Topography, soil carbon-nitrogen ratio and vegetation in boreal coniferous forests at the landscape level

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Interaktioner mellan topografi, markens kol-kvävekvot och vegetationen i boreala barrskogar på landskapsnivån

Guillermo Chaminade

PREFACE

This MSc thesis is made as a 20 credit points individual course and fulfils the requirements for a Master of Science thesis in Soil Sciences at the department of Forest Soils at the Swedish University of Agricultural Sciences. It was developed during the author's stay in Uppsala under the Erasmus-Socrates Agreement of the European Union for student mobility. The work was started in September, 2004 with the field work in Ovanmyra (Dalarna) and was finished in Madrid (Spain) in the fall 2005.

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CONTENTS

SUMMARY. This thesis was developed with the main objective of assessing the mutual influence of three of the main factors taking part in the ecological processes of the boreal forest: topography and the hydrological fluxes related to it, C/N ratio in the forest soil, and vegetation composition. The interaction between these factors has not been the main focus in any study of this kind before, although in numerous reports these variables and their role in the forests have been assessed.

The project was based on the fieldwork carried out in Ovanmyra, a private forested area located a few kilometres north of Rättvik (Dalarna). Soil samples were taken both from the humus layer and mineral soil, in order to analyze their concentrations of C and N. Topography was evaluated through the Topographic Wetness Index (Beven & Kirkby, 1979), which was calculated from a 5 m digital elevation model derived from airborne laser scanning (LIDAR), and vegetation data was obtained from a digital forest database. Finally, other soil properties, such as pH or stoniness were measured in the field to study their relation with the main variables.

Laboratory analyses provided information on concentrations and water content. These data were later studied using several statistical tools, such as descriptive statistics and a principal component analysis. The main results showed that positive correlations were found between soil moisture (through the TWI) and C/N ratio, as well as the vegetation (through forest volume) and C/N in the organic layer. Also in the organic horizon, C concentration is positively correlated to some soil attributes, such as depth of the E horizon and humus thickness.

As for the negative correlations, the stand volume proved to be higher when moisture in the soil was lower. Stoniness and C/N ratio were negatively correlated, as were pH and the C/N ratio. Some of the relations explained above were weak enough to require further studies in order to achieve definite conclusions, although most of them were considered strong enough to be representative of the mutual relations measured.
Keywords: C/N ratio, TWI, soil properties, vegetation, landscape

SAMMANFATTNING. Denna studie behandlar det inbördes förhållandet mellan tre huvudfaktorer som påverkar ekologiska processer i boreala skogar: topografin genom dess betydelse för hydrologiska flöden, C/N kvoten i skogsmarken och vegetationens sammansättning. Interaktionen mellan dessa faktorer har sällan samtidigt varit i fokus tidigare, även om ett flertal studier har utvärderat faktorerna var och en för sig.

Till grund för studien ligger ett fältarbete som utfördes i Ovanmyra, ett privatägt skogsområde några kilometer norr om Rättvik (Dalarna). Prover samlades in från både humuslagret och mineraljorden och analyserades för totalhalterna av C och N. Topografins inflytande utvärderades genom ett topografiskt fuktighetsindex (TWI, Beven & Kirkby, 1979) som beräknades utifrån en 5 meters höjdmodell (DEM), vilken tagits fram genom flygburen laserscanning (LIDAR). Information om vegetationens sammansättning hämtades från en digital databas över skogen. Andra markegenskaper bestämdes även, såsom pH och stenighet, och sambandet mellan dessa och huvudfaktorerna utvärderades.

Analyser i laboratoriet gav koncentrationer av element och vattenhalten hos proverna. Dataanalysen omfattade olika former av beskrivande statistik samt en principalkomponentanalys (PCA). De huvudsakliga resultaten visade på en positiv korrelation mellan markfuktigheten (beskriven av TWI) och C/N kvoten i humusskiktet. Koncentrationen av C i humusskiktet var även positivt korrelerad med andra markegenskaper som tjockleken hos E-horisonten och humusskiktet.

Negativa korrelationer återfanns bl a mellan virkesvolymen och markfuktigheten, mellan stenigheten och C/N kvoten, samt mellan pH och C/N kvoten. Flera av sambanden mellan de studerade variablerna var svaga och kräver mer studier för att några definitiva slutsatser skall kunna dras, även fast många samband var starka nog för att utvärdera relationen mellan variablerna.

Sökord: C/N kvot, TWI, markegenskaper, vegetation, landskap

INTRODUCTION

Carbon has long been studied as a main factor influencing the Planet's ecology. We can find a great bibliography on the issue, concerning the subject from the global level perspective, in which the most representative example would be the CO_2 emissions into the atmosphere, and their influence in the climate change, to the local level, analysing its importance to small areas natural phenomena.

In particular, the soil carbon is very interesting to study, as the soil is estimated to store twice as much carbon as the atmosphere, and three times that contained in the aboveground biomass (IPCC, 2001). Carbon in the soil is an important factor when studying global C budgets (Lehtonen *et al.*, 2004; Berg & McClaugherty, 2003; Wilding *et al.*, 2001; Liski *et al.*, 2000). Soil carbon can act as a source or as a sink for carbon dioxide in the atmosphere (Fröberg, 2004; Högberg *et al.*, 2002; Liski *et al.*, 2000; Fisher & Binkley, 2000), and can be considered as the biogeochemical linkage between the other major C reservoirs: biosphere, atmosphere and hydrosphere (Wilding *et al.*, 2001). The stock of soil organic carbon results from the balance between litter input and decomposition over time (Liski *et al.*, 2002); while stored in the soil as humus and related stable organic compounds, the C is not circulating through the atmosphere (Berg & McClaugherty, 2003). As a part of the dynamic carbon cycle of forests, soil C is linked to the development of vegetation and also affected by the past events (Liski *et al.*, 2002; Nabuurs *et al.*, 1997). Estimating its stock in reliable values is necessary for understanding the global carbon cycle, as well as for developing national inventories of greenhouse gases (Lehtonen, *et al.*, 2004); estimating its spatial variability is important when developing C budgets, explaining climate change and characterizing ecosystems (Davis *et al.*, 2004).

Nitrogen also plays an important role in the soil formation and development and there is an extensive literature on the subject, based on experiments both on the field and in the lab. It is considered a unique element among nutrients, in the sense that it has its origin in the atmosphere, is intimately tied to organic matter, but rarely accumulates to a significant degree on soil exchange complexes (Johnson & Ball, 1996). Nitrogen availability, along with low temperatures, are the two main factors controlling the productivity of boreal ecosystems (Côté *et al.*, 2000; Mäkipää *et al*, 1998).

Apart from the importance of C and N, considered separately, the relation between them is interesting in ecological terms. The C and N cycles in the soil are linked through processes of N assimilation, N mineralization, denitrification and organic matter decomposition (Yano *et al.*, 2000). The ratio C/N is widely used when researching on the ecology of the forest. This ratio indicates the availability of nitrogen in floor material, and also the forest floor's rate of decay (Fisher & Binkley, 2000), as well as the quality of the organic matter under the canopy (Côté *et al.*, 2000). It can be linked to the soil microbial biomass (Nordström Högberg, 2004), and Johnson & Ball (1996) considered the ratio as a key variable through which all ecosystem perturbations act.

The boreal forest has long been analysed through many of its forming elements, including the carbon cycle and the dynamics of the main nutrients for plants and soil organisms. Most of these elements are affected by major factors such as climate, topography and hydrology. The fauna and flora of the site also influence the amount and distribution of these elements in plants, soils, and the atmosphere. There are several studies linking all these factors between them (Ibbitt and Woods, 2004; Pellenq *et al*, 2003; Grayson *et al.*, 2002; Mackay and Band, 1997; Rodhe and Seibert, 1999), but not as many focusing on the relation between the major factors mentioned and the physical elements and nutrients present in the ecosystems (Nordström Högberg, 2004). This work is aimed to analyse the influence of three of the factors (topography, vegetation and hydrology) on the C/N ratio in the soil.

Factors affecting the carbon and nitrogen concentrations, and C/N ratio in soil

There are multiple factors that affect the amount of carbon in the soil and the C/N ratio. This work focus on the influence of topography as a main attribute for C/N ratio values, as well as the composition of the vegetation as a main source of litter eventually turning into soil nutrients, and also as modifier of soil moisture (Fisher & Binkley, 2000). Not only vegetation influences C/N ratio, but also the other way around: C/N ratio determines the stand composition (Fisher & Binkley, 2000). Low temperature, soil acidity and plant residue recalcitrance upon microbial activity are highlighted by Nordström & Högberg (2004) as main factors contributing to this raise. A study by Côté *et al.* (2000) concluded that both organic carbon and organic nitrogen were significantly affected by factors such as stand type, stand age, and the interactions between age, species composition, and soil properties. Khanna *et al.* (2001) pointed as main factors the composition of the vegetation (tree and ground species), site productivity, climate, site factors determining nutrient supply, nutrient uptake, litter decomposition and soil organic matter (SOM) protection mechanisms. At a global level, it can be said that C/N dynamics are strongly influenced by the latitude and elevation (Shaffer & Ma, 2001). Hydrology also has an important role in the distribution and amounts of these components in the soil. Mackay & Band (1997) presented a model in which they demonstrated that topographical position had an important effect on forest canopy characteristics (which at the same time influence the C/N dynamics).

The landscape level

The study is done at the landscape level. The interest of applying the landscape perspective was well pointed by Wilding *et al.* (2001), when explaining that while soils are a continuum across the landscape, their properties do not have single values and are spatially and systematically dependent, leading to vertical and lateral anisotropic conditions, and affecting directly the mean estimates of SOC.

This landscape approach is an alternative to the use of *transects* or *gradients*, used in several studies on the properties of the forests. Those carried out by Giesler *et al* (1998) and Nordin *et al* (2001) stand out in relation to the boreal forest in Sweden, working along a 90 m long transect known as the *Betsele gradient* (at a latitude of 64 ºN and near the Umeå river valley). Temperature conditions in our area of study are milder, but vegetation composition, especially regarding tree species, is very similar. Nordin *et al* (2001) chose this perspective as the objective was to study the chemical and biological properties in a high productivity gradient and, this way, compare to the results obtained by Giesler *et al* (1998), among others, which showed a positive correlation between both N concentration and pH, with the change in the composition of the vegetation, from a dwarf-shrub forest type with low plant productivity to a tall herb forest type with high plant productivity (Giesler *et al*, 1998), on a 2% constant slope. This perspective only considers the flow down the slope, and not lateral flows which may be of importance to this kind of studies.

Differently from this approach, the landscape perspective enables us to study dynamic processes that are characterized by spatial interaction, such as the hydrological processes, which may be described by modelling of flow paths across the landscape. Our area of study, although relatively small, presented quite an interesting number of heterogeneous hydrological and topographical features when observing it through the DEM, in the stage previous to the field sampling. This was very useful when setting the sampling grid, and especially when choosing where to sample the carbon and nitrogen stocks in the soil. This study attempts to relate the C/N ratio to different conditions of topography, hydrology and vegetation, which motivates an investigation at the landscape level. Thus, the possibility to study the whole area as a landscape is much more interesting. In addition, all the information and results generated in this project referred to a 3D landscape perspective, which will allow a practical use in forest planning.

This landscape perspective has been used by most of the authors working on similar studies, especially when taking into account the hydrological and topographical aspects. Some of them estimated the link between these two factors in large spatial scales, comparing hydrological and forest dynamics models (Mackay & Band, 1997) or hydrological and forest carbon models (Band *et al.*, 1993). In this study the authors, working over "large spatial scales", explain the landscape as a key concept through which we can understand the ecological processes in the forest, assuring that "the spatial patterns of forest ecological and hydrological storages are dependent on the topography through the variability of the radiation environment, precipitation and temperature conditions, and soil water drainage".

Other works focus more on the hydrological response in catchments with different topography (Seibert *et al.*, 1997; Grayson *et al.*, 2002). There are studies in which the landscape position is tested to estimate the soil drainage (Shaffer & Ma, 2001). Ibbitt & Woods (2004) developed their research with a wider objective of linking the spatial natural variability with the topographic index of a certain area.

Not only we use this perspective when studying hydrological variables; Phillips (2001) carried out a research on the spatial structure of soil variability, aiming to assess divergent pedogenesis. For this purpose, he applied the term *landscape scale* to refer to "all distances and areas large enough to encompass multiple catenas and landforms". In the end, soil evolution is related to landscape variability (Phillips, 2001)

Objectives

The objectives of this study were to:

- Assess the influence of topography and hydrology on the C/N ratio in the soil.
- Examine how the vegetation affects the C/N ratio, as related to topography.
- Compare the C/N ratio with other soil characteristics, such as stoniness, texture, moisture, soil type and depth of the E horizon.

MATERIALS AND METHODS

The area of study

The whole study was based on samples obtained in Ovanmyra, some kilometres north of Rättvik (Dalarna, Sweden; Figs. 1a-1b). The area of study is situated at a latitude of approximately 61 ºN, with a mean altitude value of 306 m (maximum: 347 m; minimum: 233 m). This is a privately owned, highly fractured forest. This area is currently under a project carried out by the Regional Forestry Board in Dalarna-Gävleborg and SLU which aim is to rearrange the forest-land ownership, since owners have several different pieces of forest distributed all over the area. To achieve this objective, the forest was scanned by airborne laser equipment (LIDAR). As a by-product, measures from the ground level were obtained, which were used to produce a high-resolution digital elevation model (DEM, Fig. 2) with 5 m cell size, which can be used for the application of hydrological modelling. The data obtained from LIDAR was a main reason for developing this project in the area.

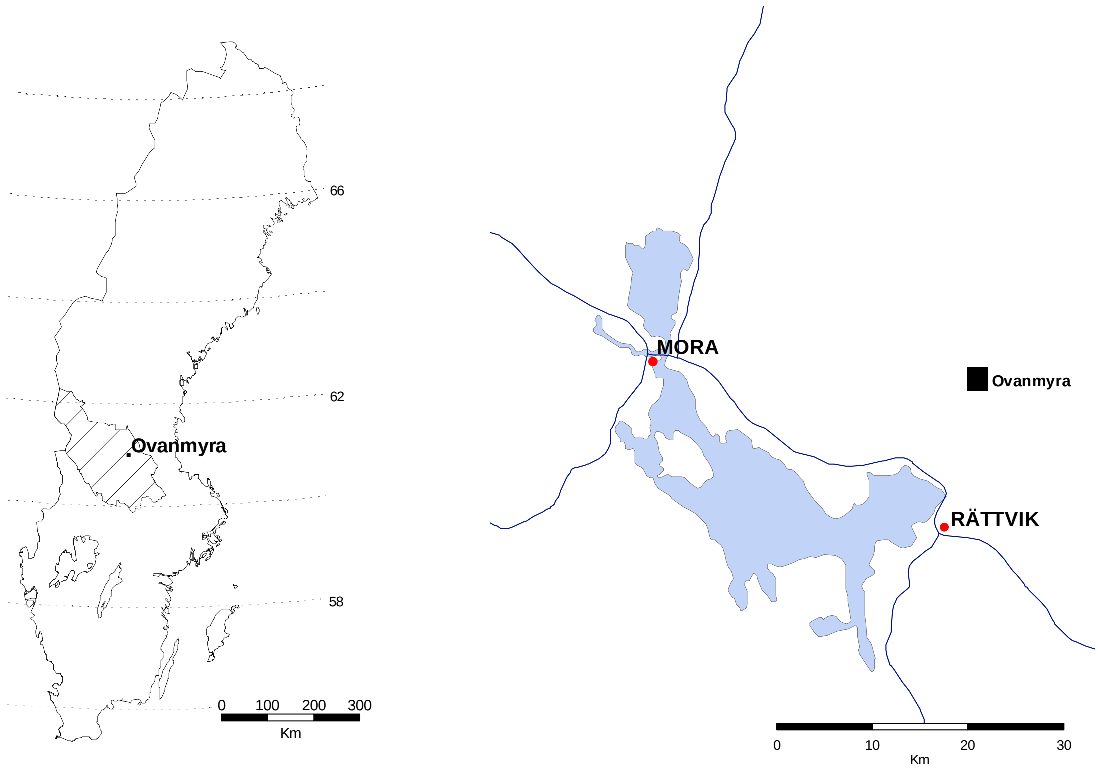
The application of the TWI values over the DEM produced the map in Fig. 2, in which it is clearly shown how the areas in the valleys present the highest values of TWI and thus, the highest humidity, whereas the driest spots are those situated in the steepest areas that form those valleys.

The dominant vascular vegetation is Norway spruce (*Picea abies* Karst.) and Scots pine (*Pinus sylvestris* L.). However, it is easy to find birch (*Betula ssp.*) all through the area, and other tree species can be found, depending on the hydrology of the place, such as rowan (*Sorbus aucuparia*), alder (*Alnus glutinosa*) and willow (*Salix ssp.*). As for the field vegetation, the most common is of heath type: blueberry/bilberry (*Vaccinium myrtillus* L.) and cowberry (*Vaccinium vitis-idaéa* L.). Also quite common is Heather (*Calluna vulgaris* (L.) Hull). Other more specific species were found in especially wet sites.

The forest is managed for wood production. Several clear cuttings were found throughout the forest. No plots were sampled in those areas, but several of them were situated in the limits or at a close distance, possibly affecting the conditions of those sites.

Topographical analysis

The topographic influence on the C and N stocks and, thus, on the C/N ratio, was evaluated through the topographic wetness index (TWI), first introduced by Beven and Kirkby (1979) as part of the definition of the hydrological model "TOPMODEL". After that it has been revised and applied in multiple occasions (Rodhe & Seibert, 1999; Seibert *et al.*, 1997; Ibbitt & Woods, 2004; Pellenq *et al.*, 2003). It is expressed in Fig. 3.



Figures. 1a-1b. Map of Sweden showing the Province of Dalarna, and detailed map of the area of study.

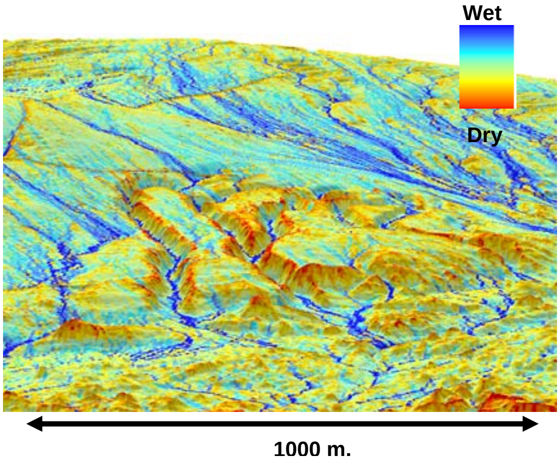


Figure 2. Example from Ovanmyra: TWI draped over the DEM.

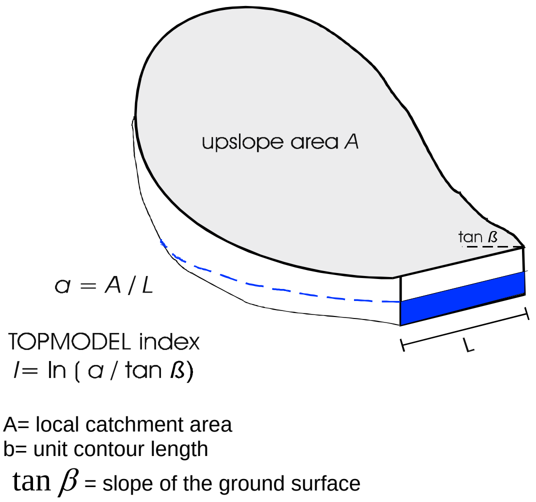


Figure 3. Graphical representation of the TWI.

The index will show a higher value as we increase the local catchment area and as the slope decreases, indicating a wetter soil (Rodhe & Seibert, 1999). I decided to use a mean TWI based on the values of the 3x3 pixel grid, which had its centre in our plot, as a way to having a set of TWI values which were more approximate to the situation on the field. Other variables were used for the study of the topography and hydrology in the area, in particular the wetness in each of the analysed horizons, through the water content in the samples (Annex 1).

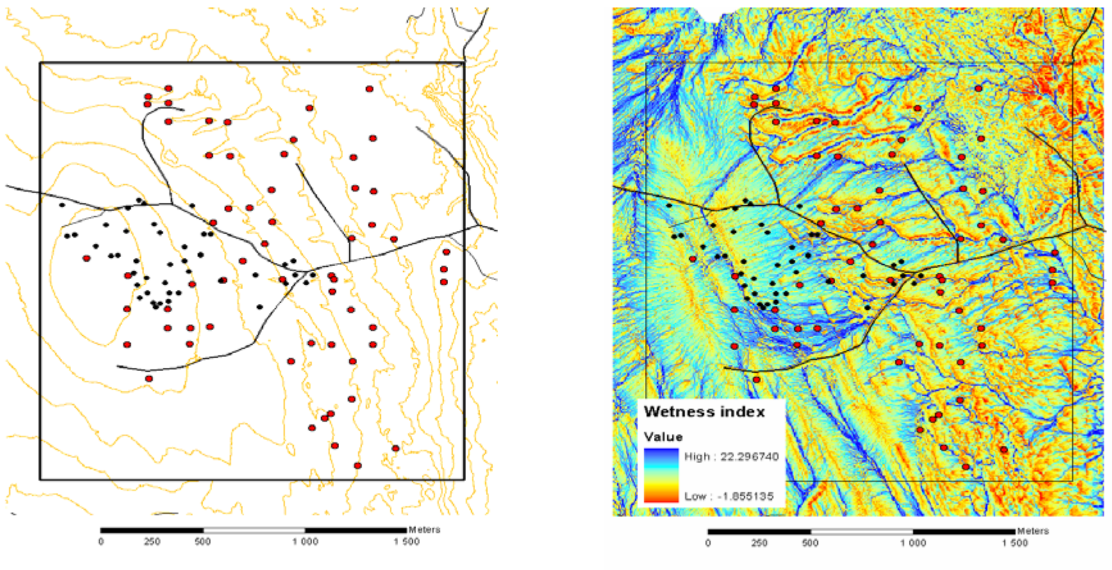
Field sampling

Through the DEM, data on altitude was obtained, and hydrological features such as water flows and overall wetness were available for the study. This information was the base for designing the sampling grid and, particularly, for selecting the locations where the soil sampling would be carried out. This was done by randomizing the sampling plots within stratas according to the information provided by value of the TWI values in the Ovanmyra area. The goal was to select sites that showed differences in wetness conditions, so that a wide range of site conditions were covered.

A Geographical Information System (GIS) was the base software used before the sampling for situating the sites on the map (Figs. 4a-4b), and during the sampling, integrated in a field-GPS (Trimble Geo-XT) which helped finding the correct plots. The positions were post-processed for differential corrections (DGPS).

The sampling grid had a surface of 2600x1900 m (494 ha). A unique code was assigned to refer to each sampling site, formed by letters from A to S (for horizontal positioning) and numbers from 0 to 2600 (for vertical positioning). The total number of sampled sites was 58. This sampling was done according to parts of the Swedish Forest Soil Inventory methodology. On each plot, 5 sub samples were collected from the humus layer, one at the centre of the plot and the other four at a 1 meter distance from it. I used a 10 cm diameter corer for this stage of the sampling. All humus cores were put together in the same bag. The mineral soil sampling was done by taking cores at different depths from a pit dug at the centre of the plot. In this case I used a mineral corer with a diameter of 7.2 cm. In peat soils where the humus depth was higher that 40 cm, only one mineral soil core was taken, at depth 0-10 cm of the mineral soil (if possible); in peat soils where the humus depth in the range 30-40 cm, two mineral soil samples were taken at depths 0-10 and 10-20 cm from the surface of the mineral soils. In the rest of the soils, three samples were taken at depths 0-10, 10-20 and 55-65 cm from the top of the mineral soil. In all the cases, for each depth I took two samples with a fixed-volume cylinder (200 cm^3), except for the 55 to 65 cm depth, in which only one soil core was extracted. Within each plot, samples from the same depth were put in the same bag. In the end, taking humus and mineral soil samples, for most of the plots there were 4 bags, 1 for the humus and 3 for each depth sampled for the mineral soil.

The stoniness and boulder content was estimated through the Viro´s rod penetration method (Viro, 1952), from the top of the mineral soil. This was done in 8 locations around the centre of the plot, separated 1 m from each other and forming a square form. Due to the micro-heterogeneity found in some of the plots, very different depths were obtained in some cases, this is the reason why eight measurements were taken and the average of them calculated as the reliable value.



Figures 4a & 4b. Field sampling grid. Red points represent sites sampled for C & N. Fig. 4b shows the TWI values.

This value is used in function II in Viro (1952) to estimate the volumetric content of stones and boulders in the soil:

$S\&B$ = 65.7 - 2.22 Pd,

where S&B is the stone content (%) and Pd is the mean penetration depth (cm).

Also, the depths of the humus layer and E horizon (if present), the soil parent material and the soil texture (Tab. 1) were estimated at each plot.

Table 1: The used soil texture classes according to the Swedish classification.

Code	Identification
0	Boulders in profile
1	Boulder/bedrock
2	Gravelly till
3	Gross sand/till
4	Thin sand/till
5	Gross silt/till
6	Thin silt/till
7	Fine silt/till
8	Clayish till
9	Peat

Laboratory analysis of samples

The pH measurements were made each day after the field work. Organic and mineral soil samples taken for that purpose were mixed with distilled water at the volume ratio 1:3, stirred and subjected to a pH analysis.

After the field sampling, the mineral soil and humus samples were pre-treated in the lab before its posterior analysis to determine the organic carbon and nitrogen presence in the soil content.

All samples were weighted wet before being dried. The mineral soil samples were dried overnight (approximately 12 hours) at a temperature of 105 °C, and weighted dry, for later calculations of moisture in the soil by comparison with the wet weight. A sieving was done with a 2 mm mesh, and the sample obtained was the one sent to laboratory for analysis. The particles larger than 2 mm in diameter were also weighted.

The humus samples were dried at a temperature of 40 °C until they were dry (during approximately ten days), and the preparation of the sample for analysis could be done. These samples were also weighted before and after drying, and ground. The humus samples were then separated in two fractions (>2 mm and <2 mm particles). In this case, generally the whole sieved sample (>2 mm and <2 mm particles separated) was sent to the lab, except in those were an extremely big quantity of material was available, in which a sub sample was sieved. The analysis, though, was done only in the <2 mm samples fraction. The total C and N analysis was made on a LECO CNS 1000 analyser.

Variables used

Three main categories of variables were used in the study, which make up the three main pillars of the study: vegetation, topography and C and N concentrations in the soil (Annex 1). The analysis of the vegetation was developed both through the data obtained in the field and from a digital forest stand database. Vegetation coverage (percentage of ground surface under canopy) for the different species was the main variable within this category used in the study from the ones estimated on the field. The digital forest stand database provided information on volume (in m^3 ha^{-1}), average and maximum height (m), basal area (m^2 ha^{-1}) and canopy closure (%). I mainly used one of these variables, the volume, in the

Table 2. Basic statistics for C, N and C/N.

Variable	N	Mean	SE Mean	StDev	Minimum	Median	Maximum	Skewness
C_O	58	41.082	0.954	7.451	15.100	43.600	49.200	-1.79
N_O	58	1.368	0.031	0.244	0.517	1.390	1.935	-0.52
C_010	56	1.474	0.143	1.092	0.236	1.250	7.675	3.41
N_010	56	0.085	0.009	0.069	0.024	0.074	0.548	5.41
C_1020	54	1.416	0.113	0.841	0.163	1.220	3.940	0.76
N_1020	54	0.079	0.005	0.037	0.021	0.077	0.158	0.09
C_5565	49	0.328	0.034	0.238	0.046	0.286	1.130	1.44
N_5565	49	0.029	0.002	0.015	0.012	0.026	0.100	2.47
CN_O	58	30.360	0.668	5.221	16.281	30.147	50.113	0.69
CN_010	56	17.157	0.586	4.466	7.195	16.674	32.500	0.52
CN_1020	54	17.245	0.633	4.694	7.244	17.124	36.822	1.17
CN_5565	49	10.371	0.500	3.533	2.716	10.885	17.773	-0.14

analysis of the data, since they all were highly correlated. A detailed study on the different vegetal species living in the area was not implemented since it required a great amount of time and was not necessary for our study. Thus, our analysis of the influence of the vegetation was focused on the characteristics provided by the digital forest stand database, as stated above.

Apart from these three main groups of variables, a fourth category including some soil properties was also studied to assess their influence on the C/N ratio and the vegetation. These properties were: texture, depth of the E horizon, stoniness, water content in the humus layer, pH and humus thickness.

Statistical analysis of data

The first statistical approach given to both the field data and the C and N data was based on classical descriptive statistics (Tab. 2), including histograms, regression plots and box plots. All these analysis were done using Minitab for Windows, version 14.12. Histograms were obtained for all the variables used in the study, in order to have a first insight of the data. It was considered that these variables were worth to analyse separately and not only in correlations between them and with other variables, especially in the case of the C and N concentrations in the soil, a main component of this study. Matrix (Draftman) plots were used as a first glance over the general correlations between most of the variables.

Correlation coefficients were calculated in order to be used as first approximations to existing relations between the variables used in the study (Annex 2). I also considered a principal component analysis (PCA) would be a reliable tool as for obtaining direct relations between the variables. This PCA would allow us to study closely the structure of the data by transforming our original multi-dimensional storage of information into a multi-dimensional structure formed by two new coordinate axes, representing the two principal components.

The PCA allowed for making a differentiation between the main variables when describing the problem and the random variation, through two principal components. It was done both numerically and graphically, and a loading plot was calculated to study the correlations mentioned above (Fig. 13). For this task, percentages of pine, spruce and deciduous species on the sites were also considered as vegetation variables. I considered this would give more information about the correlation structure between the C and N concentrations in the soil and, basically, the vegetation characteristics. The values of these variables were extracted from the digital forest database. The fact of these values being very accurate information on quantitative measurements of the vegetation proved to be positive, in contrast with the more subjective on-the-field observation of features such as coverage or percentage of species presence. On the other hand, it must be noted that these values were only on major vegetation, not showing information on the ground vegetation (herbs, grass, etc.).

RESULTS

Exploratory Data Analysis

Screening for extreme values

In-field observation of the area of study and, particularly, of the sampled sites, showed homogeneity in the general ecological conditions, but also important differences on some specific properties such as soil moisture, plant species, depth of the E horizon (when existent) or stoniness. A reduced number of plots presented extreme values on in these features. The most evident case was site P1500 extra, situated approximately 40 m far from P1500 (included in the original sampling grid) and was sampled after observing its special topographic position in a wet sink. The pH in the humus layer of this plot was almost 2 units higher than the 3rd quartile of pH values in all the humus layers, and more than 1,5 units in the case of the pH in the mineral soil. It also showed high percentages of C and N, especially in the first centimetres of the mineral soil (depth 0-10 cm) and a high C/N ratio in the humus layer. This influence was displayed in some of the regressions when comparing topographic and vegetation attributes with these soil properties. The hypothesis is that this plot was located on a lime stone parent material, which was present in some parts close to the study area. This was the only site with a thin silt (not gross silt or thin sand) texture as classified in the field.

This plot was included in the analysis of the data, as when comparing the C/N ratio patterns with and without its values, these patterns did not show important differences (Figs. 5a-5b).

Descriptive statistics

Histograms on C%, C/N ratio and other soil attributes showed normal frequency distributions and a good normality, with the possible exception of the pH and humus thickness curves, which were especially skew due to the extreme values in site P1500 extra (as explained before) in the case of the pH, and due to the presence of some peaty soils with a very thick humus layer, in the case of the humus thickness (Fig. 6)

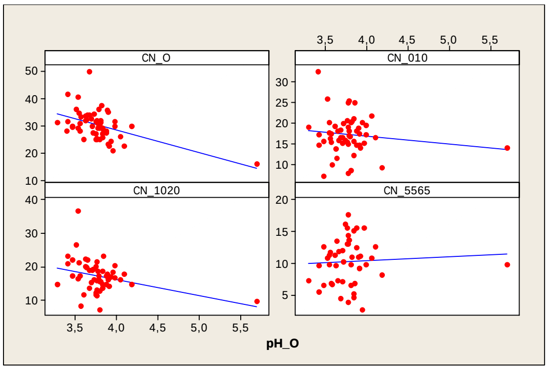


Figure 5a. Scatter plot between C/N ratio in different horizons and pH in humus layer, considering all the samples. Figures on the Y axis represent the C/N values.

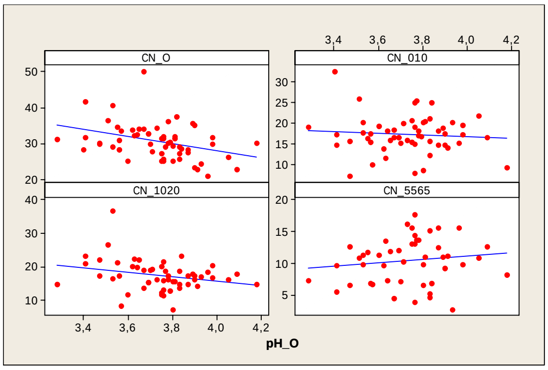


Figure 5b. Scatter plot between C/N ratio in different horizons and pH in humus layer, excluding the extreme values shown in P1500extra.

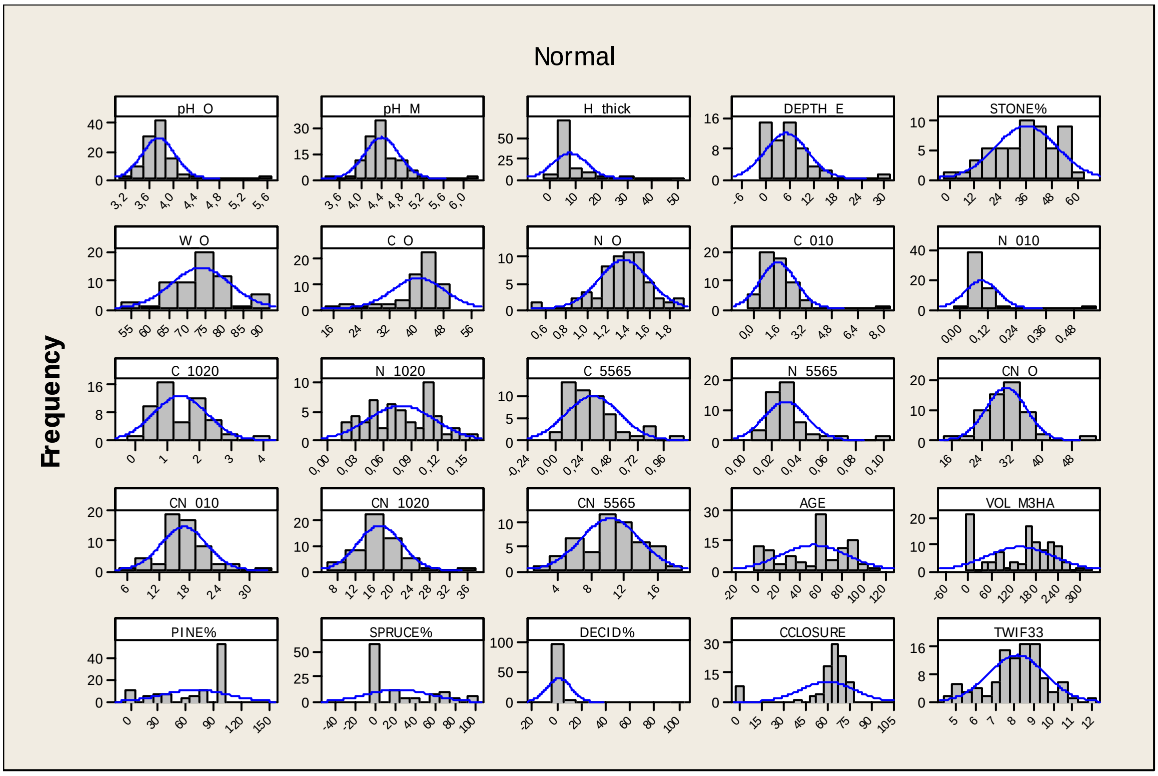


Figure 6. Histograms on main variables.

The correlation analysis implemented to obtain simple correlations between the variables showed clear patterns in some of the cases (Annex 2). All results and analysis were based both on these patterns and on the posterior PCA.

Correlations

Establishing the significance level for these correlations at r=0.500, Carbon concentrations, Nitrogen concentrations and wetness are positively and significantly correlated both in the humus layer and the mineral soil, as well as are those shown between wetness in the humus layer and the humus thickness, and age, volume and canopy closure among themselves. Nitrogen concentration at the depth corresponding 0 to 10 cm in the mineral soil is also clearly correlated to pH values both in the organic and the mineral soil. As for the negative correlations, only one surpasses the -0.500 value: the one between pine presence percentage and spruce presence percentage. This is quite a logical result, considering that they add up to 100% and the percentage values for pine and spruce show the relative presence of these species, and thus, in most cases, have opposite values; e.g. where pine is up to 70% of the major flora, spruce will be 30%, since deciduous species percentage is not relevant in the area.

C/N ratio-topography

The TWI had a small influence on the C concentration in the soil, as shown by the small correlations in the different depths (Annex 2). The same patterns or with a very slight difference appear for the C/N ratio. These patterns were negative in the case of the humus layer, as well as the last two depths in the mineral soil (10 to 20 and 55 to 65 cm). It was positive in the 0 to 10 cm depth of the mineral soil (Fig. 7). Water content in the humus has a positive correlation with TWI although not as a large value as could be expected.

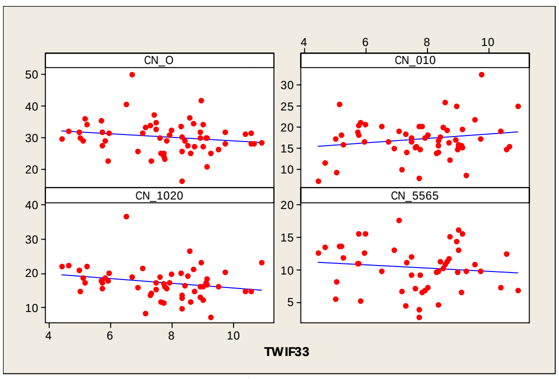


Figure 7. Scatter plot of C/N ratio and TWI

C/N ratio-vegetation

In relation to the vegetation, the carbon concentration showed a positive correlation with the stand volume, in the case of the C in the humus layer. This correlation was also positive for the C/N ratio in the same layer, although still a weak correlation (Fig. 8). The same pattern appeared for the average height instead of the volume, which was expected considering the high correlation between these two variables. However, these relations were much poorer in the case of the mineral soil, where patterns varied considerably depending on the depth, and showed a very scattered distribution.

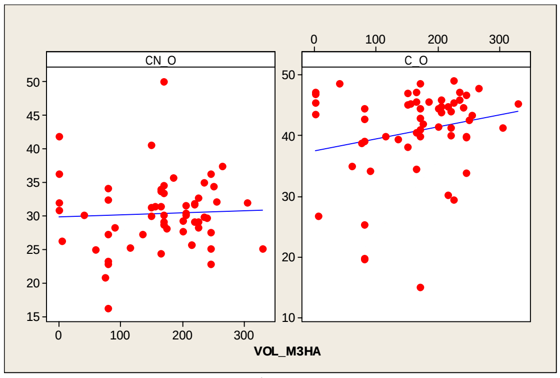


Figure 8. Scatter plot of C/N ratio and C concentration vs. volume of vegetation

The influence of the ground vegetation on the ratio was not studied, as the digital forest database did not provide information about it and a deep study was not developed in-field.

C/N ratio-other soil properties

The correlation between C/N ratio and stoniness, although not showing such a strong pattern, is negative in all the soil horizons; this is, the ratio is lower as the percentage of stones in the soil increases (Fig. 9a). Correlations between C concentration and stoniness are not strong either, but in the case of the humus layer, it shows a positive value (Fig. 9b). The results were similar for the influence of pH on the ratio: there is a negative pattern showing that the higher the pH, the lower C/N ratio in the soil. This negative correlation is strong in the humus and in the first two depths measured in the mineral soil, but is weaker, and even slightly positive, for the 55 to 65 cm depth of the mineral soil (Figs. 5a and 10).

Another interesting result was found when assessing the variation of the C/N ratio through the different depths of the soil. There is a decreasing pattern showing that the C/N ratio is higher closer to the soil surface. The value outstands for the organic horizon, while in the different depths studied in the mineral soil the value of the ratio is much lower, although still shows the same clear pattern mentioned above (Fig. 11).

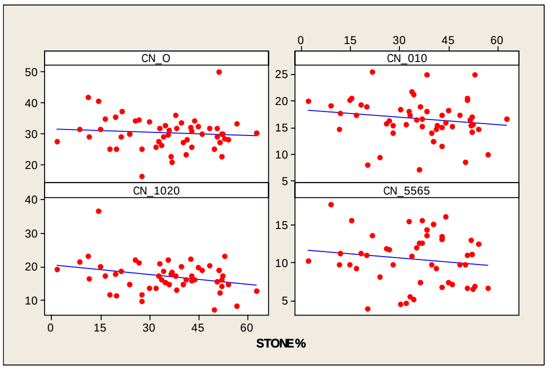


Figure 9a. Scatter plot for C/N ratio and stoniness.

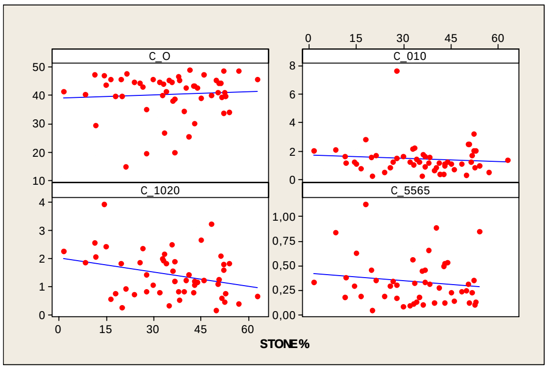


Figure 9b. Scatter plot for C concentrations and stoniness.

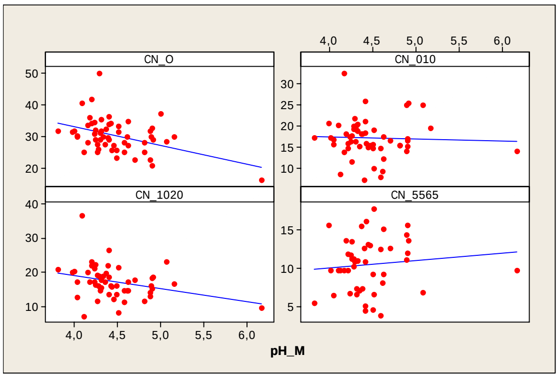


Figure 10. Scatter plot between C/N ratio in the different horizons and pH in the mineral soil.

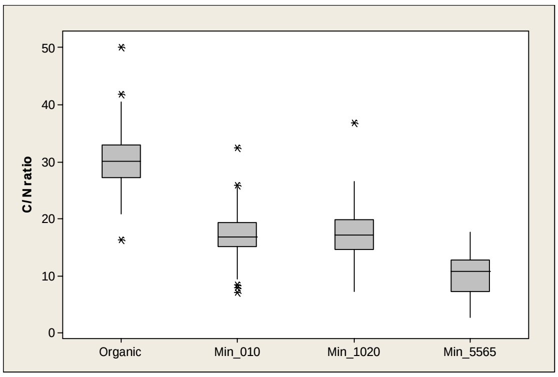


Figure 11. Boxplot of C/N ratio in the different depths of the soil

Topography-vegetation

When studying these correlations with some of the vegetation variables such as percentage of pine, percentage of spruce and the volume, patterns appeared but only in the case of the volume it was reliable, showing a negative relation between the two variables, which indicates that those sites that are more forested and have a higher volume of wood available have, in general, a lower topographic index (Fig. 12). As for the pine and spruce percentages, the pattern shown in the regression plots is clearly influenced by the number of sites presenting a 100% presence of the specie in particular, which is much lower in the case of the spruce.

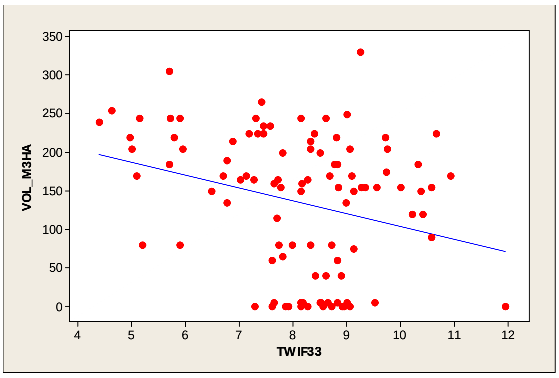


Figure 12. Scatter plot of TWI and volume of vegetation

Principal Component Analysis

A PCA was implemented in order to get a better understanding on the relations between the variables used in the study. This PCA models would allow us to quantify the common variation of the variables, as well as to assess the general structure of the data and the variation along the PC axis.

I used the general dataset in which the most important variables in the study were present. The Eigen values obtained from the PCA showed that the first 4 components explained only little more than half of the correlations between the variables (0.526). A loading plot was made in order to study these correlations more deeply (Fig. 13). This would provide information about the relationship among the soil variables, as well as illustrate the relationship among the sites, i.e. if there were any clusters. If the first two components account for most of the variance in the data, you can use the loading plot to assess the data structure and detect possible trends.

As we can observe in the loading plot (Fig. 13), some of the variables are very much related in their values. Those representing the vegetation attributes (volume, height, canopy closure and basal area) form a clear group situated at the negative extreme of the first component axis, and at the positive extreme of the second component axis. This result fits with our initial hypothesis in which the quantitative aspects of the vegetation could be assessed by any of these characteristics as they are highly correlated. Spruce and pine percentages are oppositely situated on the plot (Fig. 13, in green), showing a strong negative correlation, a result that was mentioned before in point 3.2. We can distinguish another group situated at the opposite extreme of the first component axis of variables. It is shown here that one of the main soil properties studied in the field, the pH, has a positive relation in all sampled horizons when comparing its value in the organic and mineral soil, a result that could be expected. Carbon and Nitrogen concentrations in the first layer of the mineral soil (depth 0 to 10 cm) are also positively correlated with those pH values, but this cannot be considered representative as all values of C and N concentrations are very much spread in the plot and do not show a clear relation between them. Last, we observe, in the negative semi-axis of the second component, a set of variables which includes C concentration and C/N ratio in the organic horizon, wetness in the same horizon, and depth of the E horizon and humus thickness. This would show that accumulation of C in the soil influence the formation and quantity of humus, as well as the E horizon, to a certain extent, especially that in the organic layer of the soil.

In the particular case of the topographic variables (TWIF33, W_O, W_010, W_1020, W_5565), they are positively correlated and, as it can be seen on the score plot, they form a humidity cluster which could be interpreted as a distribution along an axis representing moisture conditions (Fig. 13, in red). Depth of the E horizon also appears at the other side of the origin on this axis. As for the other variables, C% and C/N ratio are quite correlated between them in all the cases (not as clear in the case of the 0 to 10 cm depth of the mineral soil) but not clearly with other variables.

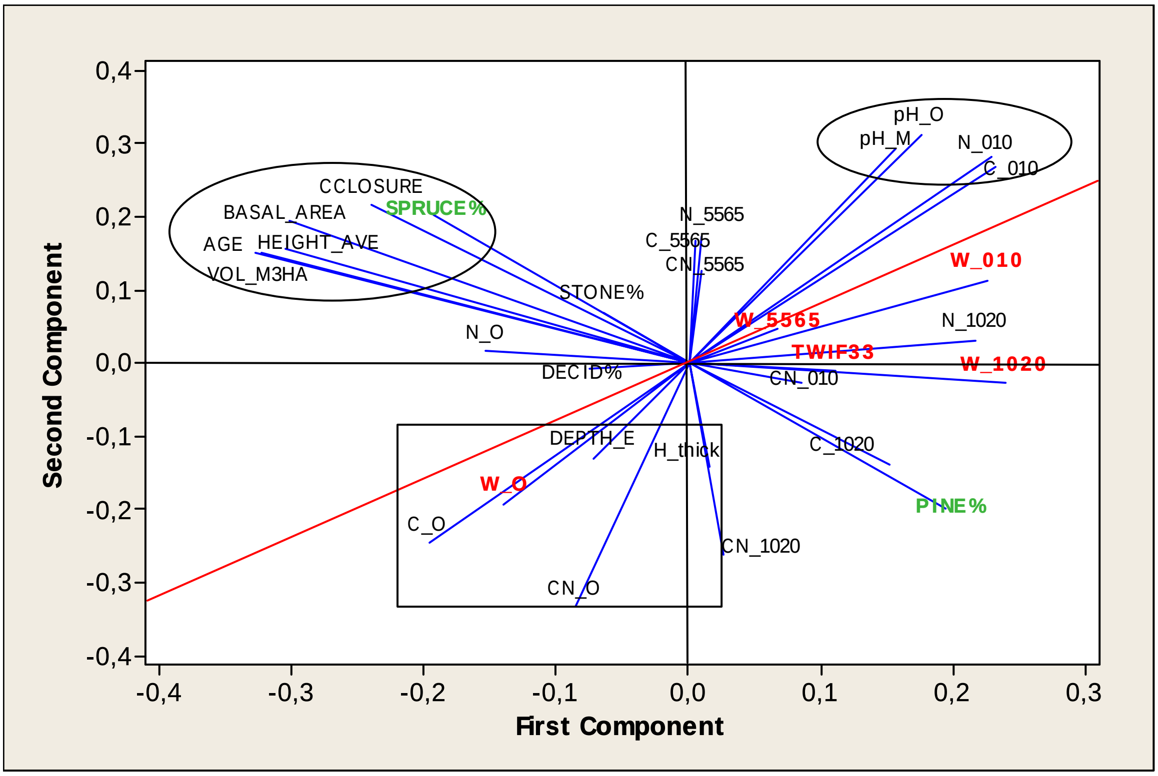


Figure 13. Loading plot for main variables.

DISCUSSION

In this thesis, the relations between topography, soil properties and vegetation have been studied, through a set of variables wide enough to be representative of the ecology of the area of study. All the data obtained during the field sampling was stored in different categories depending on the characteristics they were describing, that is hydrological, topographical, soil components or vegetation features. The direct observation of the numerical information suggested a great variance of the different variables measured, in the plots where samples were taken. This first observation was later confirmed by the statistical analysis applied to the data.

Preliminary results on the influence of topography and soil moisture, through the TWI, on C concentrations and the C/N ratio, showed a very weak relation between those variables. Not especially large concentrations of C were found in moister places, in contrast to other studies (Fröberg, 2004). On the other hand, the same author found no correlation between water flux and DOC concentrations, similarly as our results show. Water content in the humus layer was positively correlated with the TWI, although this relation, while clear, was not as strong as it can be expected. A further PCA showed the same result. This could be explained by the influence of local micro topography and soil properties when making measurements at a very small scale (Pellenq *et al.*, 2003) or by the use of a TWI not perfectly adjusted to the conditions of the area of study.

In the humus layer, Carbon concentrations, as well as the C/N ratio, had positive correlation with the stand volume. The input of litter was quite important in most of the sampled sites as it could be seen on the field. However, this correlation was weak in the case of the mineral soil. The PCA showed the same results.

Topography has an influence on the vegetation, as shown by the descriptive statistics: the higher the stand volume, the lower the TWI. This correlation, though, was small. This fact was confirmed when developing the PCA: the index was situated in the same PC axis as the volume and other descriptive attributes of vegetation, but on the opposite side from the origin. This same result was also reflected by Fröberg (2004), linking it with the C stock, when concluding that the differences in these stocks between moisture classes could not be related to differences in the biomass productivity.

Relations between other soil-defining properties and the main variables used have been much more studied in the literature. Analysis of samples showed that the concentration of organic C decreases with depth, a result that appears in other studies (Ellert *et al.*, 2001; Fröberg, 2004). The ratio C/N shows the same pattern in both organic layer and all depths of the mineral soil.

CONCLUSIONS

- Soil moisture, measured through the TWI, had a weak positive influence on the C concentration and the C/N ratio. If using the other humidity variable, the wetness in the different layers of the soil, the relation is much clearer and also positive.
- The C/N ratio in the humus layer is positively influenced by the stand volume: the higher the volume, the larger ratio in the humus. A similar correlation was not found in the mineral soil samples.
- A negative relation between stand volume and TWI was shown during the analysis of the data, meaning the most productive places in terms of biomass could be situated in upslope positions. This correlation was very weak, though, so it is not possible to have a definite conclusion on this relation. However, as shown in the PCA, stand volume would be oppositely related to moisture conditions, showing a higher rate in drier places.
- The carbon concentration, as well as the C/N ratio, has a general negative correlation with the stoniness value.
- A main soil characteristic, the pH, increases as the C/N ratio decreases. This is not a general rule, as for the last layer of the mineral soil (depth 55 to 65 cm) the relation turns slightly positive.
- The depth of the E horizon (if existent) and the humus thickness are correlated to the C concentration in the organic layer of the forest soil.

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Annex 1. Main variables used in the study

Category	Variable	Abbreviation
Topography	Topographic Wetness Index	TWFI33
	Wetness in org soil	W_O
	Wetness in min soil, 0 to 10 cm	W_010
	Wetness in min soil, 10 to 20 cm	W_1020
	Wetness in min soil, 55 to 65 cm	W_5565
Carbon & Nitrogen	Carbon percentage in organic soil	C_O
	Carbon percentage in mineral soil, 0 to 10 cm	C_010
	Carbon percentage in mineral soil, 10 to 20 cm	C_1020
	Carbon percentage in mineral soil, 55 to 65 cm	C_5565
	Nitrogen percentage in organic soil	N_O
	Nitrogen percentage in mineral soil, 0 to 10 cm	N_010
	Nitrogen percentage in mineral soil, 10 to 20 cm	N_1020
	Nitrogen percentage in mineral soil, 55 to 65 cm	N_5565
	Carbon/Nitrogen ratio in organic soil (Humus)	CN_H
	Carbon/Nitrogen ratio in mineral soil, 0 to 10 cm	CN_010
	Carbon/Nitrogen ratio in mineral soil, 10 to 20 cm	CN_1020
	Carbon/Nitrogen ratio in mineral soil, 55 to 65 cm	CN_5565
Vegetation	Stand volume (m3/ha)	Vol_m3ha
	Age	AGE
	Canopy closure	CCLOSURE
	Average height	HEIGHT_AVE
Other soil properties	Basal area	BASAL_AREA
	Pine presence	Pine%
	Spruce presence	Spruce%
	Deciduous species presence	Decid%
	Depth of the E horizon	DEPTH_E
	Stoniness	STONE%
	Humus thickness	H_THICK
	pH in organic soil	pH_O
	pH in mineral soil	pH_M

Annex 2. Pearson product moment correlation coefficients between variables.

VARIABLES	pH_M	pH_O	H_THICK	DEPTH_E	STONE%	W_O	C_O	N_O	W_010	C_010	N_010	W_1020	C_1020	N_1020	W_5565	C_5565	N_5565	CN_O	CN_010	CN_1020	CN_5565	AGE	VOL_M3HA	PINE%	SPRUCE%	DECID%	CCLOSURE	TWIF33
pH_O	0.52																											
H_THICK	0.08	-0.13																										
DEPTH_E	-0.39	-0.06	-0.35																									
STONE%	-0.01	-0.03	0.03	0.04																								
W_O	-0.06	-0.21	0.55	0.00	0.00																							
C_O	-0.29	-0.44	0.33	0.17	0.08	0.68																						
N_O	0.06	-0.04	0.40	-0.09	0.19	0.50	0.61																					
W_010	0.15	0.29	0.01	0.11	-0.08	0.03	-0.11	-0.14																				
C_010	0.48	0.62	0.01	-0.18	-0.10	-0.21	-0.38	-0.15	0.68																			
N_010	0.58	0.76	-0.08	-0.17	-0.07	-0.27	-0.40	-0.12	0.57	0.94																		
W_1020	-0.13	0.07	-0.09	0.23	-0.16	-0.13	-0.12	-0.27	0.52	0.35	0.28																	
C_1020	-0.31	-0.11	-0.11	0.14	-0.30	-0.30	-0.04	-0.33	0.19	0.13	0.07	0.71																
N_1020	-0.10	0.18	-0.23	0.06	-0.18	-0.47	-0.27	-0.31	0.26	0.39	0.36	0.69	0.87															
W_5565	-0.05	-0.02	-0.17	-0.18	-0.14	0.13	-0.08	-0.04	0.15	0.07	0.05	0.41	0.13	0.13														
C_5565	-0.02	0.05	-0.22	0.05	-0.15	-0.04	-0.11	-0.05	0.17	0.10	0.08	0.21	0.14	0.22	0.70													
N_5565	-0.04	0.07	-0.17	0.04	-0.15	-0.07	-0.10	0.01	0.16	0.15	0.13	0.20	0.15	0.27	0.60	0.93												
CN_O	-0.41	-0.48	-0.02	0.25	-0.09	0.27	0.51	-0.35	-0.01	-0.29	-0.35	0.14	0.30	0.02	-0.04	-0.08	-0.14											
CN_010	-0.05	-0.12	0.27	-0.06	-0.17	0.08	-0.08	-0.22	0.43	0.39	0.07	0.28	0.25	0.16	-0.01	-0.01	0.00	0.13										
CN_1020	-0.31	-0.32	0.12	0.18	-0.31	0.01	0.16	-0.30	0.10	-0.15	-0.25	0.42	0.69	0.29	0.07	-0.02	-0.07	0.50	0.35									
CN_5565	0.12	0.06	-0.27	0.07	-0.14	-0.10	-0.19	-0.25	0.18	0.07	0.05	0.15	0.14	0.14	0.53	0.73	0.46	0.03	0.06	0.12								
AGE	-0.11	-0.11	0.05	0.17	0.10	0.02	0.20	0.21	-0.36	-0.23	-0.20	-0.38	-0.26	-0.27	-0.17	0.10	0.10	0.01	-0.20	-0.17	0.02							
VOL_M3HA	-0.11	-0.11	0.05	0.20	0.06	0.01	0.22	0.20	-0.34	-0.22	-0.20	-0.34	-0.23	-0.25	-0.16	0.10	0.11	0.05	-0.17	-0.11	0.01	0.97						
PINE%	-0.15	0.04	-0.13	0.18	-0.07	0.06	-0.01	-0.04	0.03	-0.01	0.05	0.06	0.06	0.05	-0.08	-0.20	-0.20	-0.01	-0.11	0.06	-0.27	-0.18	-0.22					
SPRUCE%	0.16	0.02	0.06	-0.09	0.10	-0.13	-0.03	0.03	-0.11	-0.03	-0.04	-0.14	-0.07	-0.03	0.06	0.29	0.29	-0.01	-0.06	-0.06	0.22	0.41	0.45	-0.81				
DECID%	0.12	0.04	0.07	-0.14	-0.10	-0.09	-0.09	0.04	-0.15	-0.01	0.01	-0.19	-0.12	-0.05	-0.06	-0.12	-0.06	-0.13	-0.04	-0.16	-0.26	-0.02	-0.07	-0.23	-0.04			
CCLOSURE	0.04	-0.09	0.00	0.10	0.06	-0.03	0.06	0.12	-0.12	-0.07	-0.13	-0.27	-0.16	-0.14	-0.20	0.13	0.12	-0.06	0.06	-0.10	0.08	0.63	0.64	-0.31	0.33	-0.05		
TWIF	0.12	-0.09	0.20	-0.40	0.20	0.36	0.03	0.22	0.12	0.14	0.07	0.06	-0.11	-0.02	0.22	0.08	0.16	-0.17	0.19	-0.23	-0.03	-0.19	-0.21	0.03	-0.17	0.00	-0.01	
TWIF33	0.08	-0.10	0.27	-0.37	0.28	0.37	0.07	0.26	0.10	0.13	0.08	0.09	-0.08	0.03	0.14	-0.06	-0.03	-0.18	0.17	-0.23	-0.12	-0.21	-0.25	0.13	-0.25	-0.05	-0.06	0.91

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