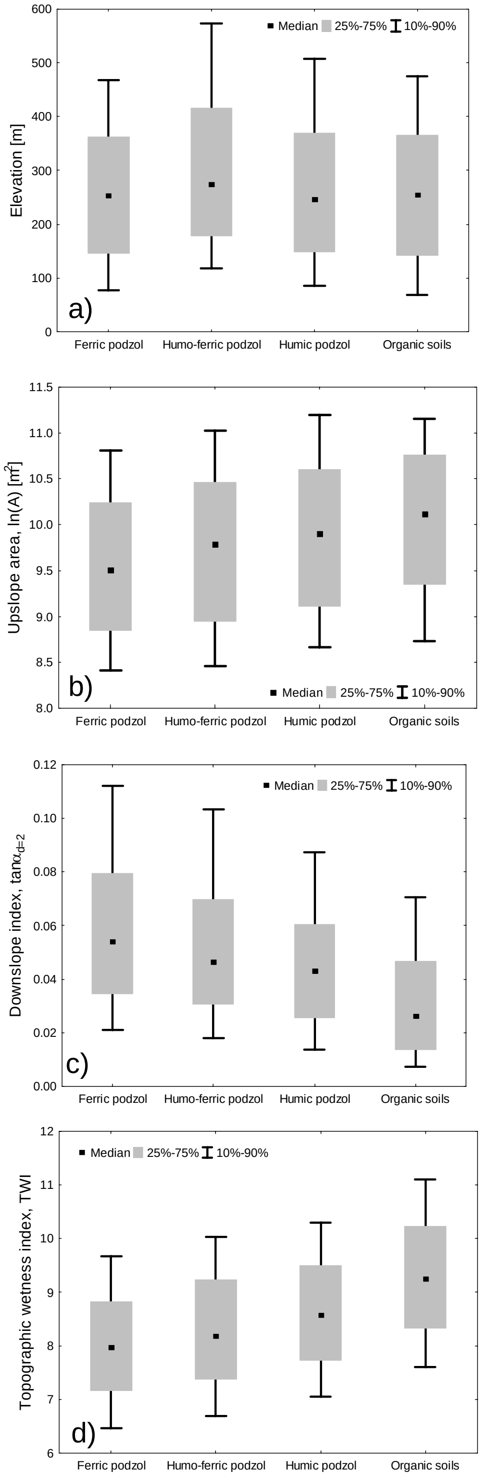

Figure 2. Values of different topographic indices for the four different soil types, a) Elevation [m a.s.l.], b) Upslope area, ln(A), A in [m^2], c) Downslope index, $\tan\alpha_{d=2}$, d) Topographic wetness index, TWI.

Consequently, the TWI also increased along the same sequence.

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

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**	**0.19**	**-0.38**	**0.38**
O	C (%)	**0.10**	0.00	**-0.17**	**0.12**
O	N (%)	**-0.11**	**0.12**	**-0.17**	**0.19**
O	C-N ratio	**0.20**	**-0.11**	**0.08**	**-0.12**
O	S (%)	**-0.07**	**0.08**	**-0.15**	**0.15**
O	pH(H_2O)	**0.07**	**0.20**	**0.04**	**0.11**
O	Ca (mmol $kg^{-1}{}_{dm}$)	**0.09**	**0.17**	0.03	**0.11**
O	Mg (mmol $kg^{-1}{}_{dm}$)	**-0.03**	**0.10**	**-0.09**	**0.15**
O	K (mmol $kg^{-1}{}_{dm}$)	**0.26**	-0.04	**0.31**	**-0.21**
O	Na (mmol $kg^{-1}{}_{dm}$)	**-0.13**	0.03	**-0.21**	**0.16**
O	(Ca+Mg)/(K+Na)	**-0.09**	**0.16**	**-0.15**	**0.21**
O	Al (mmol $kg^{-1}{}_{dm}$)	**-0.18**	-0.05	**-0.07**	-0.01
O	BS (%)	**0.17**	**0.10**	**0.06**	0.05
O	TA (mekv $kg^{-1}{}_{dm}$)	**-0.10**	**-0.08**	**-0.13**	0.03
E	Thickness (cm)	**0.18**	**0.12**	**0.07**	**0.05**
B	C (%)	0.05	**-0.09**	0.02	**-0.07**
B	N (%)	0.05	**-0.08**	0.05	**-0.08**
B	C-N ratio	0.04	-0.05	-0.03	-0.06
B	S (%)	**0.08**	-0.06	0.03	-0.05
B	pH(H_2O)	**0.16**	**0.11**	0.06	0.05
B	Ca (mmol $kg^{-1}{}_{dm}$)	-0.03	**0.15**	0.05	**0.10**
B	Mg (mmol $kg^{-1}{}_{dm}$)	**-0.10**	**0.08**	0.05	0.05
B	K (mmol $kg^{-1}{}_{dm}$)	0.03	**-0.09**	**0.14**	**-0.14**
B	Na (mmol $kg^{-1}{}_{dm}$)	-0.06	-0.02	0.01	-0.02
B	(Ca+Mg)/(K+Na)	-0.06	**0.19**	**-0.15**	**0.15**
B	Al (mmol $kg^{-1}{}_{dm}$)	-0.07	**-0.08**	-0.02	-0.06
B	BS (%)	0.05	**0.14**	**0.09**	**0.07**
B	TA (mekv $kg^{-1}{}_{dm}$)	0.03	**-0.07**	0.02	-0.07

The thickness of the O horizon was the variable that correlated most strongly with topographical indices (i.e. with TWI, r=0.38) (Fig. 3a). When soils with humus layer thickness >50 cm were excluded the relationship was still strong, although the absolute increase in thickness with TWI value decreased (Fig. 3b).

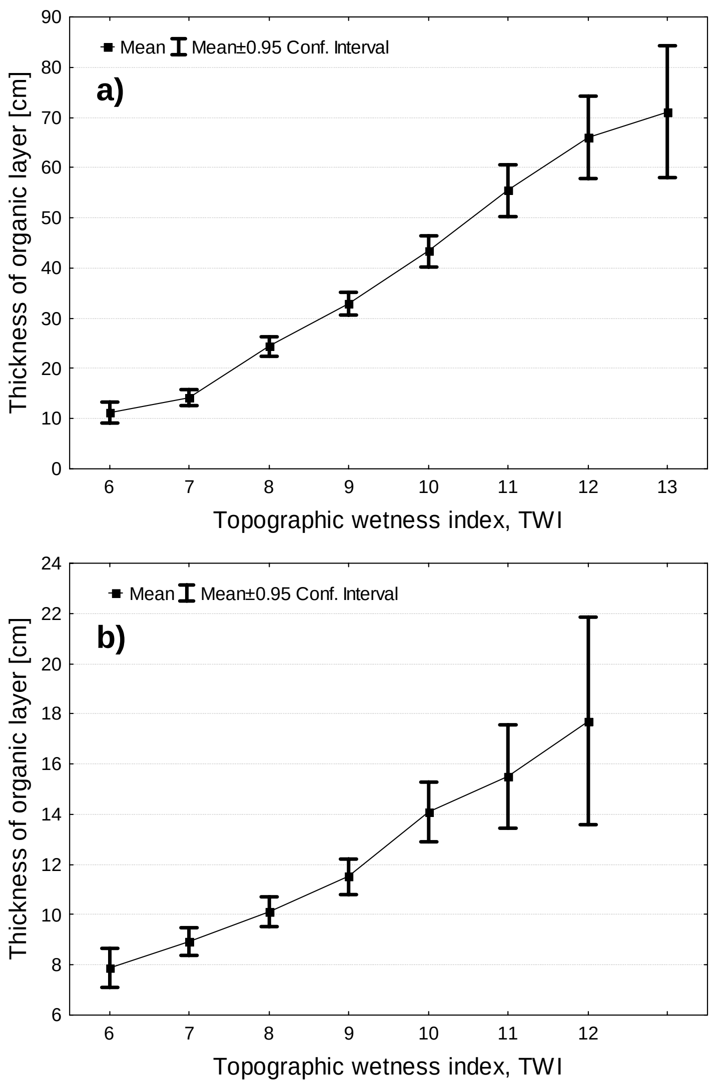

Figure 3. Thickness of the organic layer against TWI, a) all locations, b) locations with a thickness larger than 50 cm were excluded (since only few locations were remaining in the largest TWI class, these were added to the TWI=12 class) .

The thickness of the leached E horizon also increased with upslope area (Fig. 4).

The thickness of the E horizon also increased with elevation (Tab. 2). The total C and N content in the O horizon increased with TWI, which mainly seemed to be related to the negative correlation with local slope. The C-N ratio decreased with increasing TWI (Fig. 5), which was mainly caused 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.

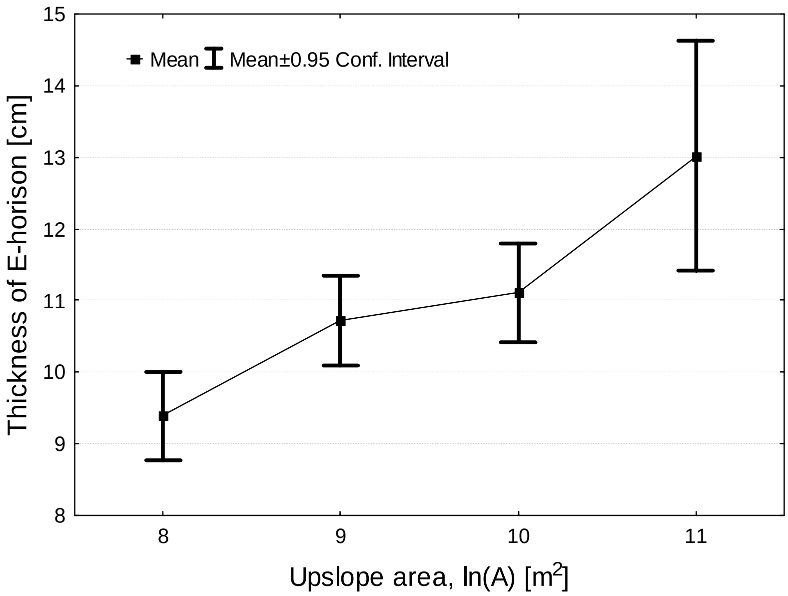

Figure 4. Thickness of the E-horison against upslope area, ln(A), A in [m^2].

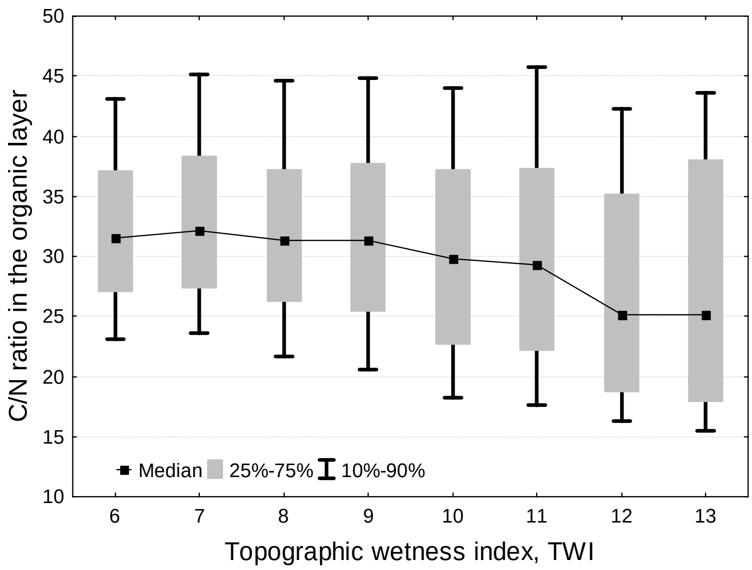

Figure 5. C-N ratio in the organic layer for different TWI-classes (medians and percentiles).

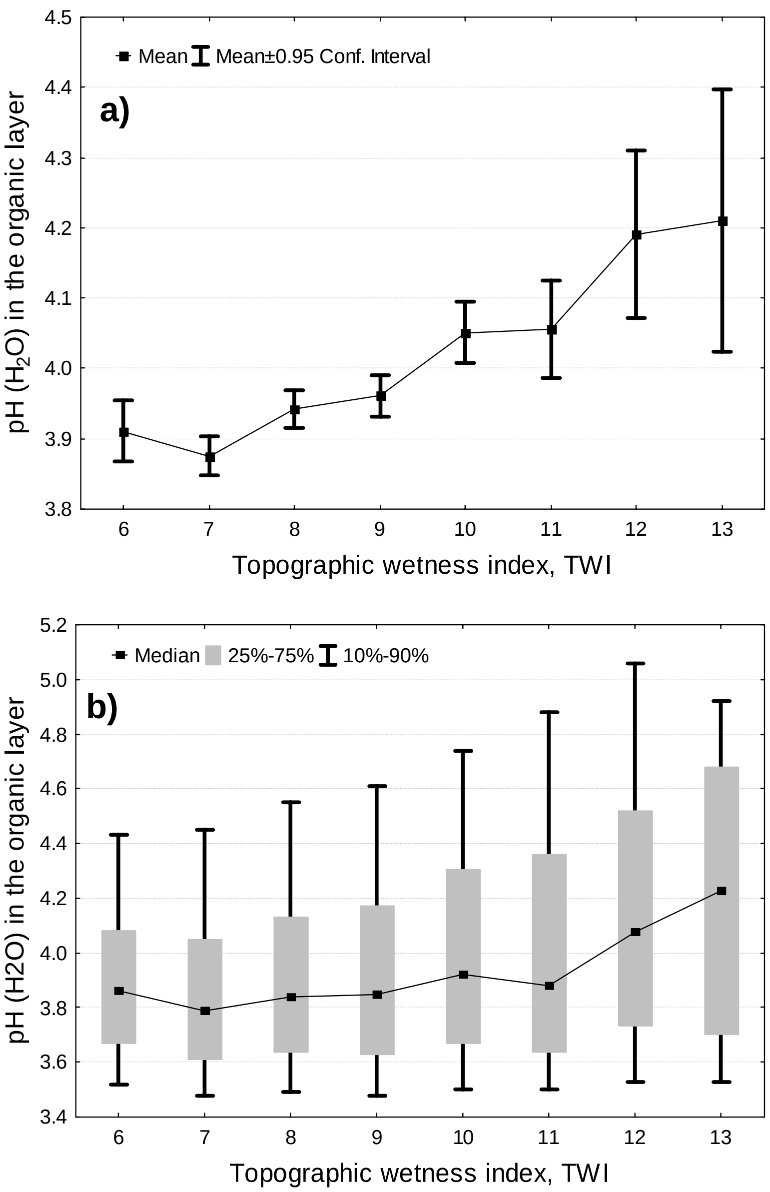

Figure 6. Soil $pH_{(H2O)}$ in the organic layer for different TWI-classes, a) mean values and confidence intervalls, b) medians and percentiles.

The pH in the O horizon increased with TWI (Tab. 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 boxplot (Fig. 6b). The variation in pH increased with TWI (Fig. 6b).
Aspect also had an influence on the pH in the organic layer with slightly, but significantly, higher values for south-facing than north-facing sites (Fig. 7).

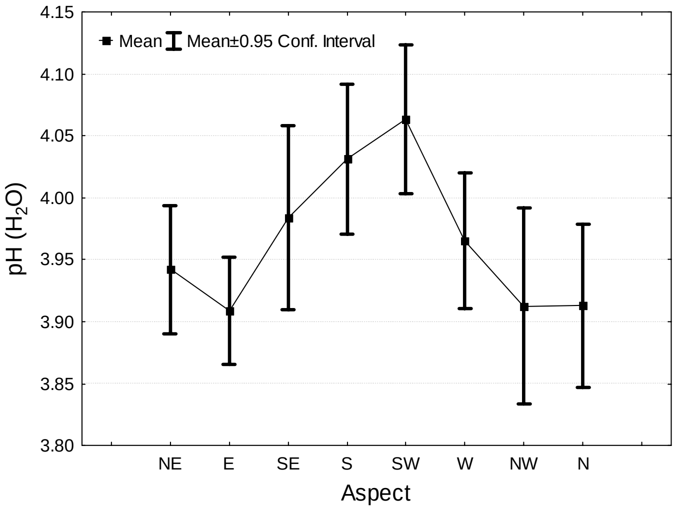

Figure 7. Variation of pH in the organic layer against aspect. Only locations where the slope to the steepest direction, tanβ, was larger than 0.05 were included.

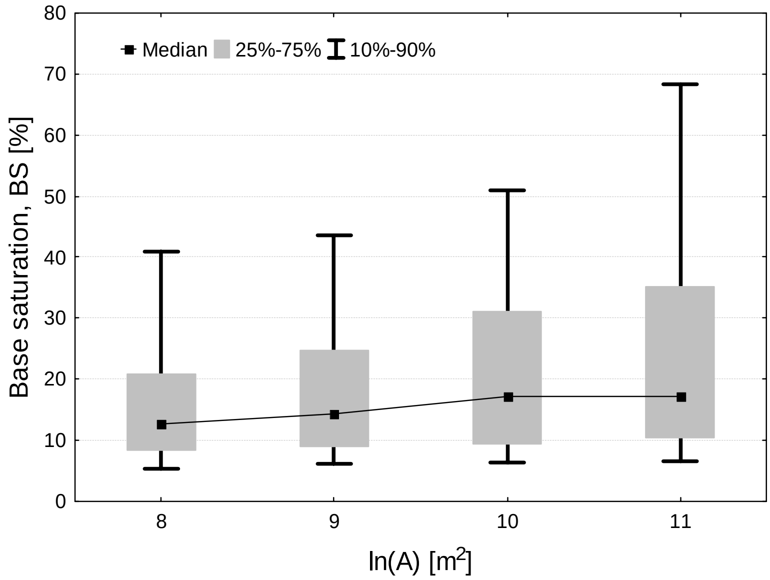

Figure 8. Base saturation [%] in the B-horizon for different ln(A)-classes (medians and percentiles), the upslope area A is given in [m^2].

For pH in the B horizon the relationships were similar as for the O horizon, but much weaker. As could be expected from the pH variations base saturation increased slightly with TWI (Fig. 8). Looking on the distribution of base-saturation values for different ln*a* classes there was a clear increase of the upper percentiles, i.e. sites with high base saturation were more frequent at sites where ln*a* was large. For total acidity there were only weak correlations.
For both O and B horizons, Ca and Mg were similarly correlated to the topographical indices, with positive relations to upslope area and TWI, and only weak or non-existing relation to slope (Tab. 2). For K and Na weak correlations were found with upslope area and stronger correlations with slope (Tab. 2). In contrast to the other base cations K had a negative correlation to TWI. The ratio between the 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.

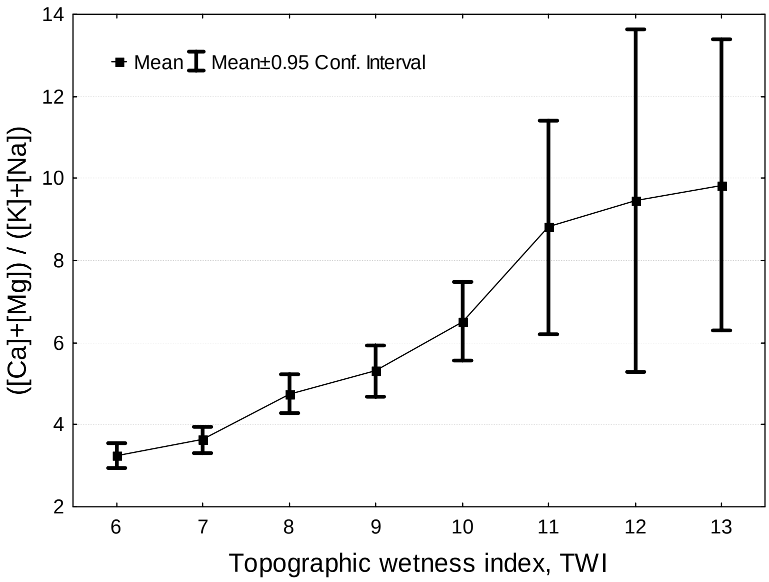

Figure 9. Ratio between the concentrations of the two-charged cations (Ca and Mg) and the one-charged cations (K and Na) in the O-horizon for TWI-classes (means and their confidence intervals).

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 the formation of the soil (Fig. 2), in this case most probably through hydrological processes. The elevation as such had no influence on soil type formation. Our results confirm and quantify the well known observation that ferric Podzols are formed on dry locations and Histosols are dependent on high water availability (Brady and Weil, 2001). We also observed the gradient between these two extremes.

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

For the O-horizon correlations between topography and soil chemistry generally were stronger 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 influenced by hydrological conditions directly, but also indirectly through different types of vegetation.

Similar to our results 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 TWI to correlate positively with nitrate (r=0.56) in the same area. The increase of C and at higher water availability is probably due to higher primary production. As oppose to our study Johnson et al found no significant correlation between TWI and C-N ratio in the organic layer. Sariyildiz et al. (2005) found the leaf decomposition to increase down slope on south facing slopes. For north facing slopes the top and the bottom had higher decomposition rate than intermediately situated sites. This observation was made for Turkish mountain regions and with fir, pine beech and oak.

Several studies have found increase of pH downslope, but 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 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 expected to be dissolved by percolating soil water and taken up by plants roots in the soil on its way down the hill slope. When plant residues decompose the chemical elements are partly mineralized and thus raising the pH.

Soil pH is also influenced by aspect, with higher pH in the more sun exposed directions, an effect that is also observed by Johnson et al. (2000) (r=0.18). Higher sun exposure can mean higher mineralization rate and thus higher concentration of base cations. A higher mean temperature and larger diurnal temperature variations might also increase the weathering rate.

Johnson et al. (2000) observed a decrease of individual exchangeable base cation concentrations in the order Ca>K>Mg>Na in both the O- and the B- horizon. We saw a similar decrease and observed also a correlation between TWI and the ratio between divalent and monovalent base cations. This correlation is caused by a stronger adsorption of divalent base cations to soil particles at increasing soil moisture content (Eriksson et al., 2005).

Despite several significant trends that could be seen in data there also was an obvious scatter. This could be expected because of the large data set with sample sites in different climatic and geologic regions. Also forest vegetation and harvesting history differed largely among the sites. One additional reason for noise might be errors in the GPS coordinates of the sample sites, causing the use of the value for a wrong grid cell. The correlations were generally slightly higher when using the mean of a 3 by 3 cell window instead of only the central grid cell and this indicates that the accuracy of the GPS coordinates in respect to the DEM was an issue.

In most diagram’s it was clear that at high TWI values the confidence intervals increased, indicating high variations at sites with high TWI-values. This issue was addressed by Zinko et al. (2005) who suspected higher resolution DEMs to reveal a high variation of TWI, both higher and lower values, in the grid cells that are currently considered as high TWI cells. This was studied by Sørensen et al. (manuscript) who did find the variation of TWI to decrease with pixel size.

It is important to consider the intercorrelation of the topographic indices. Obviously TWI is correlated to both its components upslope area and slope. Furthermore, in areas with higher elevation slopes tend to be steeper (r_s=0.19) and areas with a large upslope area tend to have smaller slopes (r_s=-0.14).

5 Concluding remarks

Despite the expected scatter due to the heterogeneity in the data set, which included data from quite different climatic region with different geology and forest management history, it was possible to find correlations between topographic indices and soil characteristics. The correlations between TWI and pH found at smaller scales could be confirmed. The value of these results is their larger generality than that of studies using smaller study sites. The use of topography as a source of information in environmental management may increase in the future, especially as the availability of elevation data at high resolution will increase.

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Effects of DEM resolution on the calculation of topographical indices

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Abstract

Topographical indices have been found useful for modelling various landscape properties. One of these indices is the topographic wetness index (TWI) which is defined as ln(a/tanβ), where a is the specific upslope area and β is the surface slope. Values of TWI have been found to be scale-dependent in previous studies. In this study a high-resolution digital elevation model (DEM) with a 5 m grid size derived from high-resolution LIDAR (LIght Detection And Ranging) data was used. From this DEM other DEMs were generated by thinning to resolutions of 10, 25 and 50 m grid sizes in order to study the effect of lower grid size and information content. These three DEMs with lower resolution were all interpolated to the orginal 5 m grid size to investigate the isolated effect of different information content using DEMs with the same grid size. The values of TWI and its components computed based on the seven different DEMs were compared in different ways.

Similarly to previous studies the computed specific upstream area decreased on average for higher resolution DEMs and computed slope values followed a narrower distribution. The variation of TWI between neighbouring cells within 50 by 50 m^2 areas decreased largely with increasing grid size. A cell by cell comparison among the TWI values computed based on the four 5m DEMs with different information content showed a clear decrease of correlation with the TWI based on the original DEM with decreasing information content.

The results show that there are considerable differences between topographic indices computed based on DEMs of different grid resolution. Just interpolating the DEMs to a higher resolution (i.e. a smaller grid size) gave more similar TWI distributions, but the pixel by pixel comparison indicated that the different information contents caused clearly different patterns of computed TWI maps.

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1 Introduction

Topography is a significant control on the spatial distribution of several environmental variables e.g Rodhe and Seibert (1999) tested the value of topography to predict the location of wetlands. Western et al. (1999) used topography to predict the pattern of soil moisture. Topography has also been used to predict soil chemistry (Chen *et al.*, 1997; Johnson, Méndez & Lawrence, 2000; McKenzie & Ryan, 1999; Welsch *et al.*, 2001). Zinko et al. (2005) estimated spatial variations in biodiversity based on topography. Flow of water, which at the landscape scale generally follows the topography, is often the most important single factor for many of these variables. From the information contained in topographic maps it is therefore possible to estimate spatial variations of hydrological, pedological and biological properties in a landscape. The general approach is to use topographic indices calculated from digital elevation models (DEMs) as a measure of the topographic control on the flow of water.

Different topographic indices allow the quantification of topographic features. These indices have become widely used especially since digital elevation models (DEMs) have become readily available. The most commonly applied of these indices, the Topographic Wetness Index (TWI), was first introduced by Beven and Kirkby (1979) as part of the runoff model TOPMODEL. This index is defined as $\ln(a/\tan\beta)$, where a is the specific upslope area and $\tan\beta$ is the slope of the ground surface. This means that locations with a large upslope area receive a high index value and are expected to have relatively higher water availability; as opposed to locations with a small upslope area that receive a small index value and therefore relatively lower water availability. Likewise steep locations receive a small index value and are expected to be better drained than gently sloped locations, which receive a high index value. Consequently, TWI is a relative measure of the hydrological conditions of a given site in the landscape. Several assumptions are underlying the derivation of the TWI. The slope of the ground surface is assumed to represent the slope of the groundwater table. The soil hydraulic conductivity and the precipitation are both expected to be uniform over the studied landscape. Finally, the natural logarithm in the expression of TWI represents an assumed decrease of transmissivity with depth (Rodhe & Seibert, 1999). All these assumptions can be relaxed but this requires additional information such as the spatial variation of hydraulic conductivities, which usually is not available. Within Swedish boreal forested landscapes the assumptions can generally be assumed to be fulfilled (Rodhe & Seibert, 1999).

Several studies have validated the usefulness of the index, which is increasingly used to estimate landscape features such as hydrological variables (e.g. (Band *et al.*, 1993; Rodhe & Seibert, 1999; Western*, et al.*, 1999; Whelan & Gandolfi, 2002), variables indirectly influenced by hydrology, such as soil chemistry (Band*, et al.*, 1993; Johnson, Méndez & Lawrence, 2000; Welsch*, et al.*, 2001; Whelan & Gandolfi, 2002), and plant species richness (Holmgren, 1994; Moore, W & Williams, 1993; White & Running, 1994; Zinko*, et al.*, 2005). Several evaluations have been made on the effect of different ways of calculating the index values.

These studies have mainly focused on computed TWI patterns (Quinn *et al.*, 1991; Tarboton, 1997; Wolock & McCabe, 1995), and only few have compared different methods based on the correlation between TWI, computed in different ways, and different environmental variables (Sørensen, Zinko & Seibert, 2006).

Topographic indices are usually computed from gridded elevation data and the resolution of the elevation data influences the computed index values. Important questions are, therefore, how the index values are affected by resolution and how index values from DEMs of different resolution can be compared. Previous studies have investigated TWI and its components and found that different grid resolutions result in different values of TWI. When comparing 30 and 90 meter resolutions the mean of the upslope area was affected. This effect was caused partly by the difference in grid size and partly by difference in information content of the DEMs (Wolock & Price, 1994). Zhang and Montgomery (1994) considered that for many landscapes a 10 m grid size is sufficient for hydrologic modelling; and that increasing the resolution to 2 or 4 m would provide no important additional information. Saulnier et al. (1997) observed an increased mean of the TWI with increasing DEM grid size. Similar results were obtained by Wolock and McCabe (2000) who found that the differences in the average values of the topographic characteristics computed from 100- and 1000 m resolutions can be corrected with simple linear equations. Usery et al. (2004) found a gradual decrease in correlation between the original 30 m resolution and the resampled DEMs of 60- up to 1920 m resolution as resolution decreased. Hancock (2005) also found the TWI to be sensitive to changes in grid size even below 10 meter grid sizes.

Except for Zhang and Montgomery (1994), who used high resolution data, these previous studies have mainly looked at grid-resolutions in the range 20 to 1000 m. In recent years high resolution data has become more available, and in this study we focus on smaller grid sizes. In this study, the finest resolution used was with a DEM of grid size of 5 by 5 m^2 derived from LIDAR data (LIght Detection And Ranging). From this DEM we generated further DEMs of different resolution and subsequently analysed the effect on the computed values for TWI and its components (slope and upslope area).

2 Materials and Methods

2.1 Elevation data

LIDAR-measured elevation data was available for a boreal forest area in Central Sweden (E 15º 10´ N 61º 00´). LIDAR is an active remote sensing technique, analogous to radar, but using laser light. LIDAR instruments measure distance between the instrument itself and a target by laser pulses. The term "laser altimetry" is synonymous with LIDAR (Dubayah & Drake, 2000; Hodgson *et al.*, 2003).

The raw LIDAR data file contained an average of five data points per square meter. This data was filtered in order to remove points where not the elevation of the ground surface but the vegetation had been measured. Based on the ground surface data points a DEM with a grid resolution of 5 m was generated by using the median value of all points in each grid cell. DEMs of 10, 25 and 50 m grid resolutions were generated using pixel thinning (Software tool: IDRISI 32 software, version I32.21 (The Clark labs®, Clark University, Massachusetts, USA)) of the 5 meter DEM. In the following text these three thinned DEMs are called T_{10}, T_{25} and T_{50}. These thinned DEMs were then transformed back to a grid resolution of 5 m using bilinear interpolation to give three resampled DEMs termed R_{10}, R_{25} and R_{50} (Fig. 1).

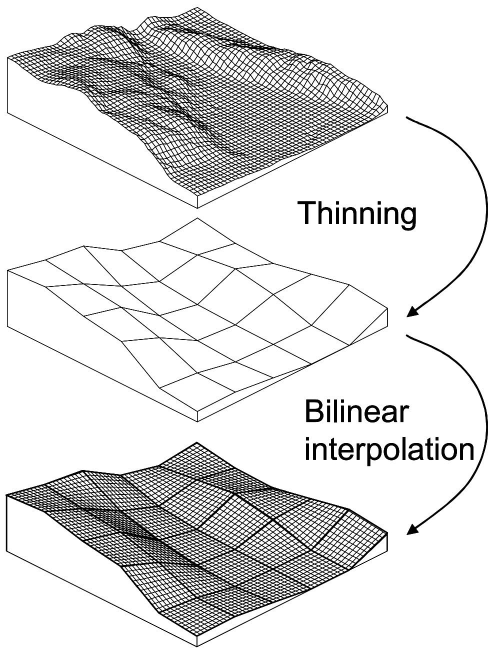


Fig. 1. Illustration of the extraction of lower resolution DEM from the original 5 m DEM by thinning, and the bilinear interpolation back to 5 m. Note the lower information content in the interpolated DEM.

While the resampled DEMs had the same grid resolution as the original DEM, they had lower information content and were characterized by smooth planes of the size of the grid resolution that had been generated by the thinning in the first step; in the following we call these planes 'squares' (Fig. 2). The idea of the resampled DEMs was to address the question of how much of the differences between values of the TWI and its components for different grid resolutions can be attributed to the resolution solely and how much can be attributed to the varying information content in the DEMs. This also addressed the question whether it is generally suitable to resample a DEM at a finer resolution to obtain a more detailed basis for topographic index calculations.

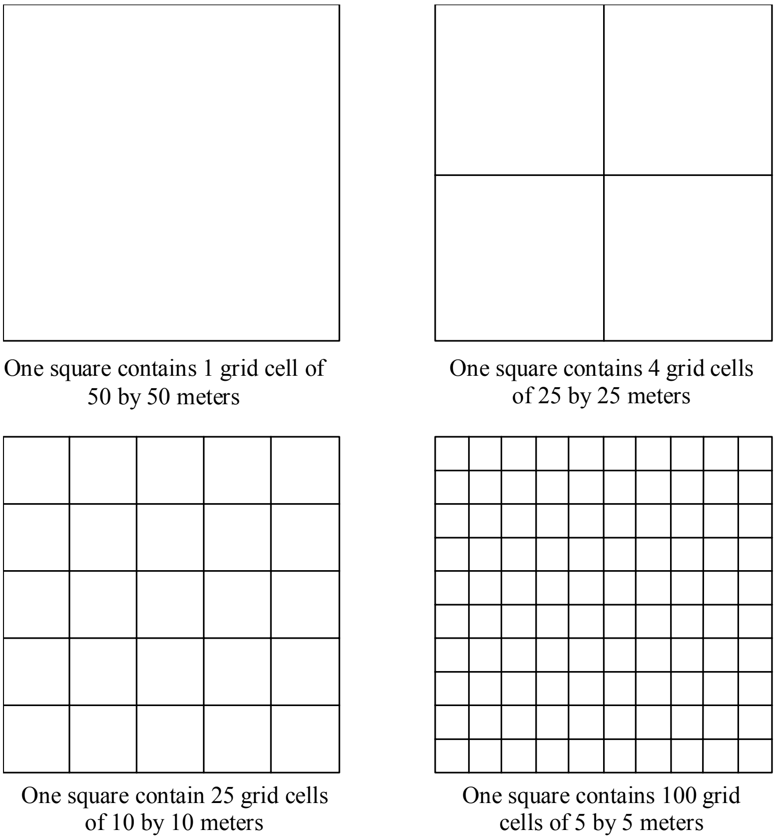


Fig. 2. The computed indices based on the DEMs T_{50}, T_{25}, T_{10} and T_5 were compared based on squares of equal size. Each square contained a different number of grid cells in the different DEMs.

2.2 Index calculation

In our calculations the area from upstream cells was routed to downstream cells as suggested by Quinn et al. (1995). In this process the accumulated area from a certain cell was allowed to take any of the 8 cardinal and diagonal directions to a neighbouring grid cell, if this cell had a lower elevation. The portion of area routed to a certain downslope cell, F_i, was computed using the slope towards this direction, $\tan \beta_i$ and the sum of all $\tan \beta_j$ values of the downslope directions. As suggested by Holmgren (1994) an exponent h was used for this computation (Eq. 1) and in this study h was set to 2, based on the findings of Sørensen et al. (2006). The accumulated upslope area (A) was then divided by an estimate of the contour length (L) to provide the specific upslope area ($a=A/L$). In the comparison we looked only at specific upslope area, because the upslope area without division by contour length is obviously scale dependent.

$$F_i = \frac{\tan \beta_i^h}{\sum_j \tan \beta_j^h} \qquad \text{(Equation 1)}$$

Traditionally the slope for the TWI is calculated as the steepest local slope from a certain grid cell or as a mean slope of all downslope directions (Quinn*, et al.*, 1991), in this study the latter method was used.

Hjerdt et al. (2004) introduced a different slope measure, called downslope index ($\tan\alpha_d$). This index is defined as the angle between the point of interest and a point in the steepest downslope direction that is *d* meters lower than the point of interest. It is proposed that this slope measure takes better consideration of the drainage conditions as it takes downslope topography into account. In this study *d* was set to 5 meters which had previously been found to be suitable in similar areas (Sørensen, Zinko & Seibert, 2006).

In our comparison, the different components of the TWI were considered. For each of the seven DEMs, five topographic features were calculated for each raster cell: specific upslope area (Quinn, Beven & Lamb, 1995), $\tan\beta$ (Quinn, Beven & Lamb, 1995), $\tan\alpha_5$ (Hjerdt*, et al.*, 2004), TWI_β (using the $\tan\beta$ slope), TWI_α (using the $\tan\alpha_5$ slope).

The downslope index $\tan\alpha_5$ integrates over several cells and, thus, values are generally less extreme than for the local slope between neighbouring cells. However, since $\tan\beta$, as used in this study, is a mean value of the slopes towards all downslope directions, for steep regions it does not have as high values as the $\tan\alpha$ slope, which considers only the steepest slope direction.

We selected a 6.25 km^2 window (2.5 by 2.5 km^2) for the further analysis. This was done to avoid any edge effects of the DEM and to limit the analysis to a comparatively homogenous region. A larger window would have included areas with glaciofluvial deposits and, therefore, different geomorphologic features. In this study no creek initiation was considered, i.e. all accumulated area was routed downwards. The reason was that the stream initiation threshold area itself is scale dependent. In the area used for this study there were also only a few small creeks in the selected window and we argue that this did not influence the results since only a few cells would have been classified as stream cells. Instead of filling up sinks in the DEM, an approach was used where, in the case of a sink, the accumulated area was routed to the closest downslope cell 2, 3 or more cells away (Rodhe & Seibert, 1999).

2.3 Data analysis

We compared the computed maps of TWI and its components based on the seven different DEMs in three different ways. First we compared the distribution functions and different statistical measures such as percentiles, mean and median for the different maps. This comparison, however, does not take the geographic position or pattern of the different maps into account.

For the maps derived from the resampled DEMs we compared the effects of the different resolutions on a pixel-by-pixel basis. Correlation coefficients (r) and the root mean square differences (RMSD) were calculated as measures of the (dis)agreement between the different maps.

Finally we investigated the variation of topographic index values based on T_5, T_{10} and T_{25} within each 50 by 50 m^2 square of the 50 m grid resolution DEM (T_{50}). The mean, the coefficient of variation as well as minimum and maximum were computed for each 50 by 50 m^2 square, i.e. based on 100, 25 or 4 values for T_5, T_{10} and T_{25} respectively (Fig. 2). Subsequently these measures where sorted according to the value for the index in question for T_{50} and running means (window of 200 data points) were computed. This analysis allowed addressing the question whether sub-grid variability is homogenous.

3 Results

The maps of the various topographic indices computed based on the different DEMs showed clear variation with resolution. Using DEMs of different grid size resulted in different patterns of the computed maps, where fine-scale features disappeared. For the slope $\tan\beta$, for instance, steep slopes along rather flat valley bottoms can not be seen in the 50m DEM T_{50} but can partly be recognized for T_{25} and show up clearly for T_{10} and T_5 (Fig. 3). However, also comparing the indices based on R_5 and T_5, i.e. the same grid resolution, indicated a substantial effect of the information content on the resulting maps (Fig. 4). The underlying larger squares could be seen in the maps based on R5. The slope obviously was basically constant for each square, whereas the maps of the upslope area indicated some artefacts at the borders between the squares.

The visual impression was confirmed by comparing the distribution functions (Fig. 5-7) and the various statistical measures (Fig. 8). The distribution functions for the specific upslope area (Fig. 5) clearly showed the difference in distribution among the seven DEMs investigated with narrowing and increasingly skewed distribution with decreasing information content and increasing grid size. The statistics summarized in figure 8 illustrated that the T_{10}, T_{25} and T_{50} gave gradually lower similarity to the T_5. Part of this difference was explained by the grid size, since the R_{10}, R_{25} and R_{50} also gradually decreased in similarity to the T_5. The rest of the difference was caused by the lower information content in the DEMs. The values of the specific upslope area were generally higher when the grid resolution increased, especially for the smaller areas and most clearly for the lower resolution DEMs. This increase was partly reduced when using the resampled DEMs where the minimum area was the same, because the grid sizes, and thus smallest possible accumulated areas, were identical. Also the deviation between the distribution functions was smaller but still significant. The skew increased with resolution and information content, except for R_{50} for which the skew decreased slightly.

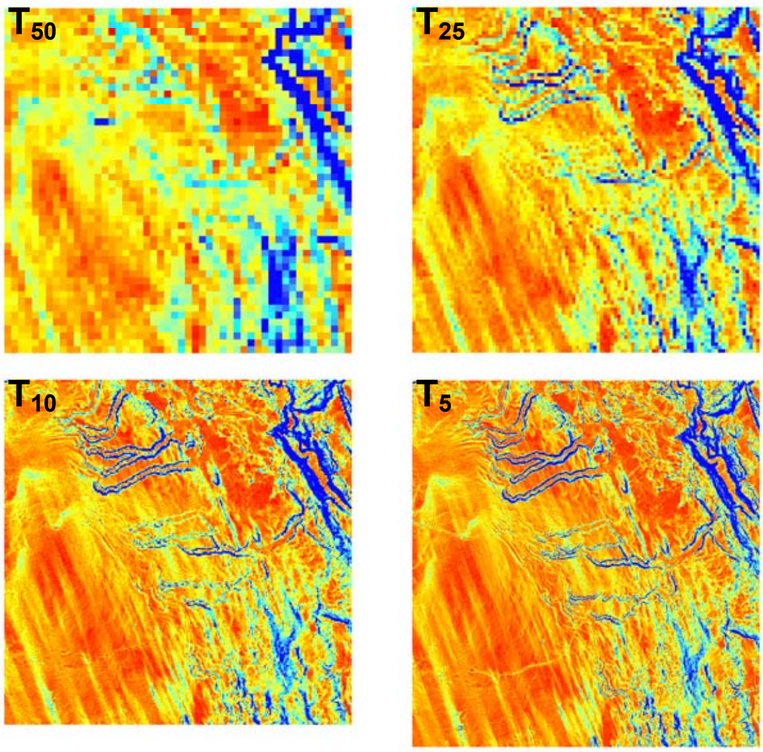


Fig. 3. Maps of tanβ for T_5, T_{10}, T_{25} and T_{50}.

With lower DEM resolution and information content, the distribution of slope was, as expected, more concentrated to intermediate slope values instead of extreme slope values (Fig. 3 & 6). The tan*β* distributions were almost identical for the resampled and the corresponding lower grid resolution DEMs (e.g., T_{50} and R_{50}, Fig. 6C). For the coarser resolutions tan*β* was generally more even, i.e. the smallest slopes were steeper and the steepest slopes less steep. The tanα deviated from the T_5 less than the tanβ (Fig. 6). For the tanα distribution the resampled DEMs were closer to the T_5 than the lower resolution DEMs. For both slope measures the skewness decreased with resolution (Fig. 8).

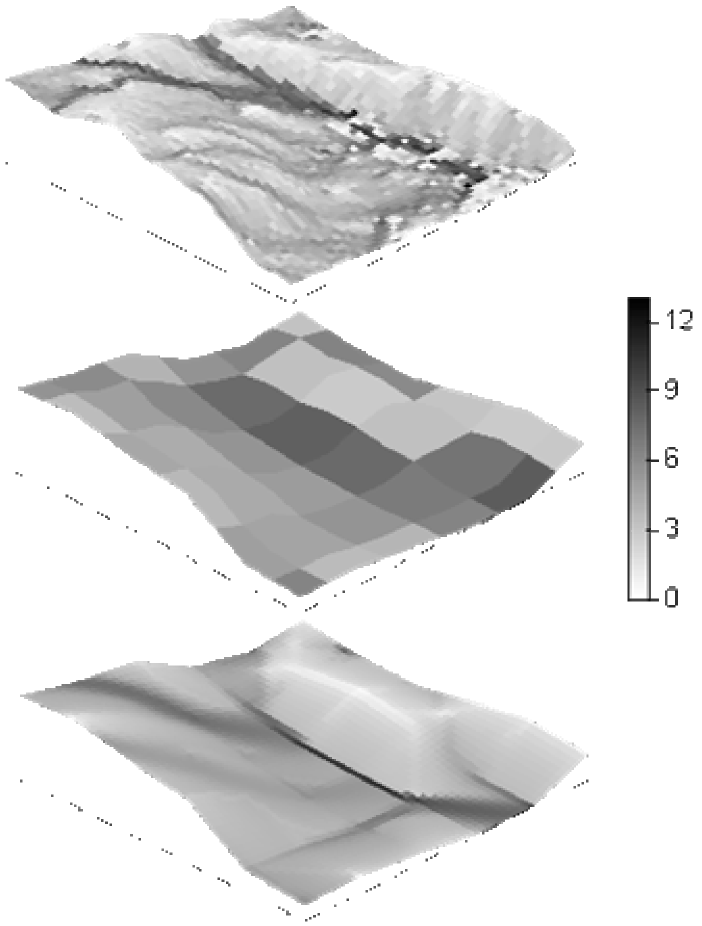
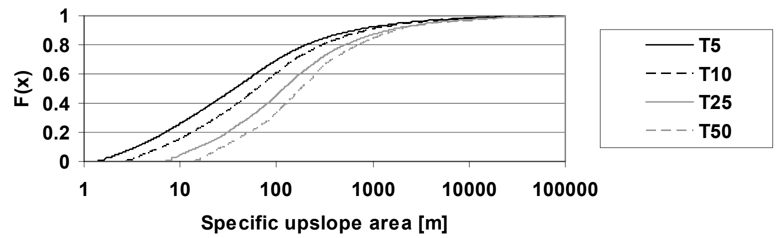


Fig. 4. Example from the maps of the specific upslope area, ln(a), for T_5, R_5 and T_{50}. (500 by 500 m^2 window)

Since the TWI_β and the TWI_α are ratios between the specific upslope area and the slope (tanβ or tanα), even the TWI_α appeared more robust than the TWI_β in general. But the differences in the specific upslope area were much higher than the difference in slope and had therefore much higher influence on the resulting TWIs. The distributions of the resampled DEMs differed less from the T_5 than the DEMs of different resolution, i.e. T_{10}, T_{25} and T_{50} (Fig. 7).

A



B

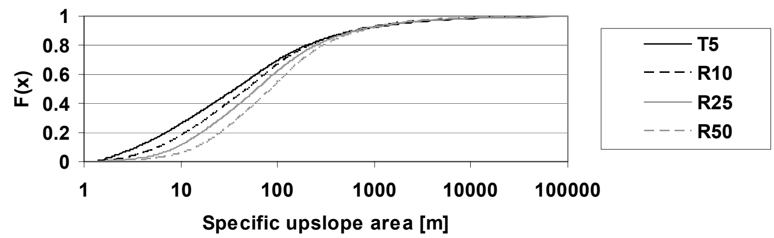


Fig. 5. Distribution functions for the specific upslope area a) for the lower resolution DEMs and b) for the resampled DEMs.

3.1 Cell by cell comparison of resampled DEMs

The cell by cell correlation among the resampled DEMs decreased with information content (Fig. 9). The specific upslope areas changed largely with information content (see even Fig. 3). Already at the 10 m resolution the cell by cell correlation between the values for upslope area was only r=0.70 and the RMSD was 1.57. At T_{25} the correlation was r=0.41 and the RMSD was 2.16. The slope measures, tanβ in particular, also lost correlation strength with decrease in DEM information. Again, this was reflected in the resulting TWI_α and TWI_β measures.

3.2 Square by square comparison of lower resolution DEMs

The square by square comparisons showed that the variability of the index values based on the finer resolution DEMs in the 50 by 50 meter squares was quite substantial. The variability of the specific upstream area, evaluated by the coefficient of variation (C_v), first decreased and then increased with the corresponding values based on T_{50} (Fig. 10a). The high variation in the squares was also displayed by smaller minimum values and higher maximum values of the finer resolution DEMs than those of the T_{50} (Fig. 10b).

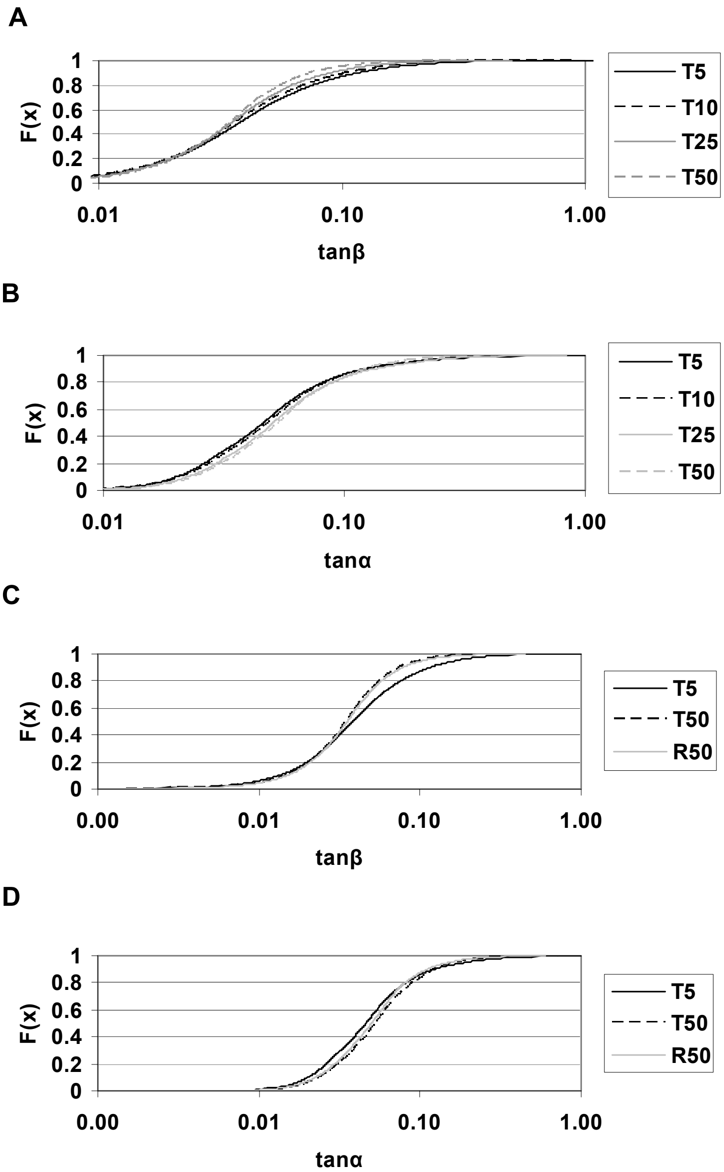


Fig. 6. Distribution functions for a) the tanβ slope of the T_5, T_{10}, T_{25}, T_{50}, b) the the tanα slope of the T_5, T_{10}, T_{25}, T_{50}, c) the tanβ slope of the T_5, T_{50}, R_{50}, d) the tanα slope of the T_5, T_{50}, R_{50}.

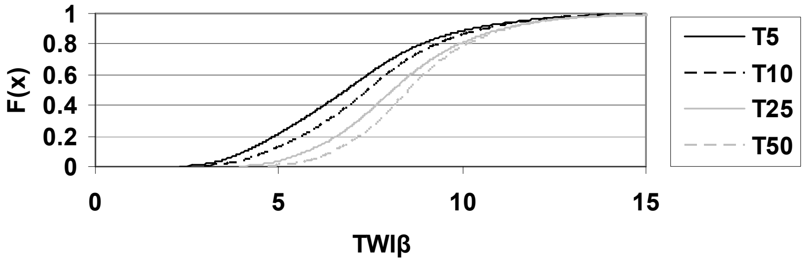


Fig. 7. Distribution functions for TWIβ of the T_5, T_{10}, T_{25}, T_{50}.

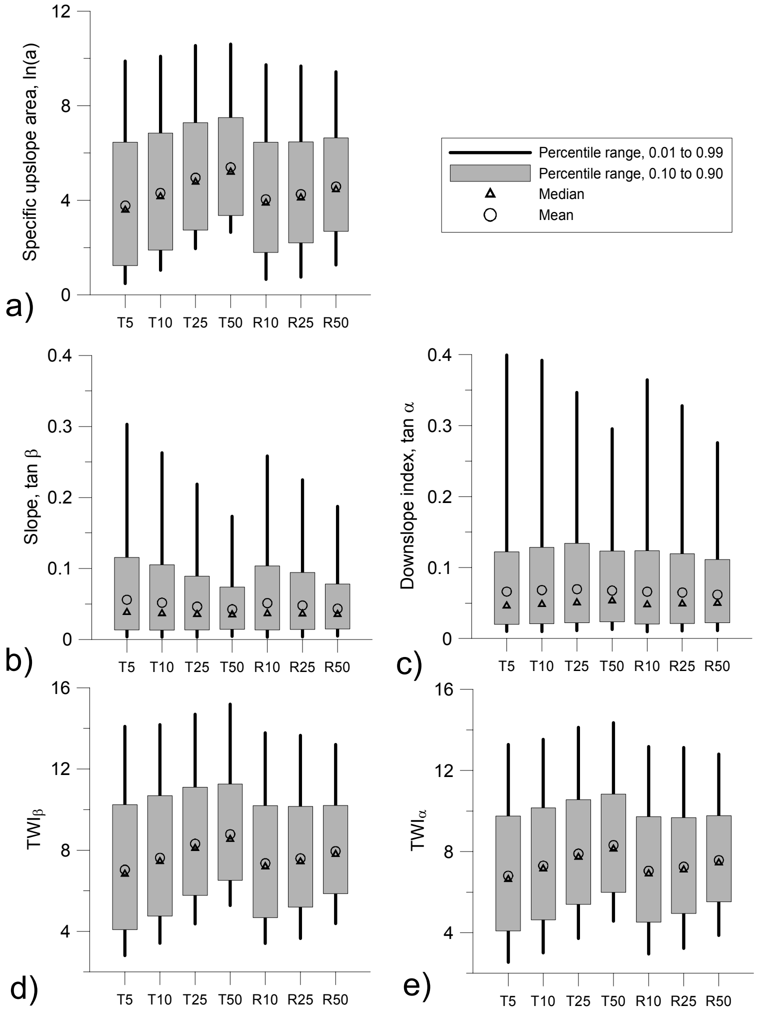


Fig. 8. Statistical summary for the seven DEMs. a) Specific upslope area, b) tanα, c) tanβ, d) $TWI_β$.

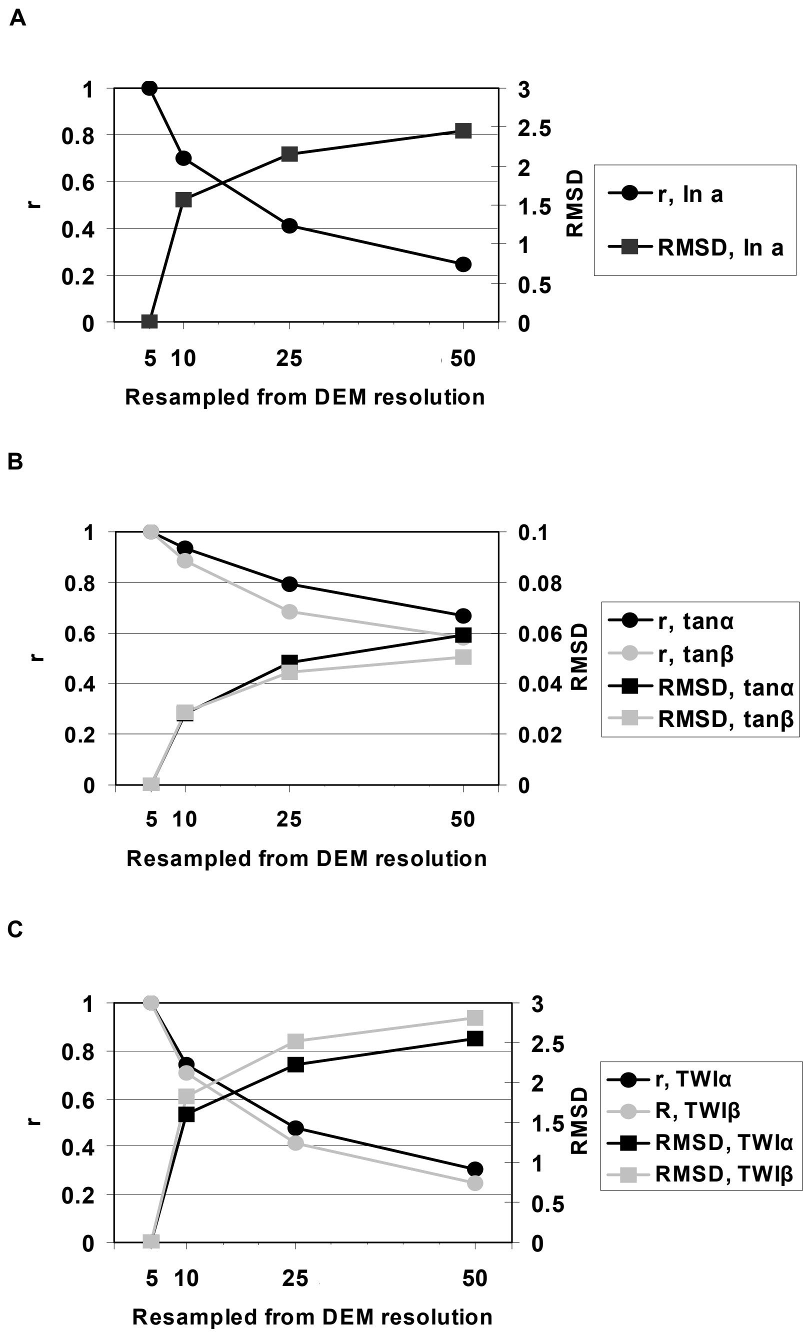
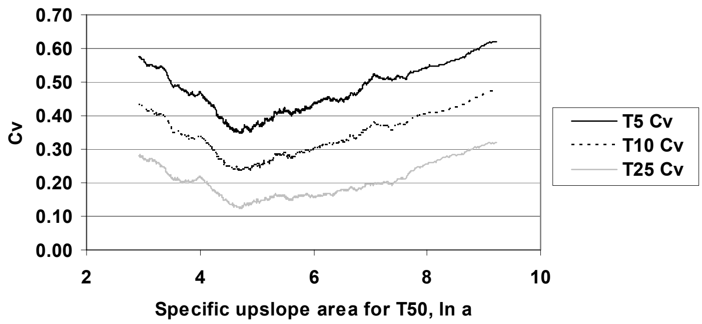


Fig. 9. Cell by cell correlation for a) specific upslope area, b) tanα slope and tanβ slope, c) TWI_{α} and TWI_{β}.

A



B

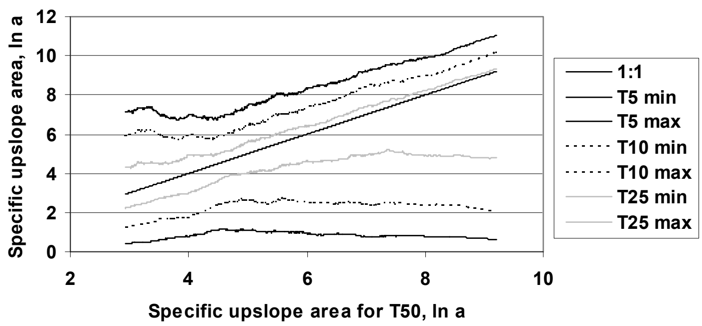


Fig. 10. Running mean values (window of 200 values) a) for the coefficient of variation b) minimum and maximum values, for the specific upslope area for T5, T10 and T25.

A similar pattern was observed for the variation of slope. For the higher resolution DEMs the minimum values increased less and the maximum values increased more than for the T50. This effect was higher for tanβ than for tanα5.

Again, the TWI_α and TWI_β reflected the trends of the specific upslope area and the slope measures.

4 Discussion

The distribution functions of the indices computed based on the resampled DEMs (R_{50}, R_{25} and R_{10}) were more closely correlated to those based on the original T_5 than the distribution functions of the indices based on the lower grid resolution DEMs (T_{10}, T_{25} and T_{50}). From this it can be concluded that generating DEMs with a higher grid resolution from DEMs with lower information content is one way to obtain higher resolution topographic index maps. The pixel by pixel comparison, however, indicated that the differences between the original and the resampled DEMs have significant effects on the computed index maps.

The upslope area was largely affected by the resolution and information content of the DEM used. One obvious reason for this is that the smallest accumulated area equals one grid cell. The minimal specific upslope area corresponds, thus, to the grid cell length. When using a more detailed DEM the flow pathways become more irregular causing the possibility for some channelling of accumulated area. While for T_{50} a grid cell in a downslope valley position will have a large upslope area, cells in similar positions in a higher resolution DEM might have a large upslope area if they happen to be located along the main flow pathway. However, cells from a higher resolution DEM might also have smaller upslope areas if they have a slightly higher elevation than the surrounding cells and, therefore, are located next to the main flow pathways. This observation agrees with previous studies for coarser resolutions (Band & Moore, 1995; Usery*, et al.*, 2004; Wilson, Repetto & Snyder, 2000; Wolock & Price, 1994; Zhang & Montgomery, 1994).

The difference in slope was generally smaller than the difference in specific upslope area. The slope distribution became narrower for coarser DEMs. This is consistent with the findings of Thompson et al. (2001) who compared DEMs of 10 and 30 meters. The tanα slope was less affected by resolution than the tanβ slope. This confirms the findings of Hjerdt et al. (2004). Since there were smaller differences for the slopes compared to the upslope area, the latter dominated the differences in the TWIs. Likewise we observed that with the same amount of information but at different resolution (the T-series) there was a shift in the distribution of the indices and their components, in agreement with the findings of Wolock and Price (1994).

Zhang and Montgomery (1994) argue that a 10 meter DEM resolution is sufficient for estimating geomorphic and hydrologic processes. Also, Usery et al. (2004) found that elevation values compare well (r=0.9) between 3 and 30 meters DEM and that this correlation decrease gradually as resolution become coarser. However, as shown in figure 5, when going from 5 to 10 meter resolution a substantial amount of details in the computed topographic indices were lost. Topographical features with smaller length scales than the resolution of the DEM will not be captured in the computed topographic indices. It is not necessarily the case that indices computed from high resolution DEMs are a better representation of the real spatial patterns. While the groundwater flow, for instance, can be expected to follow the general topography, it cannot be expected to follow all details in the ground surface. The question of an optimal resolution remains to be answered and probably depends on the variable of interest. Sørensen et al. (2006) found that different computation methods were more suitable for the hydrological properties and the chemical properties of a site. Similarly, different resolutions might be more suitable for different variables.

Within the 50 by 50 m squares with a higher value of *a* and TWI we found a larger variability among the respective index values computed from high-resolution DEMs. This supports Zinko et al. (2005) who hypothesize that their observed increase of vascular plant species richness with TWI might be caused by a larger degree of variability of wetness conditions for grid cells with high TWI. A high resolution DEM could thus be useful for locating areas of high species richness which is also highly correlated with several soil properties such as moisture and pH (Zinko*, et al.*, 2005).

Depending on the scale of the landscape the loss of information may be of importance to hydrological prediction based on topographic indices. Kuo et al. (1999) compared hydrographs for different grid sizes and found that increasing grid cell size misrepresented the curvature of the landscape. On the other hand, Wolock and Price (1994) argue that, for TOPMODEL, coarse resolution DEMs are not necessarily inappropriate because an implicit assumption is that the water table configuration mimics surface topography and may even be smoother and better represented by a coarser resolution DEM. Walker and Willgoose (1999) found grid spacing finer than 25 meters had no significant effect on the ability to extract the inferred stream network and catchment boundary.

5 Concluding remarks

The resolution and information content of a DEM has a great influence on the computed topographic indices. The estimation of upslope area seemed to be more affected than the slope. Just interpolating the DEMs to a higher resolution (i.e. a smaller grid size) might give a more similar TWI distribution, but quite different patterns can be obtained compared to TWI computed from the original 5 m DEM.

The results obtained in this study indicate that information content can indeed have a large influence on computed maps of topographic indices, even for small changes in information content. However, this does not automatically mean that the highest resolution DEM always is the most useful. Given the length scale of the topographic features controlling certain processes actually a lower resolution DEM might be more useful landscape analyses and modelling in some cases. Groundwater, for instance, can be expected to rather follow the general topographic pattern and might depend less on small-scale variations.

While it formerly was regard as a matter of course to use the best available resolution DEM this might not always be the case with extremely high resolution data becoming more readily available. The optimal resolution should represent the important topographic features for a certain variable of interest, using a finer resolution might actually weaken rather than improve correlations with topographic indices. More research and especially field mapping is needed to address the issue of an optimal resolution. One interesting approach could also be to combine the topographic indices computed based on DEMs of different resolutions.

6 Acknowledgements

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