Verification of field-based classification of Podzols and their development in relation to soil formation factors

University of Helsinki

Dept. of Forest Sciences

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Tiina Törmänen

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

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Tiivistelmä/Referat – Abstract

Suomessa maannosten nimeäminen luokittelujärjestelmien mukaan on ollut melko vähäistä. On olemassa kuitenkin useita kansainvälisiä maannosten luokittelujärjestelmiä, joista yksi on myös tässä työssä käytetty The World Reference Base for Soil Resources (WRB). WRB:n kriteerit, joilla määritetään maannoksen diagnostiset ominaisuudet, horisontit ja nimetään itse maannos, eivät välttämättä toimi kaikkialla maailmassa. Tämä on yksi syy, miksi kansainvälisten maannosten luokittelujärjestelmien päivitykselle ja testaamiselle kansallisella tasolla on jatkuva tarve. Suomessa on esiintynyt ongelmia määritettäessä podsoloituneen maannoksen spodic B horisontti kansainvälisten luokittelujärjestelmien mukaan. Myös Podsol-maannosten empiirinen testaaminen näiden luokittelujärjestelmien mukaan on puuttunut. Tiedossa ei ole ollut kuinka monella Podsoliksi luokitellulla maannoksella on diagnostinen spodic B horisontti, joka on virallinen vaatimus kansainvälisten luokittelujärjestelmien mukaan Podsoliksi luokiteltavalle maannokselle. Maannosten luokittelujärjestelmät antavat yksityiskohtaista tietoa maannoksistamme ja niiden ominaisuuksista. Nämä ominaisuudet taas ovat maannoksen kehittymisasteen indikaattoreita.

Podsolit, jotka ovat yleisimpiä metsämaannoksia Suomessa, ovat kehittyneet viiden maannostumistekijän vaikutuksesta. Nämä tekijät ovat ilmasto, lähtöaines, topografia, bioottiset tekijät ja aika. Ne määrittävät, mitkä maannosprosessit ovat vallitsevia, mitkä ominaisuudet maannokseen syntyvät ja mikä maannostyyppi lopulta kehittyy. Suomessa on tehty vain muutama tutkimus, jotka ovat tutkineet maannostumistekijöiden vaikutusta podsoloituneiden maannosten kehittymisasteeseen.

Tämän työn tarkoitus oli selvittää kenttäluokittelussa Podsoleiksi määritettyjen maannosten osuus, joilla oli myös diagnostinen spodic horisontti World Reference Base for Soil Resources (WRB) mukaan. WRB:n diagnostisen spodic horisontin kriteerit koostuvat kuudesta kohdasta, jotka perustuvat morfologisiin (horisontin paksuus ja Munsell kuiva/märkä väri) ja kemiallisiin (pH, orgaanisen hiilen määrä, oksalaattiin uuttuvan Al ja Fe pitoisuus) ominaisuuksiin E- ja B-horisonteissa. Lisäksi profiilien podsoloitumisaste määritettiin neljän indeksin (E-horisontin paksuusindeksi, Rubifikaatio indeksi, Al+Fe indeksi ja Podsolisaation kehittymisindeksi) avulla ja arvioitiin eri maannostumistekijöiden (ilmasto, topografia, lähtöaines, bioottiset tekijät, aika) vaikutus maannoksen kehittymisasteeseen. Maannosprofiilidata on peräisin koko Suomen kattavasta Luonnonvarakeskuksen Biosoil-tietokannasta.

Tutkimuksessa todettiin, että Podsoleiden morfologisiin ominaisuuksiin (albic ja spodic horisonttien väri ja paksuus) perustuva kenttämääritys toimii hyvin Suomen oloissa. Yksittäinen maannostumistekijä pystyy selittämään podsoloitumisilmiötä melko heikosti, koska maannostumisprosessit tapahtuvat samanaikaisesti ja niiden välillä on monimutkaisia yhteyksiä. Joissain tapauksissa morfologisiin ja kemiallisiin ominaisuuksiin perustuvat indeksit käyttäytyvät toisiaan vastaan. Moninaisista yhteyksistä huolimatta aika ja maaperän tekstuuri (lähtöaines) olivat tärkeimmät maannostumistekijät Suomessa. Topografialla oli vain pieni vaikutus podsoloitumiseen.

Avainsanat – Nyckelord – Keywords
Podsoli, maannosten luokittelu, World Reference Base for Soil Resources (WRB), spodic horisontti, maannostuminen, Biosoil

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HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

Tiedekunta/Osasto Fakultet/Sektion – Faculty Faculty of Agriculture and Forestry	Laitos/Institution– Department Forest Sciences	
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Tiivistelmä/Referat – Abstract

In Finland, soil classification in forestry has played only a minor role. However several international classification systems exist, one being the World Reference Base for Soil Resources (WRB) used in this study.

The criteria used in WRB to identify diagnostic properties, horizons and soil materials which are to classify a soil may not work everywhere. This is one reason why there is a continuous revision of international soil classification systems and a need to test them nationally. In Finland problems have been encountered with the criteria of international soil classification systems for defining a spodic B horizon. Empirical testing of soils classified as Podzols according to international soil classification systems has not been carried out in Finland. It is not known how many soil profiles considered to be Podzols actually have spodic B horizons, the official requirement for a soil to be classified as a Podzol. Soil classification systems provide detailed information of our soils and its properties in soil horizons. These soil properties are indicators of the degree of development in the soil.

Podzols, considered to be the most common upland forest soil type in Finland, are formed through a combination of the five soil formation factors: climate, parent material, topography, biotic and time. These factors determine which soil formation processes operate, which properties develop and then which soil type classes are formed. There have been few studies in Finland that have examined the degree of podzolization of podzolized soil profiles in relation to soil formation factors.

The aims of this study were therefore to determine the number of profiles (sampled from all over Finland) that were classified in the field as being Podzol that actually have diagnostic spodic horizons according to World Reference Base for Soil Resources (WRB). The diagnostic spodic criteria of WRB have six criteria and these are based on morphological properties (horizon thickness and Munsell dry/moist colours) and chemical properties (pH, organic carbon content and acid oxalate extractable Al and Fe contents) of the E and B horizon samples. In addition, the degree of podzolization of the profiles using a number of podzolization indices (Thickness index, Rubification index, Al+Fe index and Podzolization Development Index) was determinate and importance of various soil formation factors (climate, topography, parent material, biotic, time) on the degree of development of the profiles evaluated. The study was carried out using soil profiles covering the whole Finland. The soil profile data is from the BioSoil project, Natural Resources Institute Finland, Luke.

Study showed that field classification of Podzols based on morphological features (colour and thickness of the albic and spodic horizons) works well in Finnish soils. Except of albic colours criteria of morphological soil properties in spodic horizon are fairly equal with criteria of chemical soil properties. Podzolization intensity is poorly explained by individual soil formation factors (variables). Soil processes occur simultaneously and there is much interaction between/among soil formation factors. In certain situations, indexes based on morphological or chemical properties acts in an opposite way to each other. Nevertheless, time and soil texture (parent material) were the most important factors. Topography was noticed to have only a minor effect on podzolization.

Avainsanat – Nyckelord – Keywords
Podzol, soil classification, World Reference Base for Soil Resources (WRB), spodic horizon, soil formation, Biosoil

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1. INTRODUCTION

1.1 Background

From the end of the 19thcentury soil formation and soil classification have been research targets in soil science. The ability of the soil profile to reflect the history and development of the soil was recognized and the desire to classify soils appeared, as did classification throughout the natural sciences. However challenges to classify soils were met because of the continuous and variable nature of soils (Bockheim *et al.* 2005).

One of the earliest works concerning soil classification was made by Glinka (1914) when the main purpose was to arrange soil information and the processes behind them systematically. Later, classification systems developed as a result of increased understanding of soil properties, and soil classification focused more on them (Bockheim *et al.* 2005). Nowadays soils are classified according to national or international classification systems developed mainly to fulfil the needs of agriculture (Tamminen and Tomppo 2008). Several international classification systems exist, the most well-known being the FAO-Unesco Soil map of the world (FAO-Unesco 1990), the World Reference Base for Soil Resources (IUSS Working Group WRB 2007) and the Soil Taxonomy (Soil Survey Staff 1975). In addition, some national soil classification systems are applicable internationally, e.g. Canadian system (Soil Classification Working Group 1998). These international soil classification systems are not meant to replace national soil classification systems but rather to function concurrently and to facilitate the communication of soil information among countries which may have different national soil classification systems (Nachtergaele *et al.* 2000, Deckers *et al.* 2002). However, the criteria used to identify diagnostic properties, horizons and soil materials which are to classify a soil may not work everywhere. This is one reason why there is a continuous revision of international soil classification systems and a need to test them nationally.

Most pedogenic soil classification systems are based on soil properties that are the result of soil processes driven by a combination of soil formation factors operating at the location. Therefore the soil name gives information about the prevailing soil properties, processes and factors. While a soil is often classified in the field (based on field observations and morphological properties), confirmation requires sampling and the determination of chemical and physical properties to identify properties, horizons and soil materials that are diagnostic of each soil type. By using diagnostic properties, horizons and soil materials, the continuum of soil across the Earth`s surface can be systematically classified.

According to these international pedogenically based classification systems, a soil is classified as a Podzol if it has a B horizon meets the requirements of a diagnostic spodic horizon. The aim of these requirements is to reflect the podzolization process - the eluviation and accumulation of Al and Fe sesquioxides in the B horizon. The Al and Fe oxides are products of weathering processes in the upper part of soil. The spodic B horizon has to contain two-fold as much acid oxalate extractable Fe and Al compared to overlying horizon (usually an E horizon). In WRB classification (IUSS Working Group WRB 2007) Podzols key out 12th in the taxonomic key (Table 1).

Table 1. Key of the WRB Reference Soil Groups up to Podzols (IUSS Working Group WRB, 2007)

Soil type	Explanation
Histosol	Soils with thick organic layer
Anthrosols	Soils with long and intensive agricultural use
Technosols	Soils containing many artefacts
Cryosols	Ice-affected soils
Leptosols	Shallow and extremely gravelly soils
Vertisols	Alternating wet-dry conditions, rich in swelling clays
Fluvisols	Floodplains, tidal marsh
Solonetz	Alkaline soils
Solonchaks	Salt enrichment upon evaporation
Gleysols	Groundwater affected soils
Andosols	Allophanes or Al-humus complexes
Podzols	Eluviation and illuviation

If the B horizon does not meet the diagnostic spodic horizon criteria, classification of soil proceeds to the following soil type classes (e.g. Arenosols, Cambisols, Regosols) in the taxonomic key. Thus, a soil may not be classified as a Podzol even though it is clearly podzolized, i.e. podzolization is ongoing and dominating process, and is considered a shortcoming of classifying Podzols (Slånberg and Hylander 2004).

In Finland, soil classification in forestry has played only a minor role. This is probably because of the extensive use of A.K. Cajander's forest site types (Cajander 1949) - a classification of site productivity and fertility based on the composition of the ground vegetation. The composition of the ground vegetation integrates and is a reflection of the soil properties and fertility.

Before there was sufficient information of soil formation, Frosterus (1924) classified Finnish soils in two major class one having chemical changes and second having physical changes. Both these classes were further divided to climatic and aclimatic soils. Podzols were placed in the first class in the climatic subgroup. Podzols were further divided according to humus layer. Podzols having mor as a humus layer were classified either to iron Podzols or humus Podzols. Podzols having mould as a humus layer were classified as mould Podzols.

Later, forests soils were studied by Aaltonen (1940, 1945). He divided Finland to different zones describing different stage of soil formation (podzolization). This was based on differences in soil age and climate noticed by development of E horizon (thickness, colour). According to these studies, younger coastal areas were less podzolized than other parts of Finland. Also other kinds of sorting considering soils were used, as division of soils into organic soils or mineral soils depending of the proportion of organic carbon (Aaltonen 1949).

More recently, so-called soil maps (maaperä kartta) have been produced (http://weppi.gtk.fi/aineistot/mp-opas/). The soil types in these maps are based on the type and texture of the soil parent material and not soil formation and superimposed over the 1:20 000 topography maps of Finland. One of the first attempts at producing a soil formation based soil map of Finland was the 1:2 000 000 soil map of Scandinavia produced in 1991 (Rasmussen *et al.* 1991). Soils of Norway, Sweden and Finland were mapped according to a modified FAO-Unesco soil classification system while the soils of Denmark were classified according to the US Soil

Taxonomy. Podzols were identified as the most typical soil type in Finland, covering 60% of the land area. However, the map - at least for Finland – has low accuracy due to lack of ground survey based data about soils under forested areas (Tamminen and Tomppo 2008). As a result of the UN-ECE ICP Forest program (http://icp-forests.net/), a systematic sampling, profile description and classification of the so-called level I forest plots was undertaken in the 1980s (Tamminen & Starr 1990) and again in 2006 as part of the BIOSOIL program (http://www.forestry.gov.uk/fr/infd-73udf3).

The suitability of the WRB and US Soil Taxonomy when classifying Podzols in Finland has been studied by Mokma and Yli-Halla (2003) and Mokma *et al.* (2004). A study with the intention to improve the suitability of the US Soil Taxonomy for Finnish conditions was published in 2000 (Mokma and Yli-Halla 2000). In this latter study the complexity of US Soil Taxonomy was noticed and a simpler version developed. In Finland problems have been encountered also with the criteria of international soil classification systems for defining a spodic B horizon. The criteria have been criticized because soils that are clearly podzolized do not necessarily meet the criteria of the diagnostic B horizon (Mokma *et al.* 2004, Tamminen and Tomppo 2008). Although criticism concerning user-friendliness and suitability of international soil classification systems exist, these systems provide detailed information of our soils and its properties in soil horizons. These soil properties are indicators of the degree of development in the soil.

The degree of podzolization can have an effect on the forest growth. For example Podzols in Lapland have often been observed to have developed an ortstein layer, which weakens the movement of soil water resulting in water logging of the rooting zone and reduced tree growth especially in rainy periods (Ritari and Ojanperä 1984). Information obtained from the soil classification and nature of the B horizon can be utilized in environmental research such as determining the soil's ability to retain pollutants and rural waste waters (Gustafsson *et al.* 1998), as well as nutrients (Sauer and Juste, 1994). Soil acidity, which is one of the criteria used in defining a spodic horizon, affects the cation exchange capacity and also retention of anions, such as phosphates. Righi *et al.* (1997) proposed that changes in clay mineralogy, specifically the enrichment of smectite, in Finnish Podzols are related to soil age. Smectite has a relatively high cation exchange capacity and therefore a positive impact on tree growth and prevention of soil acidification.

Thus the degree of soil development affects the properties of the B horizon and when it is a spodic horizon or not. The influence of soil formation factors, especially time, on the degree of podzolization has been studied earlier in Finland (Jauhiainen 1972, Koutaniemi *et al.* 1988, Starr 1991, Petäjä-Ronkainen 1992, Mokma *et al.* 2004). However, these studies have been limited to a few sites. This study covers the whole of Finland and thereby it was hoped that the role of all five soil formation factors (climate, topography, parent material, vegetation, and time) could be more fully studied.

1.2. Podzols and Podzolization

Podzols (or Spodosols in the US Soil Taxonomy) are probably the most studied soil type in the world and theories about the podzolization process have been widely considered (Buurman 1984, Lundström *et al.* 2000a). It is known that Podzols are the prevailing soil type in the northern latitudes, where they are associated with the boreal climate zone and coniferous forests (taiga) thus considered as zonal soils. Podzols cover approximately 485 million hectares of world`s surface, but are also found in tropical areas (intrazonal Podzols), although covering considerably less area (approximately 10 million hectares) of the Earth`s surface (Driessen *et al.* 2001).

The word podzol is derived from the Russian words “pod” meaning under and “zola” meaning ash Ponomareva (1964). Podzols usually develop in acidic parent material although D`Amingo *et al.* (2008) found different degrees of podzolization in mafic and ultramafic parent materials. As a result of podzolization (weathering, eluviation and illuviation of aluminium and iron) a typical Podzol profile is formed (Figure 1).

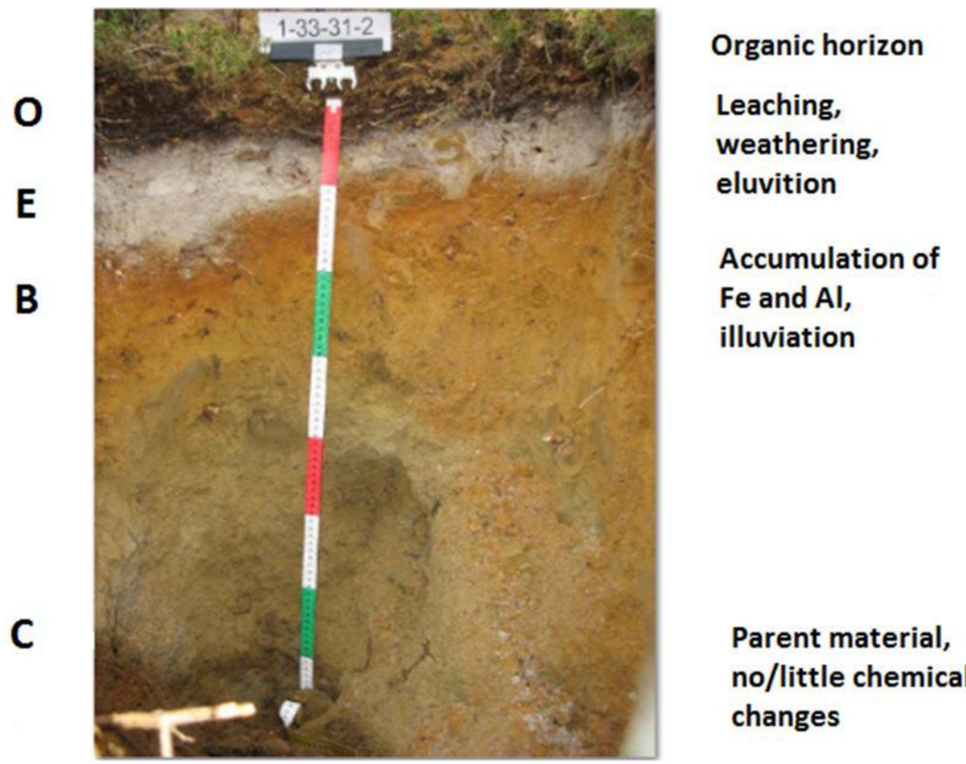

Figure 1. A photograph of a typical Podzol profile having distinct O, E, B and C horizons. Source: BioSoil database (LUKE, Natural Resources Institute of Finland).

The colour of the ash grey E horizon is because of the weathering of mafic minerals, enrichment of quartz and loss of iron oxides (Alalammi 1990, Yli-Halla *et al.* 2006) Depletion of weatherable minerals like micas (biotite), amphiboles, chlorite and pyroxenes occur in E horizon results in the enrichment of quartz E horizon (Lundström *et al.* 2000b). Some weathering also occurs in the upper part of the B horizon (Lundström *et al.* 2000a, Yli-Halla *et al.* 2006).

The Al and Fe oxides released by weathering in the surface soil are transported downwards where they accumulate to form the B horizon. The B horizon has dark, reddish to brown colour (Lundström *et al.* 2000a) caused by accumulation of iron oxides (Alalammi 1990). Aluminium oxides show an even stronger accumulation in the B horizon than iron but because aluminium oxides are colourless the enrichment is not observed by eye (Barrett and Schaetzl 1992**).** The accumulation of oxides in the B horizon increases specific surface area thus increases anion retention during podzolization (Karltun *et al.* 2000, Slånberg and Hylander 2004, Väänänen *et al.* 2008). Organic material typically also accumulates in the B horizon (Lundström *et al.* 2000a).

The boundary between the B and C horizons is often gradual and as a transitional BC horizon may be identified. The C horizon is the parent material, the material from which the soil profile has developed (Alalammi 1990). The C horizon is light coloured because of the lack of soil formation products: iron and aluminium oxides and organic matter (Lundström *et al.* 2000a) and only exhibits signs of physical alteration (Bridges 1989).

Podzolization refers to the eluviation and illuviation of aluminium and iron sesquioxides. The transportation mechanism of the Al and Fe from E horizon to the B horizon is, however, debated in the literature (Lundström *et al.* 2000a). Two major theories of podzolization are identified: the classic theory podzolization (Ponomareva 1964, Petersen 1976) and the recent inorganic colloidal sol theory (Andersson *et al.* 1982). In the classic theory the downward movement of the aluminium and iron from upper E horizon occurs as chelated organo-metallic complexes. Organic acids formed from the decomposition of litter chelate with the Al and Fe ions released during weathering of the primary minerals to form soluble organo-metallic complexes. As the soil solution gets enriched with these complexes and becomes saturated, these Al- and Fe organic complexes start to precipitate onto the grains in the B horizon. Evidence for this classical theory of podzolization was reported by Van Hees *et al.* (2000).

In the inorganic colloidal sol theory of Andersson *et al.* (1982), Al, Fe and Si moves downwards as inorganic colloidal sols. The aluminium exists as imogolite-type-material (ITM) (Lundström *et al.* 2000a), that is well-ordered, paracrystalline imogolite and less ordered noncrystalline proto-imogolite allophane (Gustafsson *et al.* 1995). Gustafsson *et al.* (1999) have found imogolite and proto-imogolite allophane in the B horizon of Swedish Podzols. Lundström *et al.* (2000b) consider that proto-imogolite cannot precipitate in E horizon because of the low pH. However, Buurman and van Reeuwijk (1984) have argued against the inorganic colloidal sol theory and consider that the imogolite (Al) and ferrihydrite (Fe) found in the B horizon are the result of the microbial degradation of organo-metallic complexes.

There is also evidence that the imogolite found in B horizons is formed in situ in Bs, BC and C horizons (Ugolini and Dahlgren 1991).

However, podzolization probably occurs through a combination of both theories, with the accumulation of Al and Fe as organic complexes more common in the south and as inorganic sols (imogolite) in the north (Gustafsson *et al.* 1995, Van Hees *et al.* 2000, Lundström *et al.* 2000b). Wang *et al.* (1986), working in Canada, stated that this difference is probably the result of the greater abundance of organic material in the soil in southerly latitudes. Gustafsson *et al.* (1995) and Pohjola and Räisänen (1998) noticed that transportation of aluminium is prevailing when compared to illuviation of iron in northern areas.

Podzolization has also been studied in Finland. The study by Yli-Halla *et al.* (2006) presents evidence supporting the classical theory of podzolization with no significant amounts of imogolite type material being found. However, Pohjola and Räisänen (1998) have found inorganic aluminium in Finnish soils.

1.3. Soil formation factors

Soils, including Podzols, are formed through a combination of the five soil formation factors defined by Jenny (1941): climate, parent material, topography, biotic and time. These factors determine which soil formation processes operate, which properties develop and then which soil type (class) are formed (Figure 2).

Podzolization is strongly influenced by climate. In podzolized areas rainfall exceeds evapotranspiration allowing water to infiltrate the soil and leach compounds from topsoil to lower parts (Alalammi 1990, Lundström *et al*. 2000a). Podzols do not exist in dry areas (Mokma and Buurman 1982). Schaetzl and Isard (1996) noticed that thicker snow cover assists podzolization by allowing more melting water to infiltrate the soil and preventing soil frost or freeze-thaw activity.

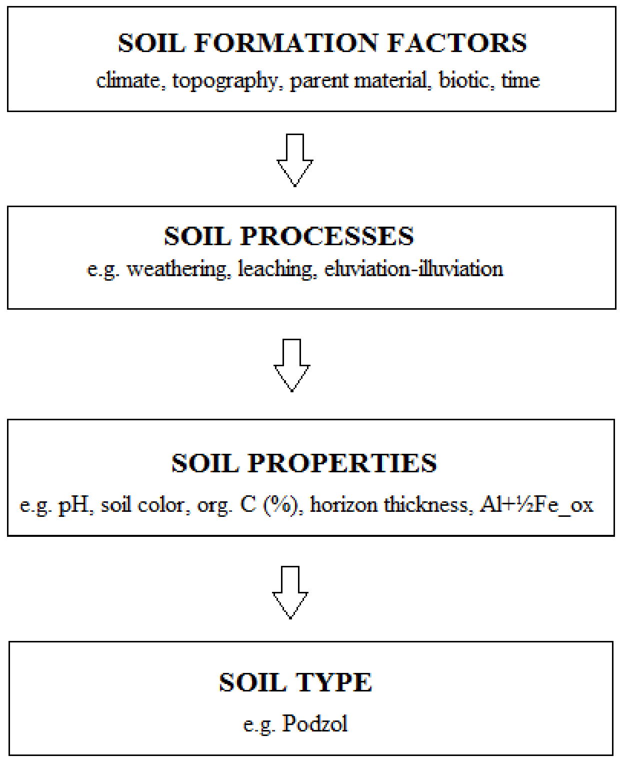

Figure 2. Relationship between soil formation factors, soil processes, soil properties and soil type affecting to soil classification.

The parent material of Podzols is usually sand or sandy till (Lundström *et al.* 2000a), which allows water to drain freely through the soil. Podzols do not develop in soils with permanent water saturation (Mokma and Buurman 1982). According to Schaetzl and Isard (1996) Podzol profiles requires a longer time to develop in loamy or fine-textured material. However, Wang and Rees (1980) found that sandy till as parent material intensify development of Podzols when comparing to outwash, alluvium or marine sand. Also the amount of carbonate, base cations and ultramafic material play a role in podzolization; with higher amount of these in the parent material slowing down the podzolization process (Lundström *et al.* 2000a). The parent material for most boreal Podzols is derived from Precambrian granites and gneiss (Lundström *et al.* 2000a, Sanborn *et al.* 2011). These areas have low mafic mineral contents (Mälkki 1998). In Finland the Precambrian bedrock is formed 3000-1500 million years ago (Tikkanen 2002).

Topography influences to podzolization especially through soil water content and movement and temperature. Lower slope positions gain more runoff water that can infiltrate to the soil when compared with the upper parts of the slope and south facing slopes have more intensive podzolization because of the greater amount of radiation they receive. Since many chemical reactions increase with temperature, weathering rates tend to be faster on south facing slopes.

Podzols usually occur under coniferous forests and shrubs which produce acidic litter (Lundström *et al.* 2000a). Plants, such as coniferous trees, have symbiotic ectomycorrhizal fungi attached to their roots. The fungi exude low-molecular weight organic acids which are active in the weathering of minerals in E horizon and therefore have a major influence to podzolization (van Breemen *et al.* 2000).

According to Jenny (1941), the thickness, intensity and number of horizons are signs of soil maturity and increase with time. Of the soil formation factors, time is the only independent factor while other are more or less interlinked with each other (Fitzpatrick 1971). The influence of soil age to podzolization can be studied with chronosequences (Jauhiainen 1973, Starr 1991), i.e. using space for time and ensuring as far as possible that the other soil formation factors are constant (Barrett and Schaetzl 1992). Such studies show that the degree of podzolization, the enrichment of aluminium and iron in the illuvial horizon in particular, increases with soil age (Lundström *et al.* 2000a).

1.4. Research aims

Podzols are considered to be the most common upland forest soil type in Finland (Rasmussen *et al.* 1991). Other soil types that occur are Histosols, Gleysols, Arenosols, Cambisols, Regosols and Leptosols (Lilja *et al.* 2006). However, empirical testing of soils classified as Podzols according to international soil classification systems has not been carried out in Finland. It is not known how many soil profiles considered to be Podzols actually have spodic B horizons, the official requirement for a soil to be classified as a Podzol. Also there have been few studies in Finland that have examined the degree of podzolization of podzolized soil profiles in relation to Jenny’s soil formation factors. The aims of this study were therefore to:

- Determine how many of 116 profiles sampled from all over Finland that were classified in the field as being Podzol actually have diagnostic spodic horizons according to World Reference Base for Soil Resources (WRB)
- Determine the degree of podzolization of the profiles using a number of podzolization indices (Thickness index, Rubification index, Al+Fe index and Podzolization Development Index)
- Evaluate the importance of various soil formation factors (climate, topography, parent material, organisms, time) on the degree of development of the profiles. In order to evaluate the effect of time, soil age was determined for each soil profile.

It was hypothesized that:

- Some of the profiles classified in the field as Podzols would not meet the criteria of a diagnostic spodic horizon, and
- The degree of podzolization would be more strongly correlated to certain of the surrogate soil formation factors (profile database variables) than others.

2. MATERIAL AND METHODS

2.1. Study plots and profiles

The study was carried out using soil profiles covering the whole Finland. Finland's mean annual precipitation in Finland ranges from 400 to 750 mm being the highest in southern and eastern parts of the country, and the mean annual air temperature ranges from < -2 °C in northern areas to over +5 °C in most southern parts (Tilastoja Suomen ilmastosta 1981-2010). Mean annual evapotranspiration ranges from < 450 mm in south Finland to < 100 mm in most northern parts (Alalammi *et al.* 1987). The climate is humid, with precipitation exceeding evapotranspiration (Tilastoja Suomen ilmastosta 1981-2010). According to the Köppen-Geiger climate classification most of Finland belongs to *Dfc* (subarctic or boreal) climates but the coastal areas in the south has *Dfb* (warm summer/hemiboreal) climate (Peel *et al.* 2007). The soil profile data is from the BioSoil project, Natural Resources Institute Finland, Luke (formerly the Finnish Forest Resource Institute, METLA). The BioSoil project was carried out as part of ICP Forests (International Cooperative Programme on the Assessment and Monitoring of Air Pollution Effects on Forests; icp-forests.net/) and EU Forest Focus programme (Tamminen and Ilvesniemi 2013). The aim of the project was to provide information about soil types, texture, and changes in carbon, nutrients, acidity and heavy metals in the forest soils of Finland. The data was collected from the network of the so-called ICP Forests Forest Focus Level I plots in 2006-2007 which were first sampled in 1986-1995 (Tamminen and Starr 1990).

The Forest Focus Level I plots are located systematically on 16 km x 16 km grids throughout most part of Finland with exception of Lapland where a 24 km x 32 km grid was used. In Finland, BioSoil database includes 631 plots (Figure 3). In the whole of Europe the total number of Level I plots is around 6000 (icp-forests.net/).

A detailed description of all the data and variables collected at each plot is given in BioSoil Kuvio- ja puusto-ohjeet (2006). The site description included information of latitude, longitude, elevation (m, asl.), soil moisture, slope aspect, topographical position, bare rock cover (%), soil type, parent material, content of coarse fragment (%), soil texture, site type and Sphagnum cover (%).

Coordinates of the plots were identified with certain formulas given in Biosoil Field Protocol (Tamminen 2006). In the field plots were located with map and GPS. If plot had heterogeneous site type or vegetation figures, then plot was divided to several parts. One main figure, having > 50 % coverage of the plot or covering the centre of the plot, was selected for sampling (Tamminen 2006). Site type classification (OMT, MT, CT, CLT) was performed according to Cajander (1949) forest site type theory. Tree measurements and sampling from under vegetation were executed according to Biosoil Field Protocol.

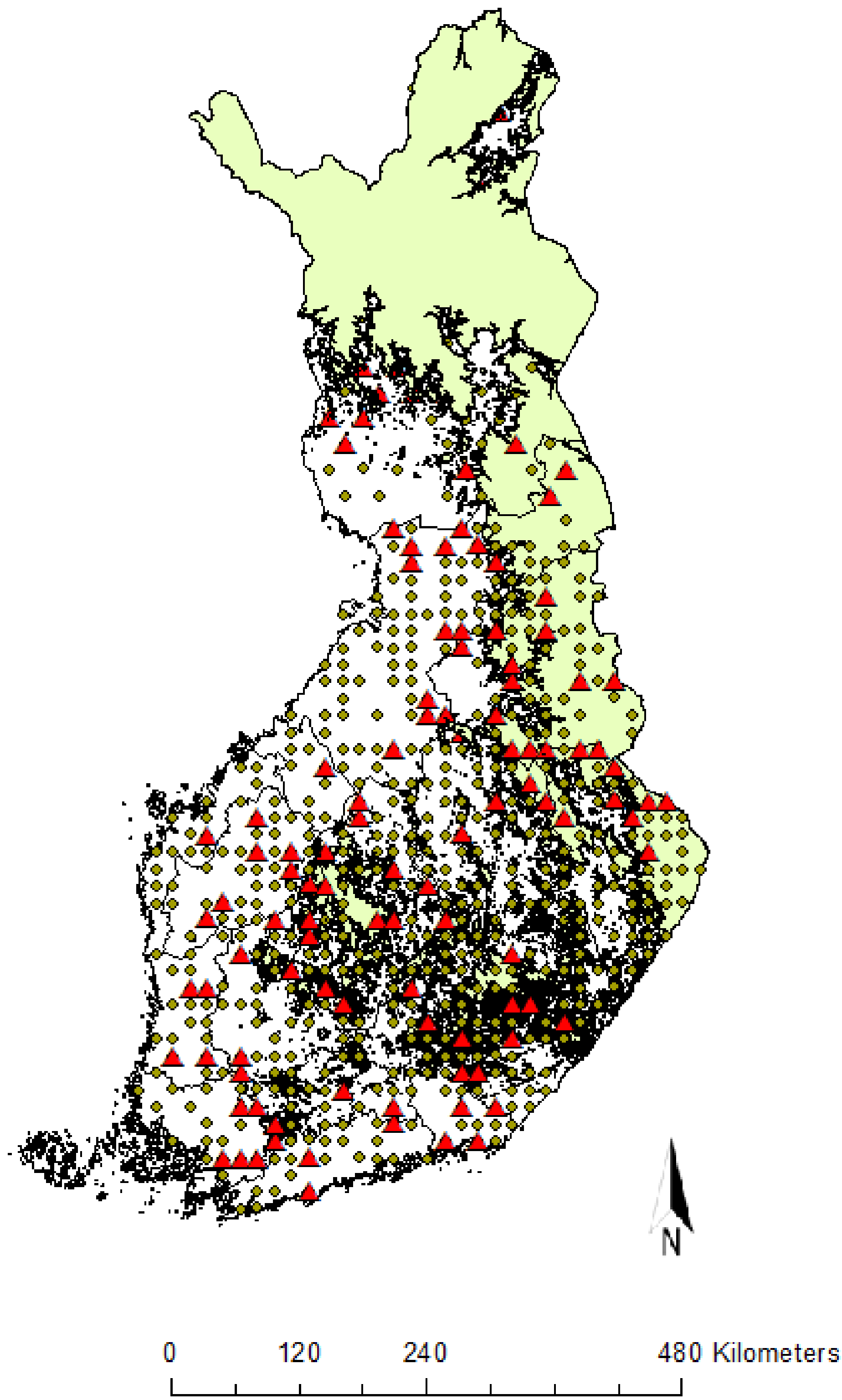

Figure 3. Map of the locations of 636 BioSoil profiles (green circle). Profiles (n = 116) classified as Podzols in the field and used in this study are marked with red triangles. Supra-aquatic areas are shaded green.

Each circular plot for soil sampling has a radius of 11.28 m and thus 400 m^2 in area (Figure 4). Thickness of soil horizons, stoniness of the soil and mean grain size in mineral soil were identified before the actual soil sampling from multiple places: centre of the plot and also 10 m from the centre towards north, east, south and west. Then ten sample points (radius = 1 m) for sampling were systematically located around the plot centre at 9 m distance and 36°. The directions for sample plots were 18, 54, 90, 126, 162, 198, 234, 270, 306 and 342 degrees. These sample points were numbered towards clockwise.

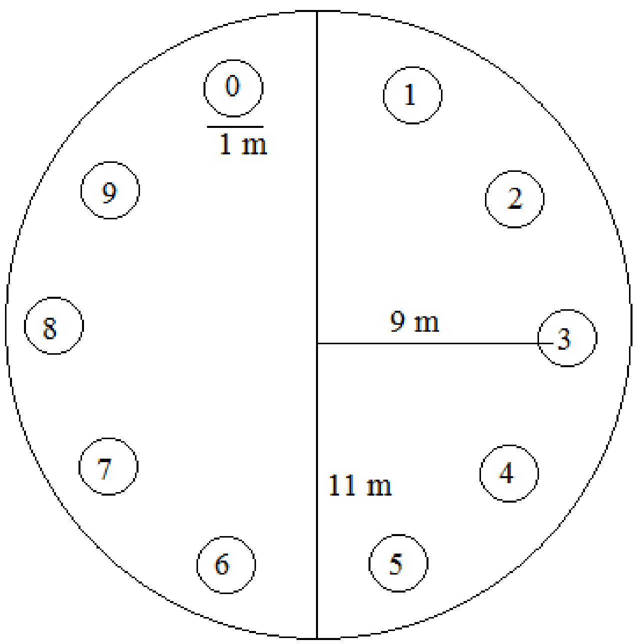

Figure 4. Level I sample plot design. Circular plot has 11 m radius. Ten sample points (radius = 1 m) for sampling were numbered clockwise and systematically located around the plot centre at 9 m distance and 36°. One of the ten sample points was selected for excavation of soil pit and sampling by soil horizon (see text).

Two sets of soil samples were taken: so-called cm-samples and horizon samples. The horizon samples are the ones used in this study. While the cm-samples were taken from the ten sample points by fixed-depth layers, the horizon samples were taken from one of the ten sample points after excavating a soil pit. For the cm-samples the litter and moss layer (Ol) of the organic horizon (mor or moder types) was removed and the remaining humus layer (Of + Oh) taken for analysis. If the thickness of the humus layer exceeded 10 cm then the 10-20 cm layer was also sampled and, if necessary also the 20-30 cm layer. Mineral soil was sampled from 0-10, 10-20, 20-40 and 40-80 cm layers. Stoniness of the soil was measured according to Viro`s rod penetration method (Viro 1958).

For the horizon samples, one of the ten sampling points was selected for excavating a soil pit. Selection of which point to excavate was based on location (not too close to a tree, stone/boulder or other object, and so on) and, based on experience of the sampling crew, considered representative of the plot. The size of the soil pit was at minimum 40 x 40 cm and reached into the C-horizon (typically 60 to 80 cm deep). For the soil description, the profile was photographed, described according to FAO-ISRIC Guidelines (1990) and then classified in the field based on the World Reference Base of Soil Resources (FAO 1998) classification system. An attempt was made to identify the soil type and the main soil properties/horizons and diagnostic properties/horizons. Soil from the organic layer, the upper mineral soil horizon (usually E horizon or then an A horizon), and the B horizon (upper 10 cm if thicker than 10 cm) was then sampled. In some cases an upper and lower B horizon was sampled. Details of the profile description and soil sampling are given in the BioSoil Field Protocol (Tamminen 2006). The field form used to make the profile description is presented in Appendix I.

2.2. Selection of profiles from BioSoil database

For the purposes of this study all profiles classified in the field as Podzols (n= 165) were initially selected (Figure 5). Further selection was based on whether acid oxalate extractable Fe and Al data were available (123 profiles). Acid oxalate extractable Fe and Al contents are included in the chemical definition of the diagnostic spodic horizon. One of these 123 profiles one not have a B horizon and a further two profiles did not have an E horizon. These three profiles were therefore also excluded from further study as soil classification of Podzols according to WRB requires data on the E and B horizons as it is necessary to determine if they are, respectively, albic and spodic.

Finally, only those profiles having glacial till or glaciofluvial deposits as parent material were included. As a result the four profiles with quaternary clay and silt parent material were excluded. Such fine textured parent material would hinder drainage and therefore the eluviation-illuviation process central to the podzolization process. Accordingly, a final set of 116 profiles classified in the field as Podzols was selected to determine if they could officially be classified as Podzols according to WRB (Figures 3 and 6).

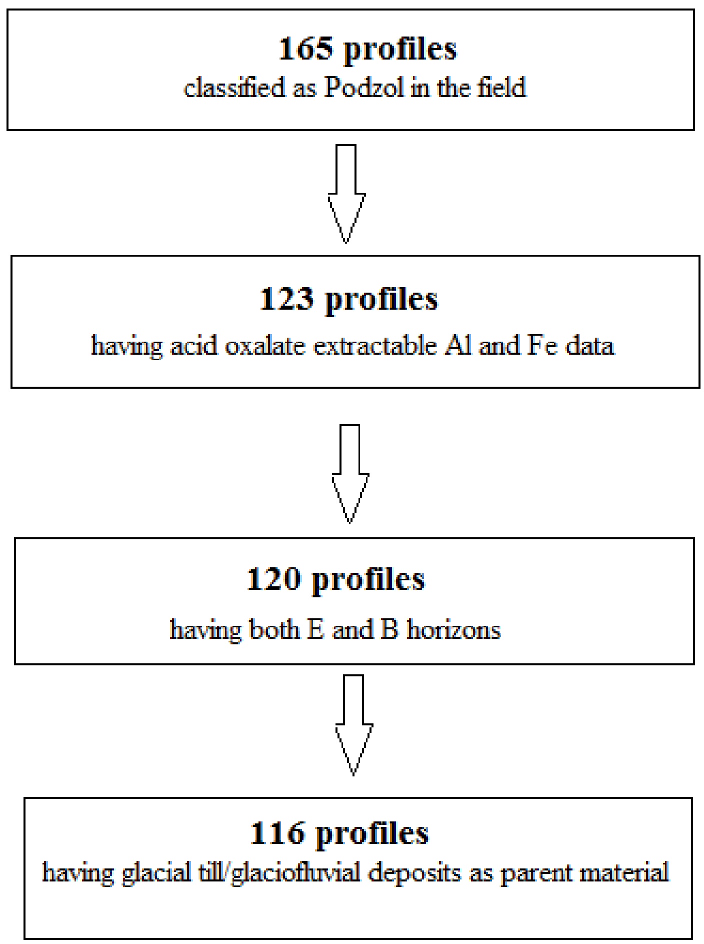

Figure 5. Selection of study profiles used in this study.

The selected soil profiles were distributed all over the Finland and in both supra- and sub-aquatic areas, i.e. areas that have respectively always been above water or have been under water during different stages of the Baltic Sea.

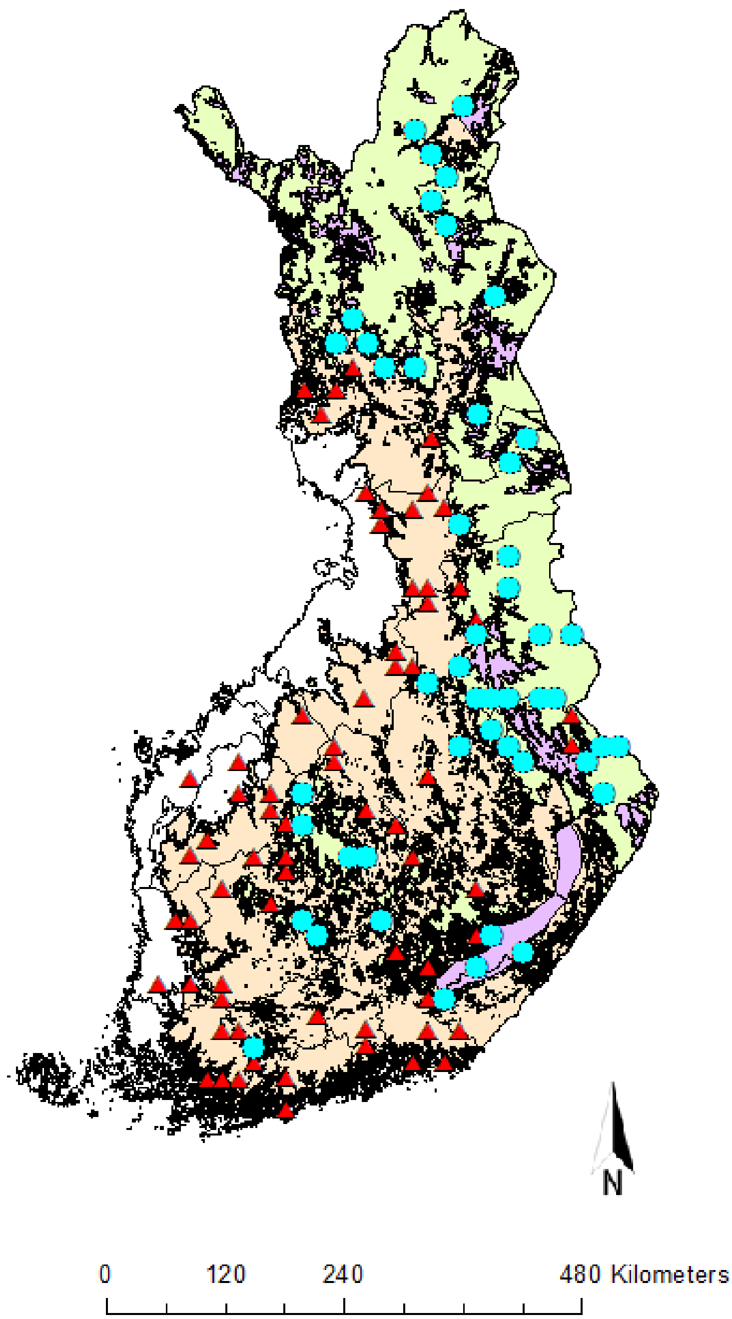

Figure 6. Locations of soil profiles (n=116) used in this study. Red triangles are profiles that are located in sub-aquatic areas and blue circles in supra-aquatic areas. Green shaded areas indicate supra-aquatic areas, beige coloured areas indicate under the Yoldia Sea and the Ancylus Lake and white areas indicate areas under the Littorina Sea. Areas coloured in purple indicate areas under local ice lakes.

2.3. Soil analysis and spodic horizon properties

In this Master`s thesis the diagnostic spodic criteria of the World Reference Base for Soil Resources (WRB) 2007 updated version (IUSS Working Group WRB 2007) has been used. Accordingly, there are six criteria, some of which are alternatives, and these are based on morphological properties (horizon thickness and Munsell dry/moist colours) and chemical properties (pH, organic carbon content and acid oxalate extractable Al and Fe contents) of the E and B horizon samples.

Soil colour was determined using Munsell Soil Colour Charts (Munsell Soil Colour Charts 2000). Both field moist and dry colour was determined. Soil samples were dried and sieved (< 2 mm). Soil pH was measured in 0.01 N CaCl2 solution. This value was converted to a pHwater value by adding 0.5 pH units to the measured 0.01N CaCl2 value (Mälkönen 2003). Organic carbon content was measured with Leco CHN 600 elemental analyser. For acid oxalate extractable Al and Fe content measurement the sample was shake in 0.2 M Acid ammonium oxalate solution (pH 3) and then solution was measured with Inductive Coupled Plasma Atomic Emission Spectrophotometer (ICP-AES). The acid-ammonium oxalate extracts amorphous/non-crystalline (”active”) forms of aluminium and iron (McKeague and Day 1965). Organic complexed forms of Al and Fe can be extracted with Sodium Pyrophosphate Extraction (Schwertmann 1973) and Dithionite–Citrate–Bicarbonate extraction measures free, non-silicate forms of Al and Fe in the soil. However, oxalate extractable contents of Al and Fe are used in many studies (Tamm 1922, McKeague and Day 1965, Gustafsson *et al.* 1995, Gustafsson *et al.* 1998, Mokma *et al.* 2004, Yli-Halla *et al.* 2005). The optical density of the oxalate extract (ODOE) was not determined. Details of the laboratory methods used are explained in the laboratory manual of ICP forest programme (http://www.icp-forests.org/pdf/FINAL_soil.pdf).

The morphological and chemical analysis data of the E and B horizons of each profile were evaluated to determine if the horizons were respectively albic and spodic diagnostic horizons. Presence of albic horizon is included in morphological criteria of spodic horizon.

2.4. Indexes of podzolization

For each profile the degree of podzolization was quantified using four indexes: E horizon thickness, B horizon rubification, B horizon Al+Fe indexes and podzolization development index (PDI) (Birkeland 1999, Starr 1991).

The thickness index was calculated by dividing the thickness of the E horizon by the maximum thickness of all the profiles and then subtracting the values from 1. When a profile had two E horizon samples (an upper and lower E horizon), the thicknesses were summed and used in the calculation of the thickness index. The subtraction of the standardized E horizon thicknesses from 1 was done after evaluating scatter plots and correlations showing the relationship between the E horizon thickness and the B horizon rubification and Al+Fe indexes. It was only by subtracting the standardized E horizon thickness values from 1 that the E thickness index became positively correlated with both the rubification and Al+Fe indexes and thus augment the other two indexes making up the PDI value. Thus, thickness index values closer to 1 indicate thinner but more strongly eluviated (developed) E horizons. This, of itself, indicates that a relatively thick eluviated surface horizon initially develops and then the lower boundary shifts towards the surface resulting in a thinning of the developing E horizon during podzolization, Aaltonen (1952) noted that there is a tendency for the thickness of the surface eluviated horizon to be thicker in younger (coastal) soils than in older soils.

The rubification index (Buntley and Westlin 1965) was calculated by subtracting CDE (Colour Development Equivalent) value of the E horizon from CDE value of the B horizon and standardizing the results. The CDE values were calculated as the product of the moist Munsell colour hue and the chroma, where hue pages 5Y, 2.5Y, 10YR, 7.5YR, 5YR, 2.5YR, 10R and 5R were given the numerical values of 1, 2, 3, 4, 5, 6, 7 and 8, respectively, i.e. in order of increasing redness (decreasing yellowness). Increasing chroma represents increasing colour intensity. The differences in the E and B horizons CDE values were then standardized using the maximum difference to give the profile rubification index. A value closer to 1 indicates increased redness (iron oxide accumulation) of the B horizon relative to that of the E horizon (Birkeland 1999). If the profile had an upper (B1) and lower

(B2) B horizons, then the CDE value of the B1 horizon was selected. Similarly if there were two E horizons then the CDE value of upper E horizon was used.

For the Al+Fe index the Al+½Fe_{ox} (%) value of the E horizon was subtracted from the Al+½Fe_{ox} (%) value of the B horizon, and the difference divided by the maximum difference of all profiles. This standardized index expresses the degree of the Al and Fe eluviation-illuviation process, with values closer to 1 indicating greater enrichment of Al and Fe oxides in the B horizon. It is the same index used by Starr (1991), except that dithionite extractable Fe contents were used in his study.

The PDI was calculated as the sum of the standardized thickness, rubification, and Al+Fe indexes. In theory, the PDI index thus can vary from 0 (least) to 3 (most developed/podzolized).

2.5. Quantification of soil formation factors and profile age

Variables from the BioSoil site description database (BioSoil Kuvio- ja puustotiedot, Maastotyöohjeet 2006) and estimated profile age were used as to quantify the soil formation factors of Jenny (1941) (Table 2), which was estimated from the location of the profile in relation to the Baltic shoreline history (see later) Seven of the variables were continuous variables and fourteen of the variables were categorical variables (Appendix II). Profile latitude, longitude and elevation were used as surrogate measures of climate. Both MAP and MAT tend to decrease with latitude and MAT with elevation (Tilastoja Suomen ilmastosta 1981-2010). The slope across the plot and its aspect affects the amount radiation (temperature) received. Slope position affects water balance of the site, with lower slope positions receiving more runoff and having higher water tables than upper slope positions. Sphagnum cover also describes the soil moisture status of site. Soil texture (silt %, sand %, coarse fragments %) and bare rock cover % are descriptors of the parent material factor. The site type (Cajanderian) is an indicator of the biotic soil formation factor as well soil moisture conditions and parent material. The independent soil formation factor of time is taken as the time since the deglaciation and emergence of the site above water due to the land uplift. The location and elevation of the plots were used to classify each profile as being either supra-aquatic or sub-aquatic. Supra-aquatic sites can be expected to be more podzolized than sub-aquatic sites because they have been exposed to a longer period of soil formation processes. Supra-aquatic areas mostly occur towards the north.

Table 2. Jenny's soil formation factors and BioSoil variables (continuous and categorical) used to quantify the influence of each factor on the degree of podzolization in the study. BioSoil variables in parentheses would have an indirect influence the soil formation factor concerned.

Soil formation factor	Biosoil variable
Climate	Latitude Longitude Elevation Moisture Slope aspect
Topography	Topographical position Slope aspect Moisture Sphagnum cover % (Elevation)
Parent material	Supra-/Sub-aquatic Silt % Sand % Coarse fragments % Mean grain size Parent material Bare rock cover % (Moisture) (Sphagnum cover %) (Site type)
Biotic	Site type Sphagnum cover % (Moisture)
Time	Soil age Young/old (Supra-/Sub-aquatic) (Elevation)

To estimate the age of each soil profile the location and elevation of the BioSoil plots in relation to the several stages of the Baltic Sea (Gluckert *et al.* 1993) and information on the date of deglaciation and lake isolation from multiple sources were used. It was assumed that the date of the lake isolation (lake become an independent from the Baltic Sea) was equal to soil age. The geological database Hakku (http://hakku.gtk.fi/) created by Geological Survey of Finland and GIS enabled supra-aquatic areas and areas under the Littorina Sea to be identified. The Hakku "Highest_shoreline_10 m" GIS layer was used to identify areas (plots) covered by the Yoldia Sea and the Ancylus Lake and thereby date other profiles. Sub-aquatic areas may have been under several stages of the Baltic Sea. These stages from oldest to youngest are: The Baltic Ice Lake, The Yoldia Sea, The Ancylus Lake and The Litorina Sea (Gluckert *et al.* 1993).The age limits (yrs, cal BP) for the various Baltic Sea stages (the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake and the Littorina Sea) used to date the soil profiles are presented in Table 3.

Table 3. Age limits (yr, cal BP) for the various stages of the Baltic Sea history. BIL = Baltic Ice Lake, YS = Yoldia Sea, AL = Ancylus Lake and LS = Littorina Sea. Data from Ojala & Palmu (2007) and, Walker et al. (2009).

BIL	YS	AL	LS
> 11700	11700-10700	10700-9000	9000-7500

In supra-aquatic areas podzolization has started after deglaciation (soil emerged from the ice sheet). Deglaciation in southwestern Finland was determined after Sauramo (1924). Deglaciation of East, South and Middle Finland was determined with data combined from multiply sources (Sauramo 1924, Alalammi 1990, Donner 1995, Lunkka *et al.* 2004, Pajunen 2004, Johansson and Kujansuu 2005) and deglaciation curves defined. Deglaciation in Northern Finland was determined mostly according to Johansson and Kujansuu (2005). North Finland was uncovered from ice about 10 000 years ago, ice melting last from western parts of Lapland (Lunkka *et al.* 2004).

In sub-aquatic areas profile ages were determined with data combined from multiple sources (Eronen and Haila 1982, Gluckert and Ristaniemi 1982, Gluckert *et al.* 1993, Mäkilä *et al.* 2013, Pajunen 2004, Saarnisto 1981, Salomaa 1981, Starr 1991) and average values for profile age were used. As a limit for highest shoreline for Yoldia and Ancylus Lake, approximately a line from Pori via Jyväskylä to Kajaani (Saarnisto 2000) was used. Sub-aquatic areas in the north side of that line were determined as areas under The Ancylus Lake except coastal areas under the Litorina Sea. Sub-aquatic areas in south of that line were classified as areas under Yoldia Sea if the elevation was sufficient.

All the age data was assembled in ArcGIS (version 10.2.4.) and the BioSoil plots were then located and approximate soil age determined.

2.6. Data handling and statistical analyses

Descriptive statistics (mean, median, standard deviation, minimum/maximum values, and variance) were calculated for soil properties used in classification, indexes describing intensity of podzolization and also for continuous and categorical variables indicating soil formation factors. For categorical variables frequencies were calculated. The relationships between the continuous variables indicating soil formation factors were expressed using Spearman`s correlation coefficients. Simple linear regression models were used to describe the influence of soil formation factors on the degree of podzolization. One-way ANOVA was used in testing for differences in podzolization between various categorical variables describing the soil formation factors when there were more than two categories. This was followed by Tukey`s multiple comparison test. In testing for differences in podzolization indexes between the dichotomous variables supra aquatic and sub aquatic areas and between young and old soil, the student t-test was used. A threshold P value (α) value of 0.05 was used to define significance. All statistics were performed with either Microsoft Excel 2010 or IBM SPSS statistics 22.

3. RESULTS

3.1. Diagnostic spodic B horizon

3.1.1. Soils classified as Podzols according to WRB

The six criteria used to identify a spodic horizon using the WRB 2007 updated version is given in Appendix III. Of the 116 profiles classified as Podzol in the field, the percentages that meet each of the criteria are presented in Figure 7. It can be seen that 100 %, 97 % and 100 % of them had B horizons that met criterion 1 (pH), criterion 2 (organic carbon content) and criterion 6 (thickness), respectively (Figure **7**). None of the profiles had a natric horizon (Criterion 4) or tephric material (Criterion 5), which are not relevant in Finnish soils anyway. Criterion 3 had the least number of profiles in agreement. 49 % of the profiles had E and B horizons that met criterion 3a (soil colour). 91 % of the profiles had B horizons that met criterion 3b (soil colour + Al+½Fe_{ox}).

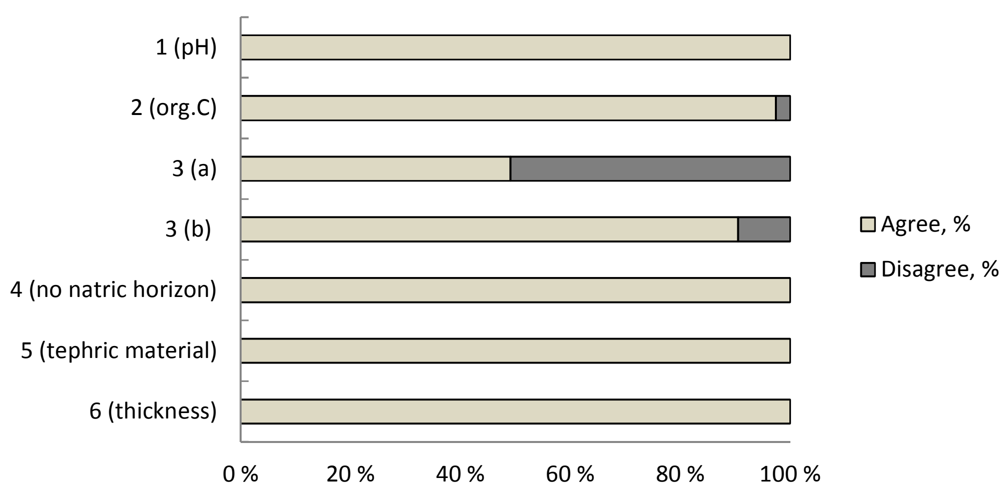

Figure 7. Percentage of the profiles (n=116) that meet each of the criteria for a spodic horizon defined according to WRB 2007 version.

To meet the criterion 3a, there has to be an overlying albic horizon and the B horizon immediately underlying it has to meet one of four possible colour criteria. Only 53 % of the profiles had an albic horizon (Table 4). The E horizons in the other profiles had too low moist/dry values, that is, the colour was too dark. The criteria used to identify an albic horizon using the WRB 2007 updated version is given in Appendix IV.

Table 4. Proportion of the study profiles (n=116) that meet WRB spodic horizon criteria 3 in addition to already meeting spodic horizon criteria 1, 2 and 6. To meet spodic criteria 3, the B horizon has to meet one or both of 3a or 3b. See Appendix III and IV for further details of criteria.

Criterion	Agree		Disagree	
	n	%	n	%
3a Albic	61	53	55	47
3a i Albic + 5YR or redder	12	10	104	90
3a ii Albic + 7.5YR + value ≤ 5 + chroma ≤ 4	54	47	62	53
3a iii Albic + 10YR or neutral + value and chroma ≤ 2	0	0	116	100
3a iv Albic + 10YR 3/1	0	0	116	100
3a Albic + spodic colour (i,ii,ii or iv)	57	49	59	51
3b With or without albic horizon and any of:	116	100	0	0
3b i Cemented by organic matter	n/a	n/a	n/a	n/a
3b ii Cracked coatings	n/a	n/a	n/a	n/a
3b iii Spodic colour + iii Al_{ox}+½Fe_{ox}	105	91	11	9
3b iv ODOE of ≥0.25	n/a	n/a	n/a	n/a
3b v Fe lamellae	n/a	n/a	n/a	n/a
3a and/or 3b	106	91	10	9

n/a data not available

49 % of the horizons meet the part 3a criterion, thus have albic and spodic colours (Figure 8). Within that group is horizon 3222, where only the lower B meets the 3a spodic criterion. Upper B horizon does not meet the colour criterion. However it is classified as Podzols.

Figure 8. A soil profile having an albic horizon and a spodic colour according to WRB. Source: BioSoil database (Natural Resources Institute of Finland).

Only 10 % of the profiles meet the criterion 3a i. Three of the profiles (853, 3615, and 3649) had duplicated values for colour but only one of the colour values met the3ai criterion. Most of the profiles (90%) met the colour criterion 3a ii (Figure 9). Four profiles (853, 3222, 3615, and 3649) had two B horizon samples (upper and lower B) but one of them met the colour criterion 3a ii. None of the profiles met the criteria 3a iii and 3a iv.

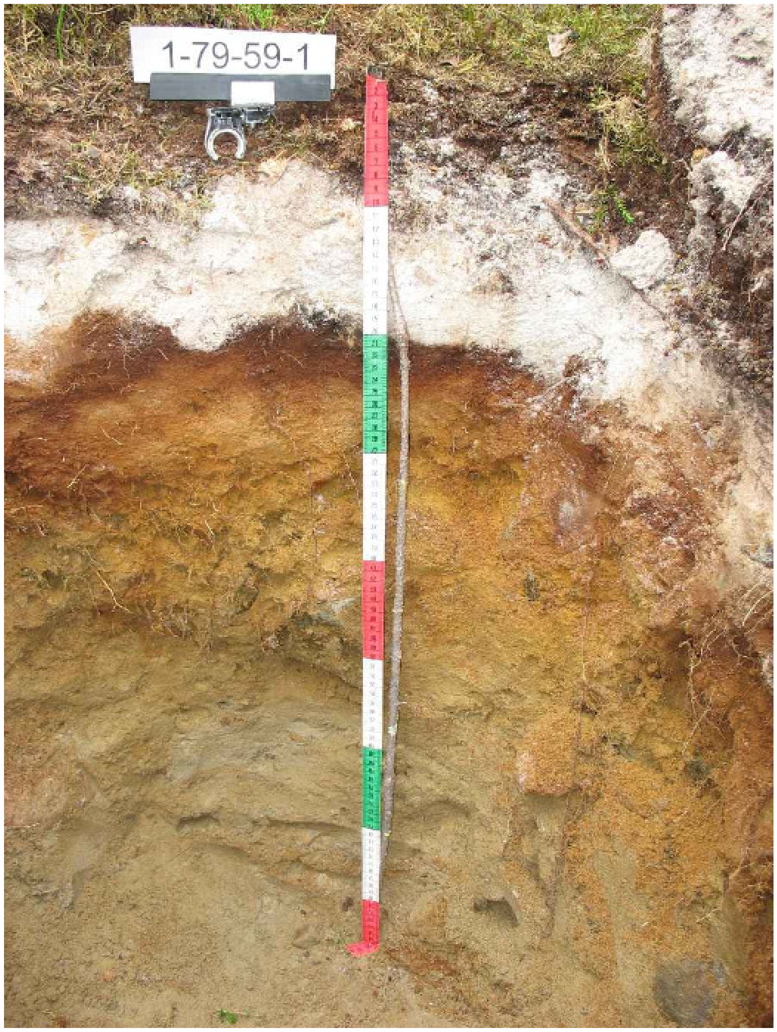

Figure 9. Most of the profiles had an upper B horizon with a colour meeting the WRB (2007) spodic criteria 3a ii. Photos from BioSoil database (Natural Resources Institute Finland).

To meet the criterion 3b, the B horizon has to have a certain colour criteria and one of four chemical criteria (Figure 10). As there is no data available on cementation by organic matter, presence of cracked coatings, ODOE values or Fe lamellae, criterion 3bi, 3b ii, and 3b iv can be ignored and only criterion 3b iii considered. According to this criterion, a B horizon has to have at least 0.5 % of oxalate extractable Al + ½Fe and at least more than one-half of oxalate extractable Al + ½Fe compared to overlying horizon (Appendix III). This criterion is clearly trying to describe the podzolization process of eluviation-illuviation of Al + Fe oxides within the profile. According to criterion 3b iii, 91 % of the B horizons met the required value for a spodic horizon.

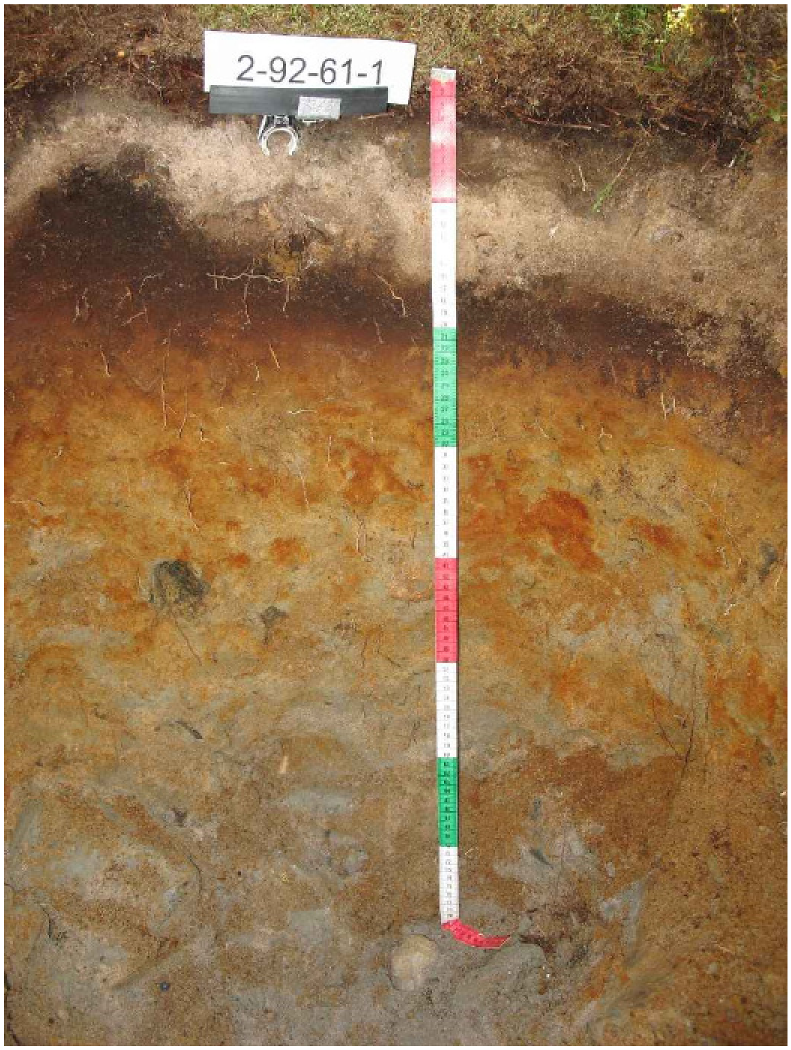

Figure 10. Soil profile meeting the 3b criterion (spodic colour + illuviation and amount of oxalate extractable $Al+Fe_{ox}$). Source: BioSoil database (Natural Resources Institute of Finland).

Using the WRB 2007 definition of a spodic horizon, that is all six criteria, then 106 (91 %) of the 116 profiles classified as Podzols in the field could actually be officially classified as Podzols. If the studied profiles are classified with the morphological (criterion 6, thickness of B horizon) and chemical properties (criteria 1, 2 and 3b iii), then 88 % of the profiles would be classified as Podzols. This is almost the two-fold the amount compared to results using only morphological properties and compulsory chemical methods as the criteria for soil classification.

3.1.2. Non-podzol profiles

Of the 116 profiles classified as Podzols in the field ten (9 %) did not have a spodic B horizon as defined by WRB 2007 and therefore should be re-classified (Table 4). All of these ten profiles were located in sub-aquatic areas (Figure 11).

The B horizon of seven out of these 10 profiles did not meet criterion 3a (albic horizon + spodic colour) or criterion 3b (spodic colour + $Al+Fe_{ox}$), and four did not meet the organic carbon criterion, criterion 2.

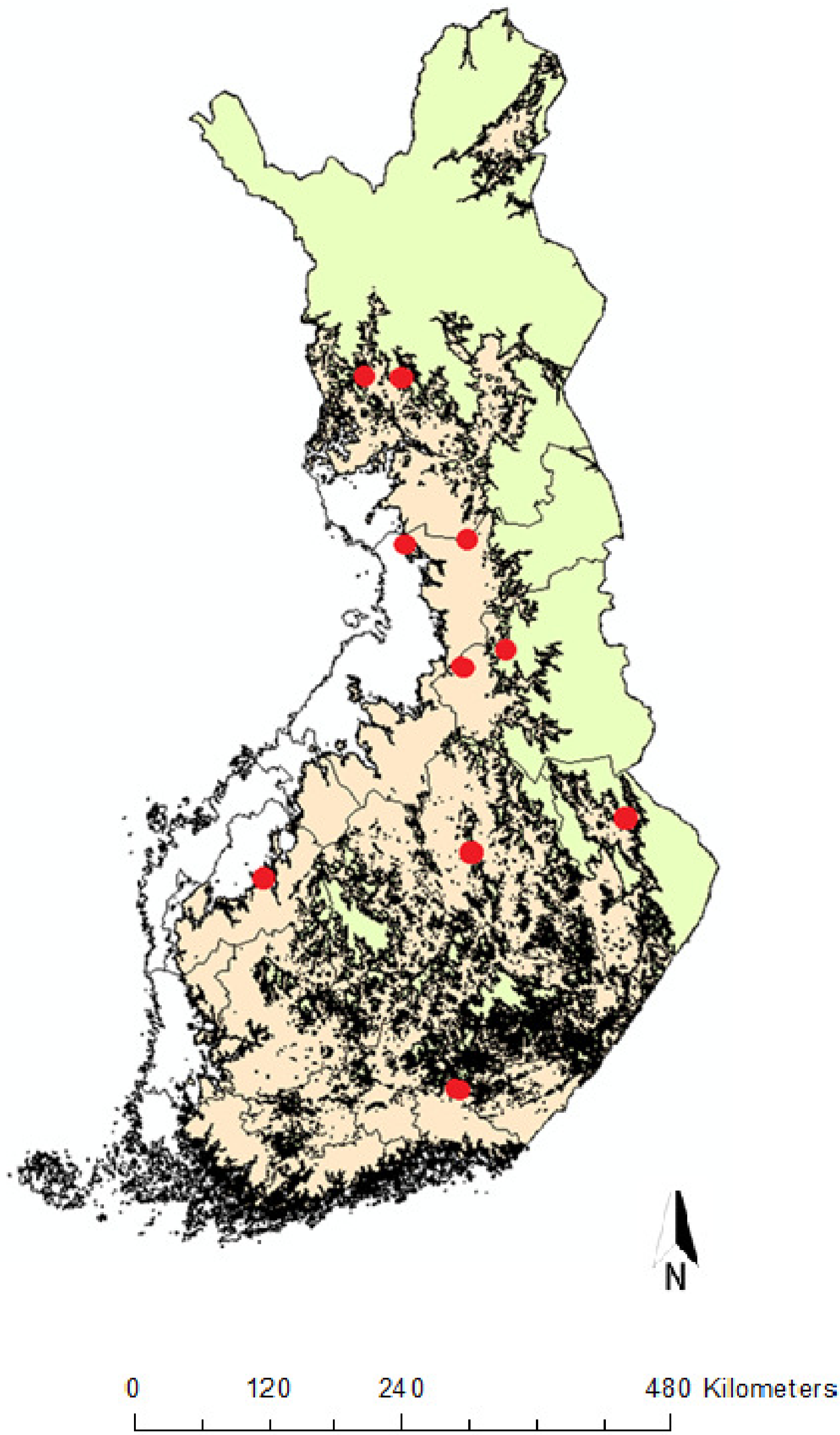

Figure 11. Map showing the location of profiles classified in the field as Podzol but not having a spodic B horizon (n=10) (green = supra aquatic areas, beige = sub aquatic areas, white = areas under The Littorina Sea).

Using the WRB (2007) classification key, these ten profiles would key out as Arenosols, Cambisols and Regosols (Table 5). Cambic horizon should have soil texture in the fine earth fraction of very fine sand, loamy very fine sand, or finer which should be indicated with 50 % or more of the fraction between 63-125 µm grain size class (IUSS Working Group WRB, 2007). In the BioSoil data, the sand fraction is defined 63-2000 µm hence some of the cambic horizons might be classified with too coarse fraction.

Table 5. The percentages of re-classified profiles in non-podzol dataset.

	non-PZ	Arenosol	Cambisol	Regosol
n	10	2	2	6
%	9	20	20	60

Profile photographs are available for three of the ten non-Podzols (Figure 12). So, even though these soils appear to be Podzols, they do not meet the WRB criteria for a Podzol and therefore would, in principle, need to be re-classified.

Figure 12. Profiles classified as Podzol in the field but not having a WRB spodic horizon. Left-sided profile did not have an albic horizon and did not meet criterion 3b iii (Reclassification: Cambisol). Profile in the middle did not meet spodic colour criteria (Reclassification: Regosol). Right-sided profile did not meet organic C criterion (Reclassification: Arenosol). Source: BioSoil database (LUKE, Natural Resources Institute of Finland).

3.2. Degree of podzolization and effect of soil formation factors

3.2.1. Indexes of podzolization development

The degree of podsolization was quantified using four indexes: Thickness index, Rubification index, Al+Fe oxalate index, and Podsolization Development Index; the latter being the sum of the first three indexes.

Of the 106 profiles classified as Podzols according to WRB in the preceding chapter, 20 were excluded for this analysis. Those profiles from plots having more than one soil parent material category present (n = 18) were excluded.

In addition, profile numbers 3615 and 3825 were excluded. The former showed enrichment of iron and aluminium in E horizon rather than B horizon. However it was classified as Podzols according to WRB because it met the optional 3a criterion, i.e. had an albic horizon and the B horizon had a spodic colour. The later was excluded because it had a B horizon with a thickness of <10 cm. As a result the analysis of the degree of podzolization and the effect of soil formation factors was restricted to 86 of the WRB based Podzol profiles.

The cumulative frequencies of Thickness, Rubification, and Al + Fe indexes for the 86 podzol profiles are shown in Figure 13.

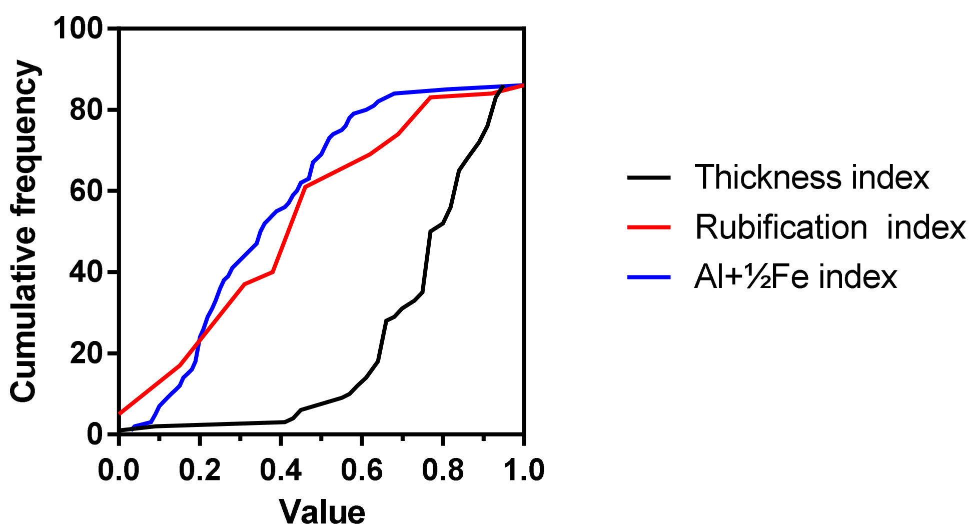

Figure 13. Cumulative frequencies of Thickness, Rubification, Al+Fe indexes for the 86 podzol profiles.

Figure 14 shows the relationship between the four indexes and Spearman`s correlation coefficients The Al+Fe index was not significantly correlated with Thickness index but was nearly significantly correlated with Rubification index . The apparent two outliers in the figure (profiles 1802 and 3646) are the profiles with the thickest E horizons, hence having the lowest Thickness index values. Profile 1802 also has the highest Rubification index value.

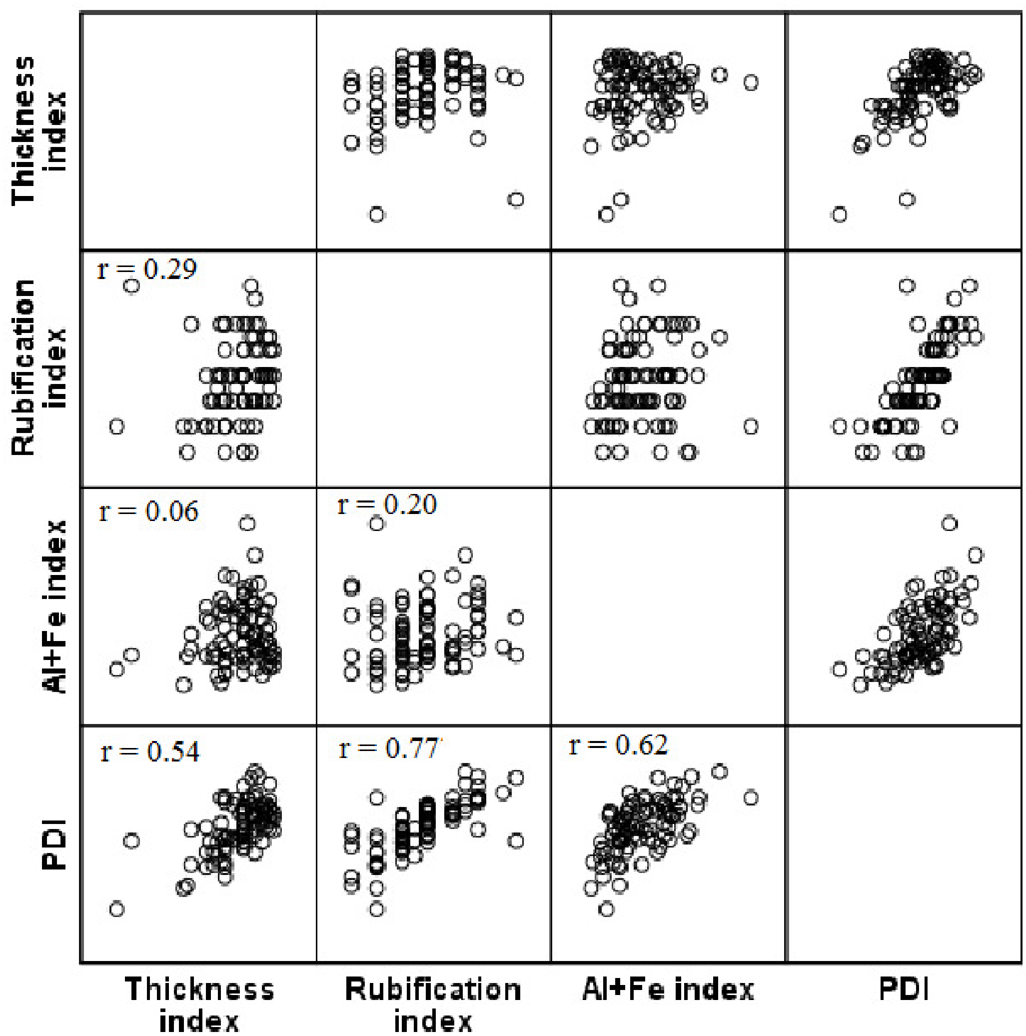

Figure 14. Scatter plots showing the relationships between the Thickness, Rubification, Al+Fe and Podzolization Development Indexes. The r values are the Spearman`s correlation coefficients.

3.2.2. Variables indicating soil formation factors

The seven continuous BioSoil variables used to describe the influence of the soil formation factors are described in Table 6. The 86 studied Podzol profiles were evenly distributed throughout Finland (Figure 6). The spodic horizons were dominated by sandy material with little clay, but clearly had high coarse fragment content (indicative of till material).

Table 6. Descriptive statistics of BioSoil continuous variables describing soil formation factors. Soil texture values are presented for diagnostic spodic horizon. (n=86).

Variable	Min.	Max.	Mean	Std. dev.
Longitude, decimal degree	21.9594	30.5339	26.0619	-
Latitude, decimal degree	60.3372	69.2067	63.3834	-
Age, yr cal BP	3200	11700	10202	1374
Elevation, m asl	20	280	145	57
Silt, %	2.6	56.9	26.3	8.7
Sand, %	41.6	97.0	71.5	9.3
Coarse fragments, %	0.0	82.1	34.2	21.6

Longitude, latitude and elevation are considered to describe the influence of the climate soil formation factor, the soil texture variables to describe the influence of the parent material soil formation factor, and age the influence of the time soil formation factor.

The frequencies and percentages of the profiles for each of the 12 categorical BioSoil variables are presented in Figures 15-19. The classes for each categorical variable are presented in Appendix II. In general, most plots were on moist or dryish sites having good water infiltration capacity. The plots were commonly located on flat areas or on hill slopes. Most of the plots were between 100 and 200 m asl, the most common elevation classes being 100-150 m and 150-200 m (asl). The parent material was most loose, mostly median to coarse textured till material. Although most of the plots were located in sub-aquatic areas, the profiles were generally old (> 10 000 yr, cal. BP).

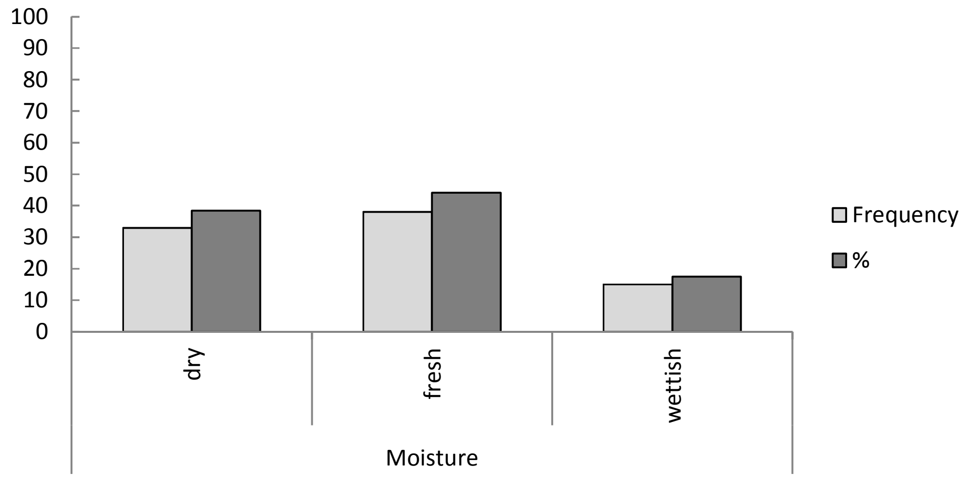

Figure 15. Frequency (counts and percentages) distributions of the selected 86 study Podzol profiles according to the Moisture categorical variable (Appendix II) describing the influence of the climate soil formation factor.

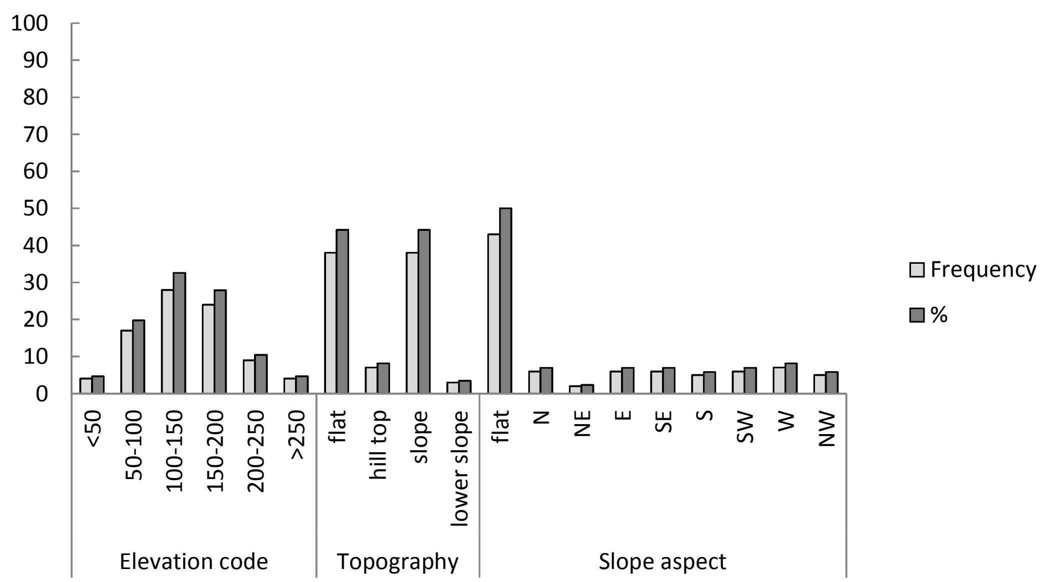

Figure 16. Frequency (counts and percentages) distributions of the selected 86 study Podzol profiles according to the categorical variables elevation, topography, slope aspect; (Appendix II) describing the influence of the topography soil formation factor.

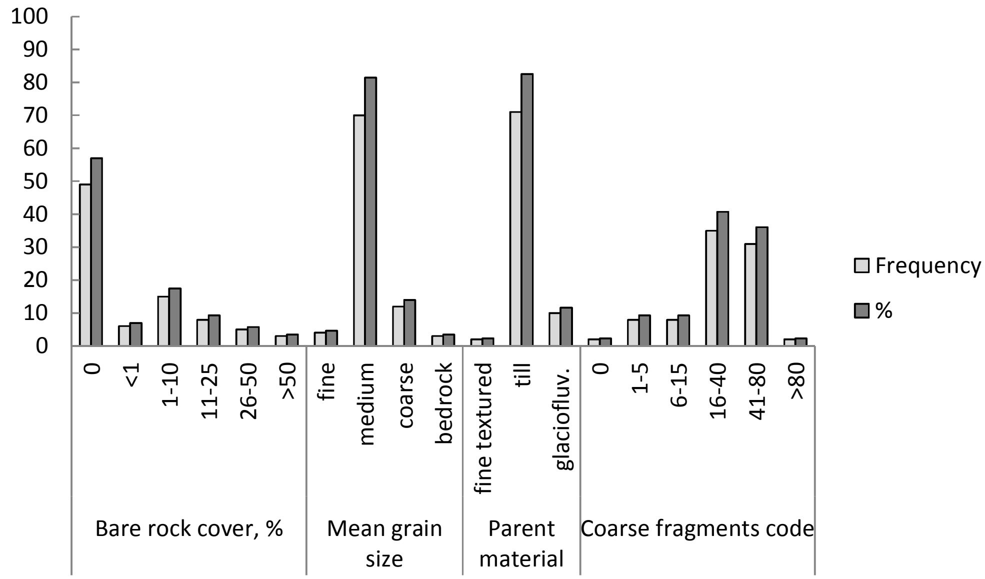

Figure 17. Frequency (counts and percentages) distributions of the selected 86 study Podzol profiles according to the categorical variables Bare rock cover, mean particle size, coarse fragment(Appendix II) describing the influence of the parent material soil formation factor.

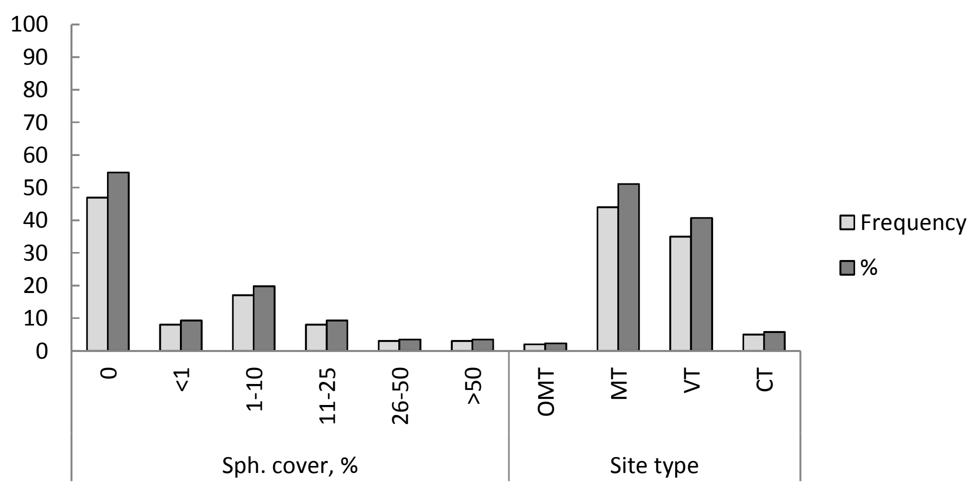

Figure 18. Frequency (counts and percentages) distributions of the selected 86 study Podzol profiles according to the categorical variables Sphagnum cover and site type(Appendix II) describing the influence of the biotic soil formation factor.

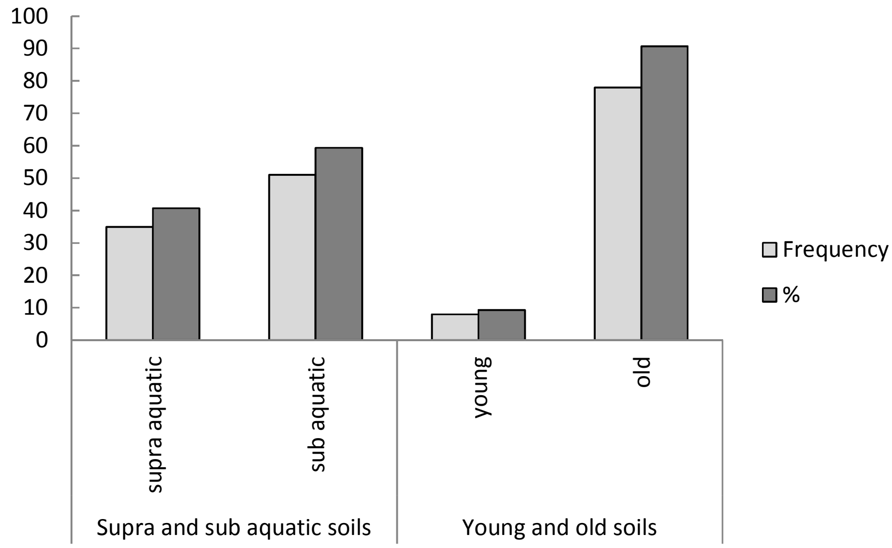

Figure 19. Frequency (counts and percentages) distributions of the selected 86 study Podzol profiles according to the categorical variables Supra-/sub-aquatic, young and old soils(Appendix II) describing the influence of the time soil formation factor.

Of the 86 Podzol profiles 41 % were in supra-aquatic areas and 59 % (n=51) were in sub-aquatic areas, i.e. have been under sea level. Of the sub-aquatic profiles, 17 % had been under the Yoldia Sea, 34 % under the Ancylus Lake and 8 % under the Litorina Sea (Figure 20).

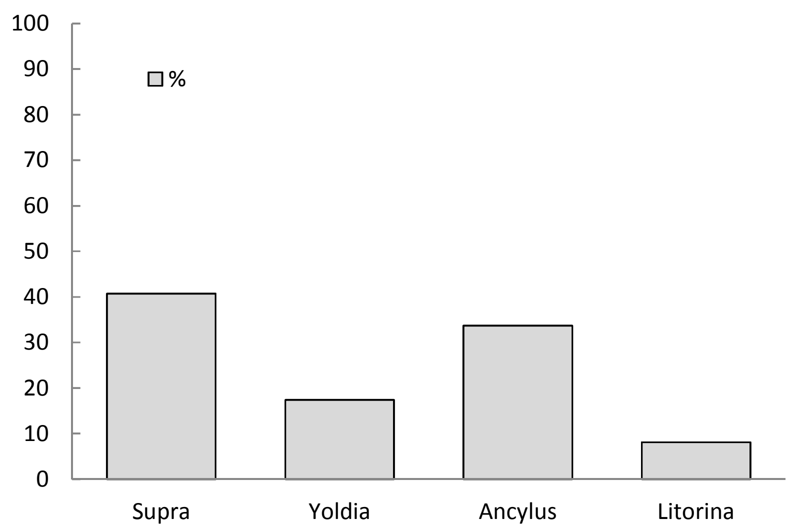

Figure 20. Percentages of profiles classified as Podzol according to World Reference Base for Soil Resources (WRB) located in supra-aquatic areas and areas of various stages of the Baltic Sea (Yoldia Sea, the Ancylus Lake and the Litorina Sea, see Table 3).

3.2.3. Degree of podzolization in relation to variables describing soil formation factors

The Spearman correlations between each of the podzolization indexes and the seven BioSoil continuous variables describing the influence of the soil formation factors are presented in Table 6 and significant correlations indicated. The results of testing for differences in each podzolization index for each of the 13 BioSoil categorical variables describing the influence of the soil formation factors are presented in Table 7.

Table 6. Spearman correlation coefficients for the relationships between the podzolization indexes and each of the 7 BioSoil continuous variables describing the influence of the soil formation factors. Significant ($p \leq 0.05$, n=86) correlations are in bold.

Variable	Thickness	Rubification	Al+Fe	PDI
Longitude, decimal degree	0.10	0.12	0.18	0.18
Latitude, decimal degree	0.04	-0.04	0.06	0.01
Age, yr cal BP	**0.21**	**0.23**	**0.23**	**0.32**
Elevation, m asl	0.02	0.07	**0.29**	0.19
Silt, %	0.14	**0.26**	0.20	**0.28**
Sand, %	-0.14	**-0.25**	-0.18	**-0.27**
Coarse fragments, %	0.20	0.12	0.11	0.20

Table 7. Results of testing for differences in podzolization index values (E horizon thickness, B horizon rubification, illuviation of oxalate extractable Al and Fe between E and B horizons, and PDI) for each categorical variable (13) describing soil formation factors. Values are the ANOVA *F* ratio for categorical variables having >2 classes and t-test value for categorical variables having only two classes. Values in bold indicate significant ($p < 0.05$) differences.

Categorical variable	Thickness		Rubification		Al+Fe		PDI	
	F	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Moisture	2.949	0.058	2.721	0.072	0.204	0.816	2.185	0.119
Elevation	0.660	0.654	0.676	0.643	**2.388**	**0.045**	1.205	0.314
Topographical position	0.543	0.654	0.497	0.685	1.103	0.353	0.317	0.813
Slope aspect	**2.094**	**0.046**	1.388	0.215	0.470	0.874	1.700	0.112
Coarse frag.	0.508	0.769	2.316	0.051	1.900	0.103	**0.363**	**0.033**
Bare rock cover	2.298	0.053	0.920	0.472	0.874	0.502	1.046	0.397
Soil type	1.043	0.357	0.734	0.483	2.057	0.134	2.669	0.075
Texture	0.195	0.824	0.290	0.749	2.684	0.074	1.194	0.308
Parent material	0.827	0.483	0.779	0.509	2.031	0.116	1.229	0.305
Site type	**3.148**	**0.029**	1.087	0.359	0.925	0.432	0.438	0.726
Sph. cover	0.667	0.650	**2.978**	**0.016**	0.962	0.446	1.083	0.376
Supra-/Sub-aquatic [a]	1.947	0.055	1.065	0.29	0.626	0.533	1.787	0.077
Young/Old [a]	-0.754	0.453	-0.584	0.561	-2.168	0.033	-1.701	0.093

[a] = t-test values

Photographs of profiles forming a chronosequence (3 200 to 11 700 yr, cal BP) are shown in Figure 21. The series of photographs shows the general development of a Podzol profile, in particular a strengthening of E and B horizon colours within and between the soil profiles is seen. Thicknesses of the horizons vary and in some profiles the E horizon is not continuous. The lower boundary of the E horizon is more distinct compared to that of the B horizon, which is more transitional. Podzolization Development Indexes slightly increases as soil age of the profile increases although not continuously.

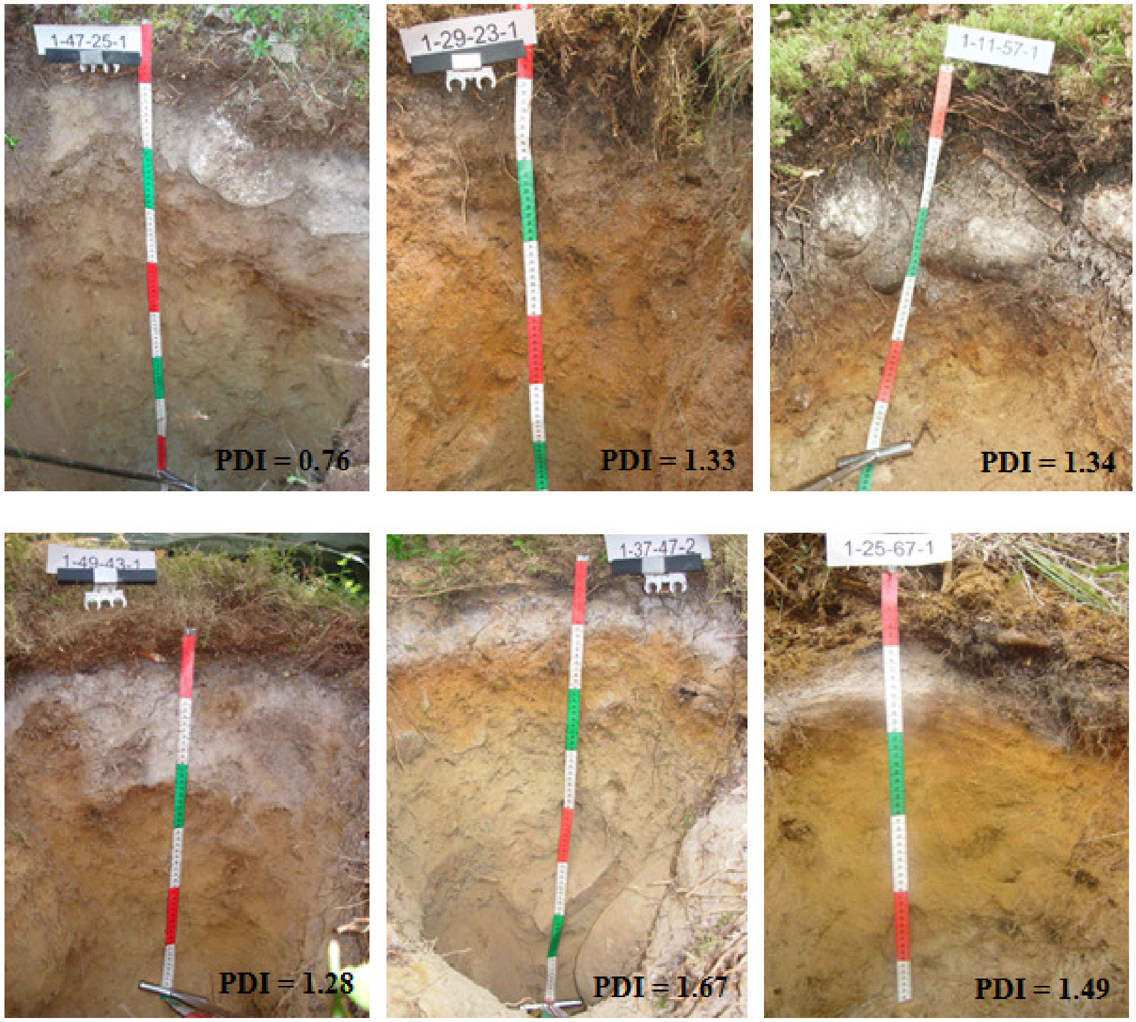

Figure 21. A chronosequence of the soil profiles. From upper left to lower right soil ages are: 3 200, 6 300, 8 500 and 9 900, 11 000 and 11 700 years (cal BP). Source: BioSoil database (LUKE, Natural Resources Institute of Finland).

3.2.3.1. Thickness index

The E horizon thickness index did not show a significant relationship with latitude, longitude (Figure 22) or elevation (Figure 23), variables which describe climate (Table 2).

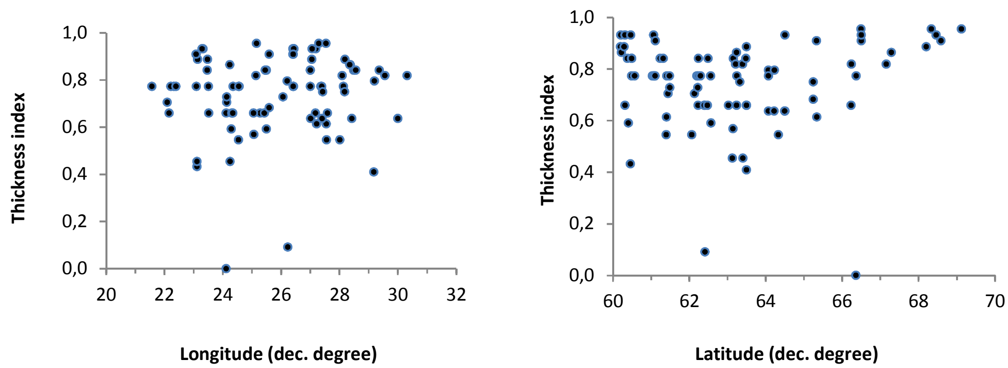

Figure 22. Relationship between latitude/longitude (dec. degree) and Thickness index.

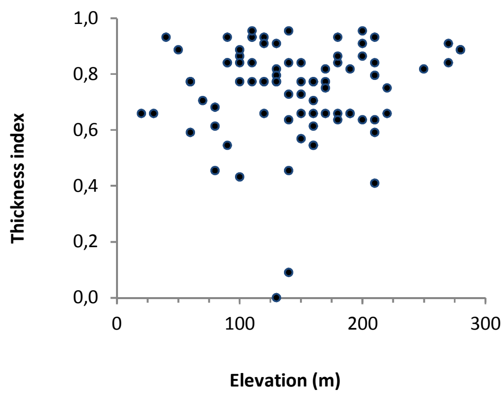

Figure 23. Relationship between elevation (m asl) and Thickness index.

Thickness index was nearly significantly different among the three moisture classes (Figure 24). However, the thickness index significantly differed among the nine slope aspect classes indicating a topographic effect on meso-climate.

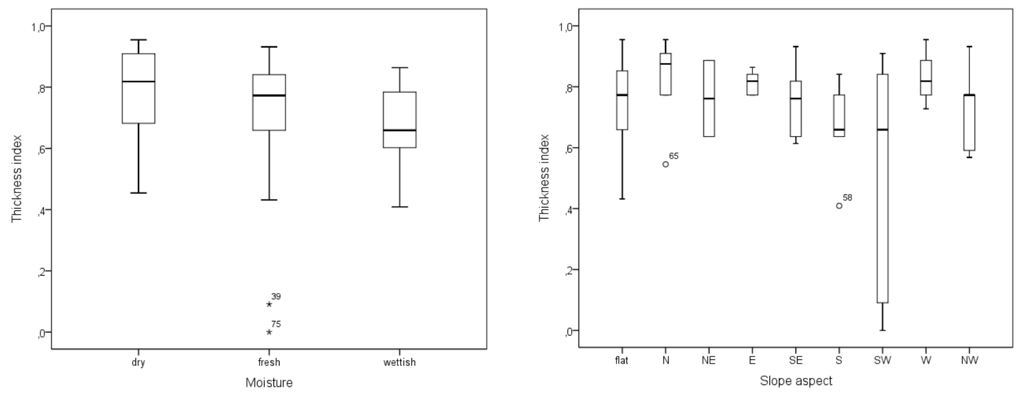

Figure 24. Thickness index values by moisture class (left) and between different slope aspect classes (right).

The thickness index showed no significant difference among the topographical position classes (Figure 25).

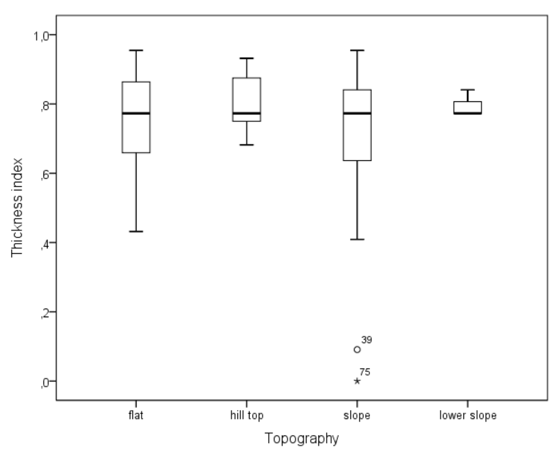

Figure 25. Thickness index values by different topographical positions.

The soil texture variables silt, sand and coarse fragment contents, which describe the parent material soil formation factor, were not correlated to the E horizon thickness index (Figure 26).

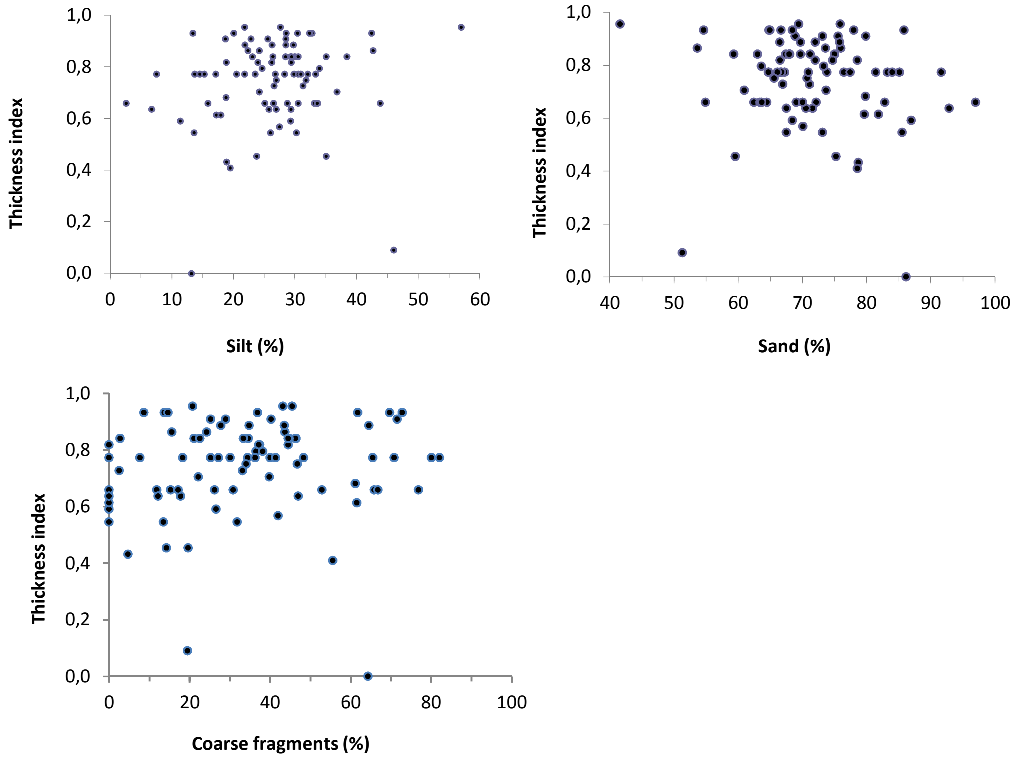

Figure 26. Relationship between silt/sand/coarse fragments content (%) and Thickness index.

The thickness index was nearly significantly different among the bare rock cover classes and parent material classes (Figure 27).

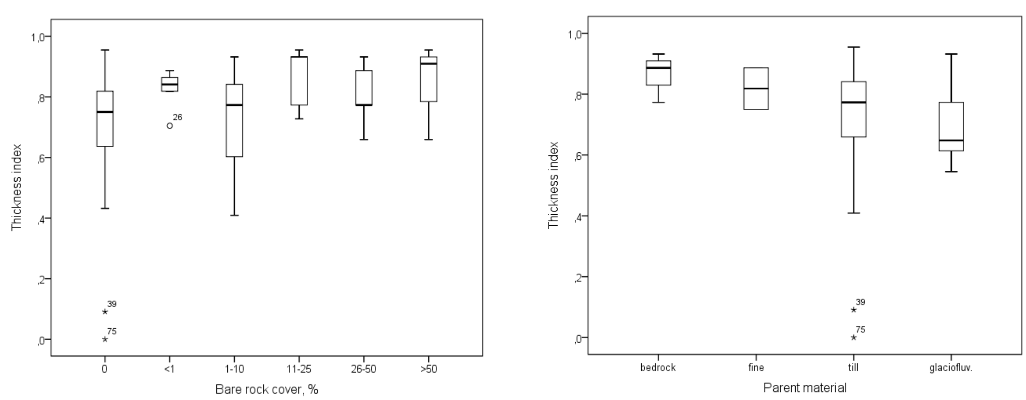

Figure 27. Thickness index values by bare rock cover (%) class (left) and between different parent material classes (right).

Thickness index significantly differed among the site type classes (Table 7), with values increasing from moist, fertile grove-like sites (OMT) to poor, dry sites (Figure 28). Thus E horizon thickness tended to increase towards the more fertile and moist sites. Site type is an indicator of biotic soil formation factor.

There was no significant difference in the E horizon thickness index among the Sphagnum cover classes, which reflects site moisture conditions related to topography.

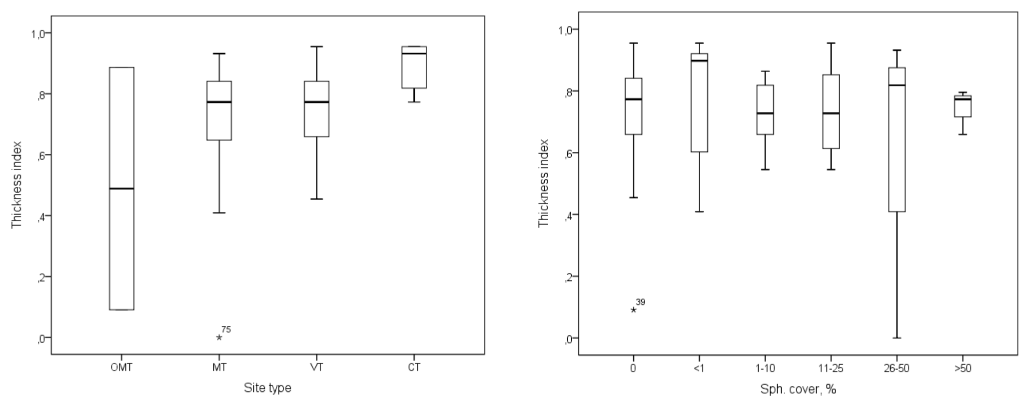

Figure 28. Thickness index values by site type class (left) and between different Sphagnum cover classes (right).

The correlation between thickness index and profile age was significantly correlated (Figure 29). The positive correlation coefficient (Table 6) indicates that the thickness of E horizon decreases with time.

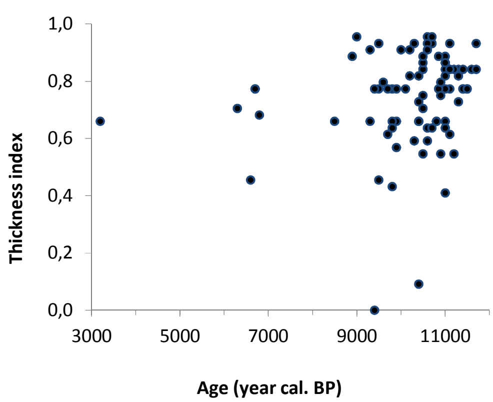

Figure 29. Thickness index values by soil age (yr, cal. BP).

The thickness index was nearly significantly different among the Supra/sub aquatic classes (Figure 27). The thickness index was not significantly different among the Young/old classes. Thickness index increases in supra aquatic areas and old soils when comparing to sub aquatic areas and young soils (Figure 30).

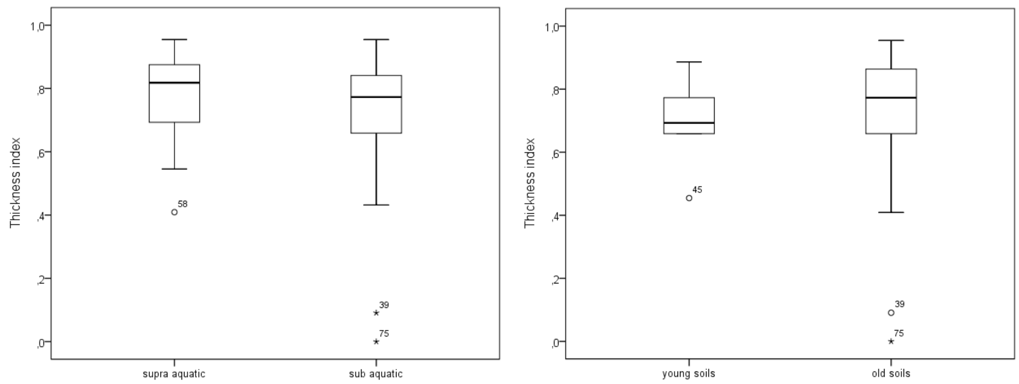

Figure 30. Variation of Thickness index mean values between supra and sub aquatic areas (left) and young (< 9000 yr cal. BP) and old (> 9000 yr cal. BP) soils (right).

Relationship between development of E horizon and Al+Fe (%) is showed in Figure 31. Thickness of E horizon in total data (n=86) decreases when Al+Fe (%) in the B horizon increases.

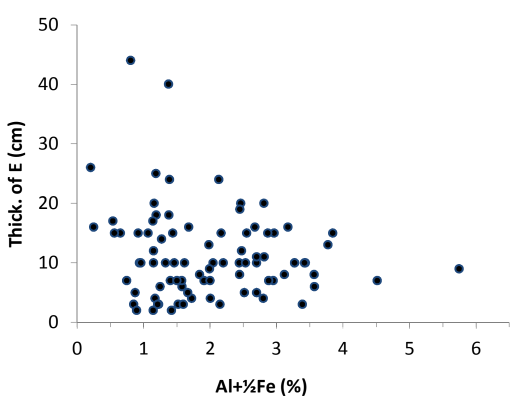

Figure 31. Relationship between Al+½Fe (%) in B horizon and thickness of E horizon (cm) in all BioSoil data (n=86).

3.2.3.2. Rubification index

The rubification index did not show a significant relationship with latitude, longitude (Figure 32) or elevation (Figure 33), variables which describe climate (Table 2). Rubification index increased towards east when decreased towards north.

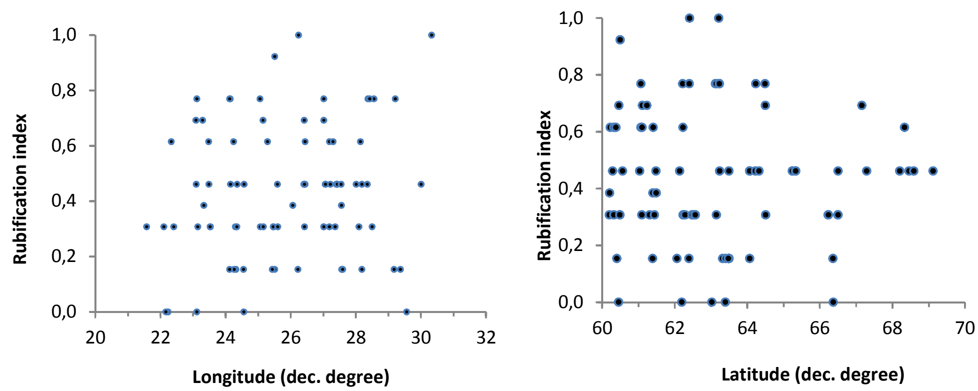

Figure 32. Relationship between latitude/longitude (decimal degree) and Rubification index.

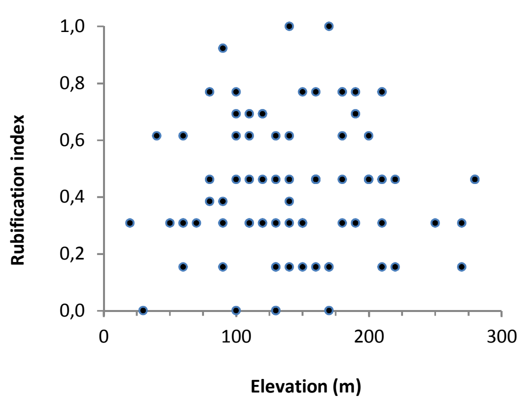

Figure 33. Relationship between elevation (m, asl) and Rubification index.

Rubification index was not significantly different among the three moisture classes or among the nine slope aspect classes (Figure 34). Podzolization indicated with Rubification is more intense in soils with dryer conditions. Podzolization between different slope aspect classes varies east having the highest Rubification index.

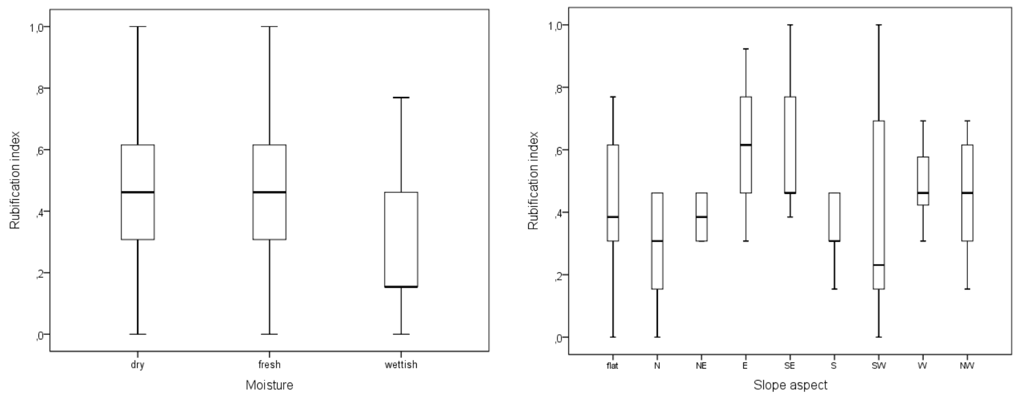

Figure 34. Variation of Rubification index mean values between different soil moisture conditions and in various slope aspects.

The Rubification index showed no significant difference among the topographical position classes (Figure 35). Rubification was greater on slope positions than on flat sites.

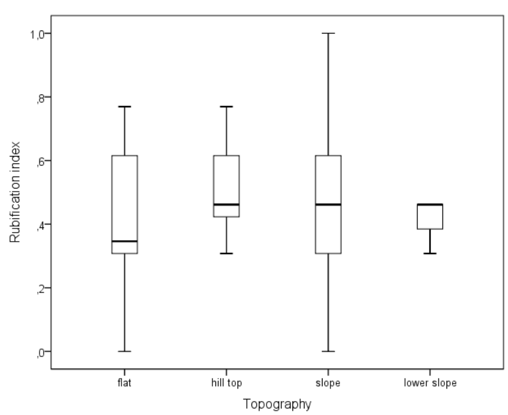

Figure 35. Variation of Rubification index mean values in different topographical positions.

The soil texture variables silt and sand, which describe the parent material soil formation factor, were correlated to Rubification index (Figure 36). The Rubification index increased with silt and coarse fragment contents (%) and decreased with sand content (%). Coarse fragment contents (%) were not correlated to the Rubification index.

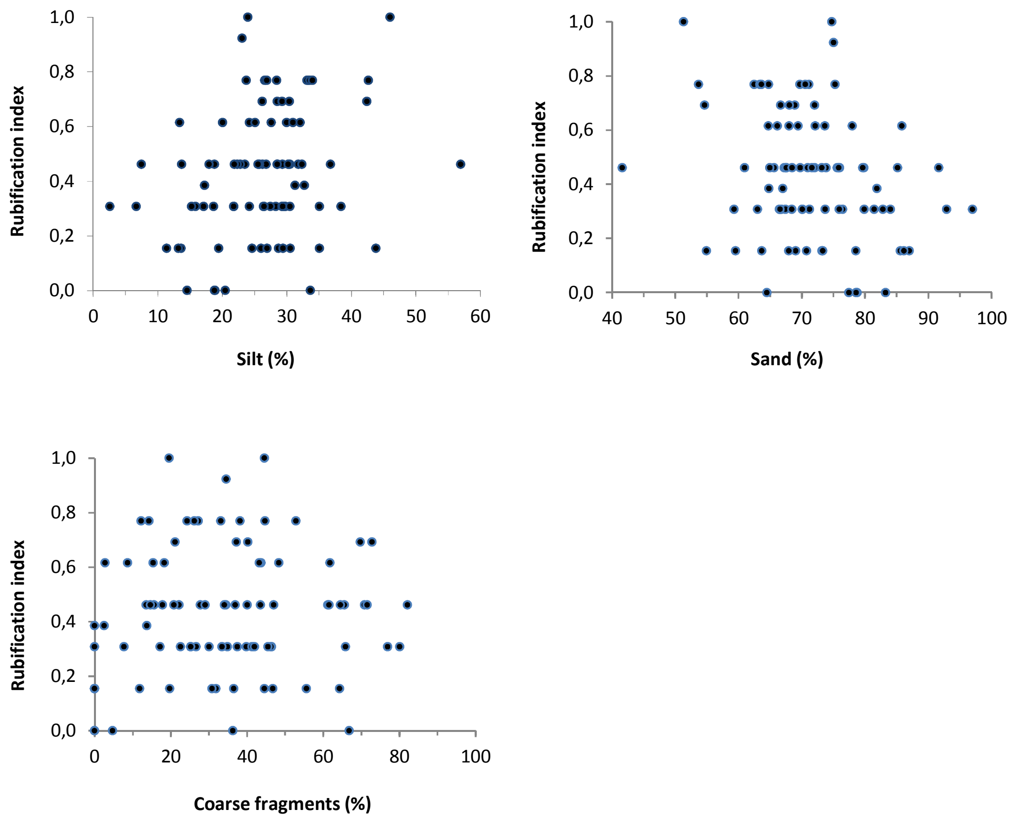

Figure 36. Relationship between Rubification index and silt, sand and coarse fragments contents (%).

The Rubification index was not significantly different among the bare rock cover classes and parent material classes (Figure 37). The difference between coarse fragments classes was nearly significant, indicating an influence of parent material (Table 7). Variation is larger in areas with less bare rock cover and more loose soil. Share of the fine earth in the soil increases Rubification index. Variation is largest in the mean grain class of medium coarse soil. Soils having more coarse fragments have largest Rubification indexes thus indicating more intense podzolization in unsorted material. Till as a parent material and as a soil type has largest Rubification indexes.

Ranges are high in various classes identifying large variation in parent material of Finnish soils.

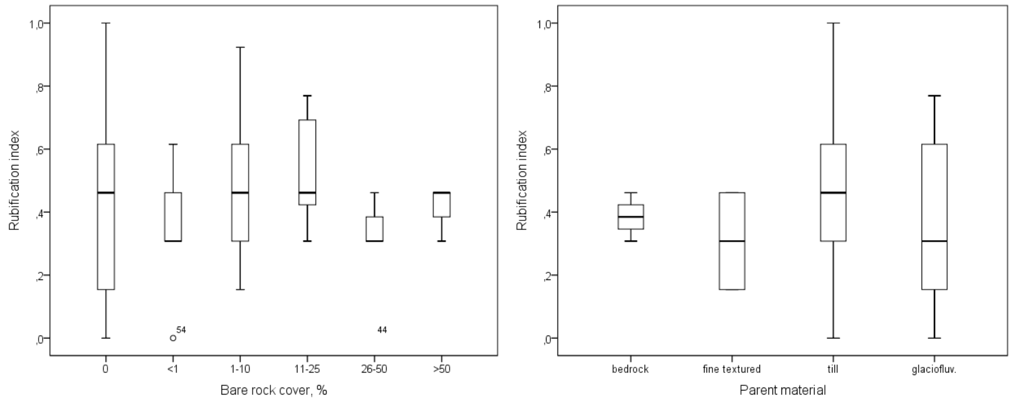

Figure 37. Variation of Rubification index mean values between areas with different bare rock cover (%) (left) and between different parent material classes (right).

Rubification index was not significantly differed among the site type classes (Table 7), with values decreasing from moist, fertile grove-like sites (OMT) to poor, dry sites (Figure 38).

There was significant difference in the Rubification index among the Sphagnum cover classes, which reflects site moisture conditions related to topography, climate and biotic factor. Podzolization is more intense in soils having less Sphagnum cover (%) although the increase is not continuous. The smallest Rubification index is associated with Sphagnum cover is > 50 %.

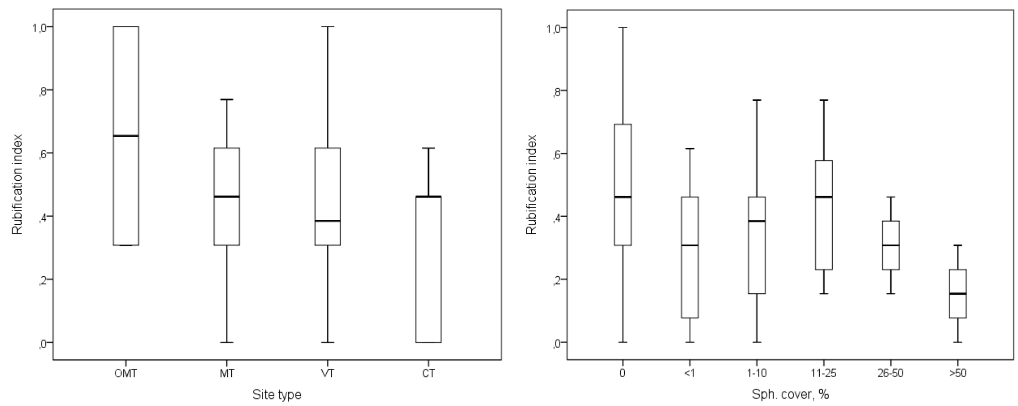

Figure 38. Variation of Rubification index mean values between areas with various site types (left) and Sphagnum cover classes (right).

The Rubification index and profile age was significantly correlated (Figure 39). Rubification index increases as soil age (yr, cal. BP) increases.

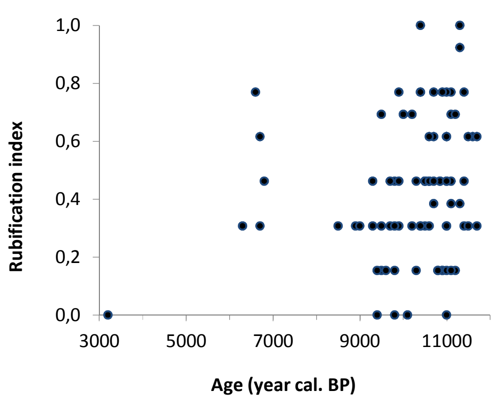

Figure 39. Relationship between soil age (yr, cal. BP) and Rubification index.

The Rubification index showed no significant difference among Supra/sub or young/old classes (Figure 40). Podzolization based on Rubification index is more intensive in supra aquatic areas and old soils compared to sub aquatic areas and young soils.

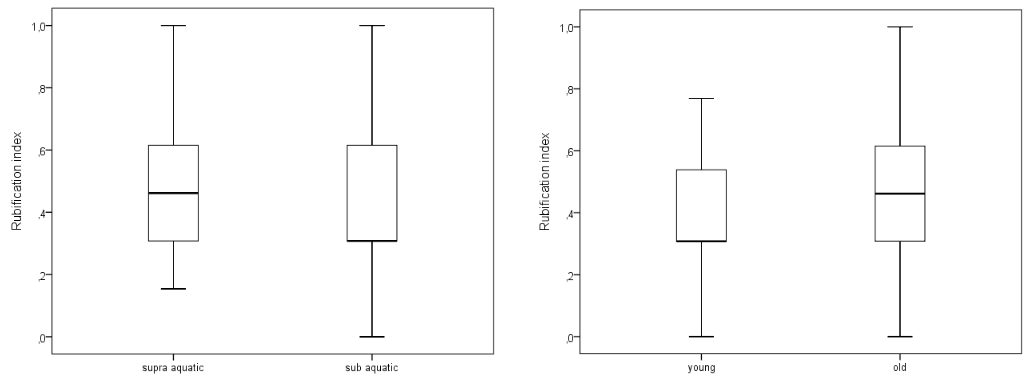

Figure 40. Variation of Rubification index mean values between supra (1) and sub (2) aquatic areas (left) and young (1, < 9000 yr, cal. BP) and old (2, > 9000 yr, cal. BP) soils (right).

3.2.3.3. Al+Fe index

The Al+Fe index did not show a significant relationship with latitude and longitude (Figure 41). The Al+½Fe index increased eastwards when decreased northwards. Al+Fe index was significantly correlated with elevation (Figure 42). These variables describe climate (Table 2).

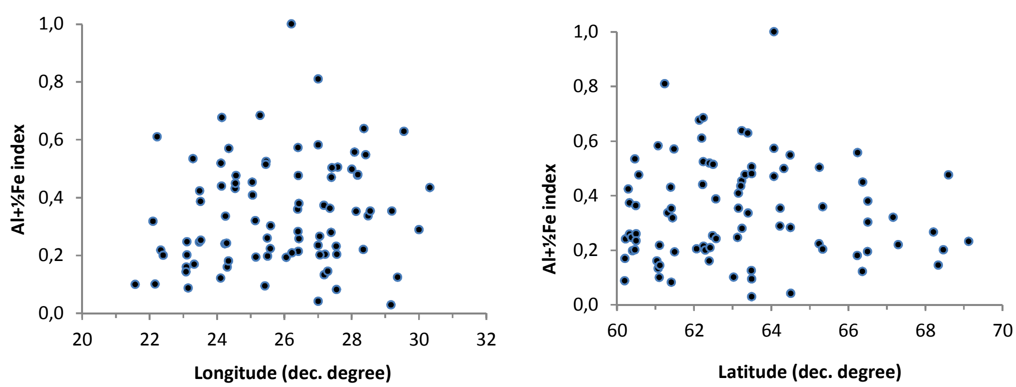

Figure 41. Relationship between latitude/longitude (decimal degree) and Al+½Fe index.

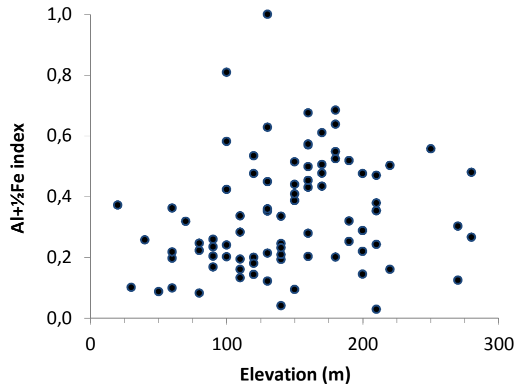

Figure 42. Relationship between elevation (m, asl) and Al+½Fe index.

Al+Fe index was not significantly different among the three moisture classes (Figure 43) or the nine slope aspect classes. In general podzolization was more intense in profiles with moist conditions. Podzolization between different slope aspect classes varied however, southeast aspects having the highest Al+Fe index values.

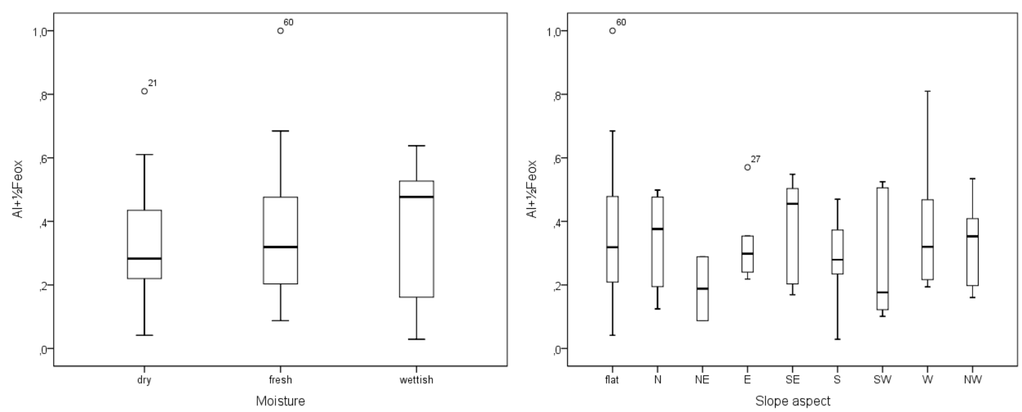

Figure 43. Variation in the Al+Fe index in different moisture classes (left) and in slope positions (right).

The Al+Fe index showed no significant difference among the topographical position classes (Figure 44). The Al+Fe index was greater on lower slopes where the variation in the index was also the smallest.

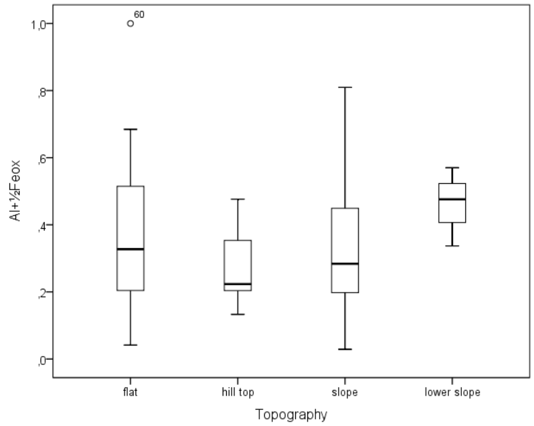

Figure 44. Variation in the Al+Fe index in different slope positions.

The soil texture variable silt which describes the parent material soil formation factor was correlated to the Al+Fe index (Figure 45). Sand and coarse fragment were not correlated with Al+Fe index. The Al+Fe index increased with silt and coarse fragment contents (%) and decreased with sand content (%).

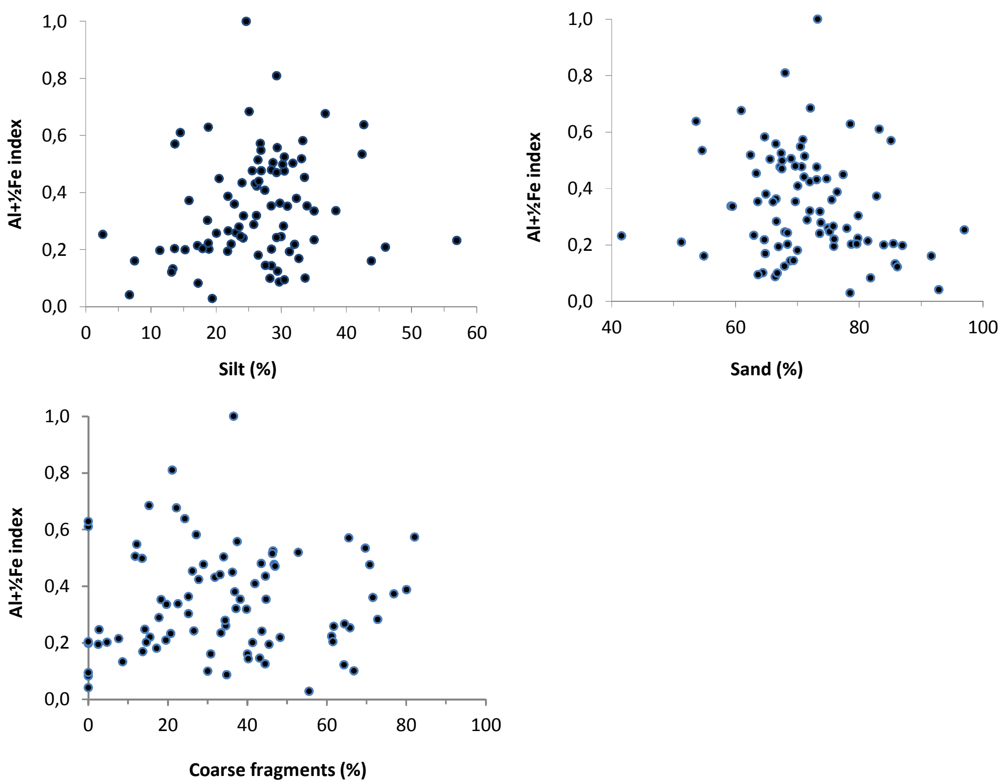

Figure 45. Relationships between the Al+Fe index and silt, sand and coarse fragments contents (%).

The Al+Fe index was not significantly different among the bare rock cover classes and parent material classes (Figure 46).

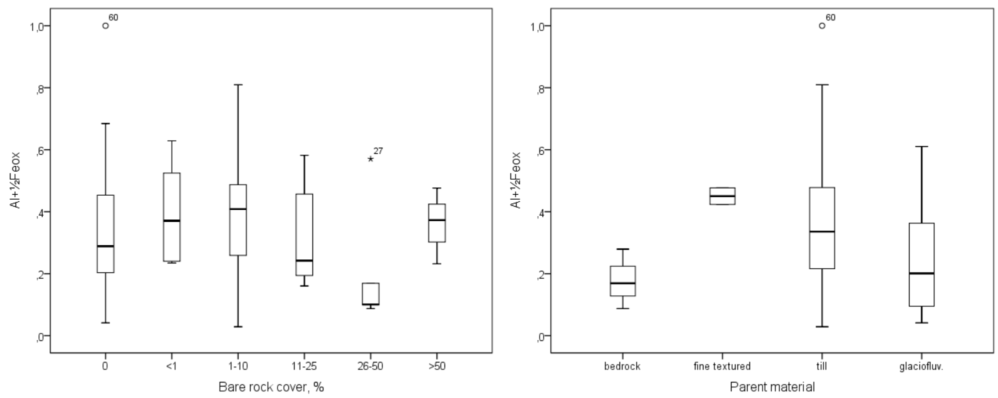

Figure 46. Variation of Al+Fe index mean values between areas with different bare rock cover (%) (left) and parent material classes (right.

Al+Fe index was not significantly different among the site type and the Sphagnum cover classes (Figure 47). The Al+Fe index increased towards least fertile site types. The Al+Fe index tended to be greater at sites with higher Sphagnum cover (%).

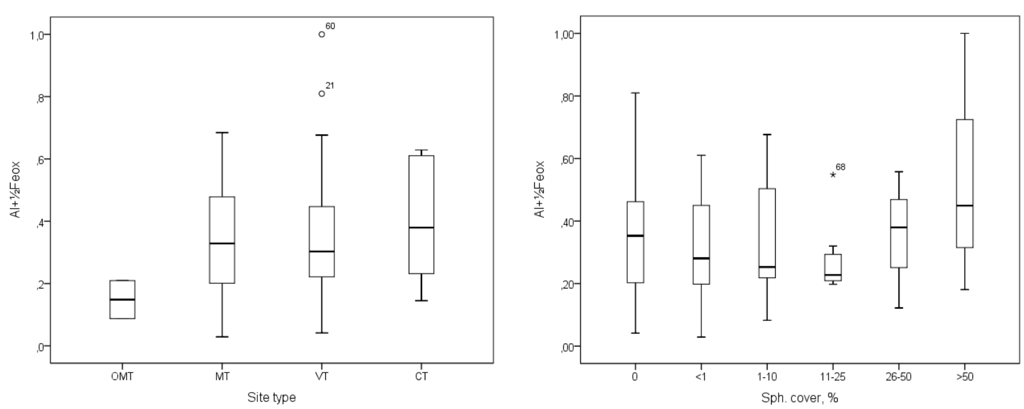

Figure 47. Variation of Al+Fe index values between site types (left) and Sphagnum cover classes (right).

The Al+Fe index was significantly correlated with soil age (yr, cal. BP) (Figure 48).

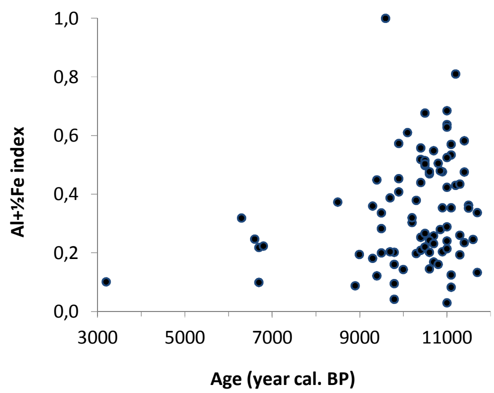

Figure 48. Relationship between soil age (yr, cal. BP) and Al+½Fe index.

The Al+Fe index was significant between young/old classes indicating the influence of the time soil formation factors (Figure 49). However the difference was not significant between supra/sub- aquatic areas.

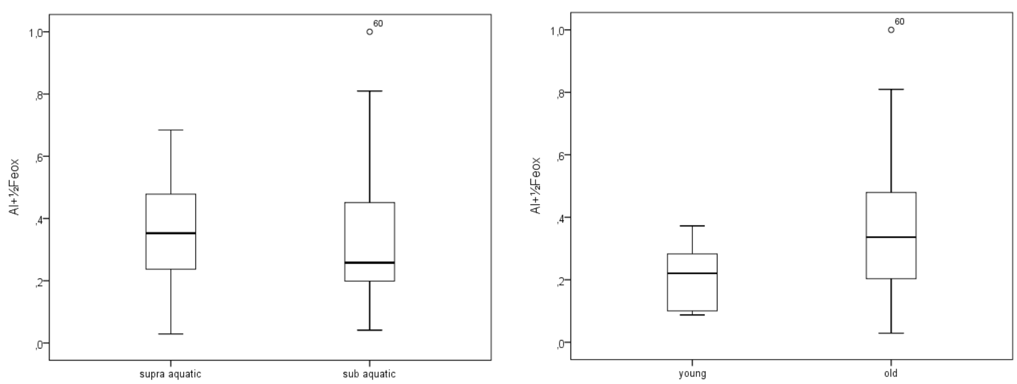

Figure 49. Variation in Al+½Fe index values between supra- and sub-aquatic areas (left) and young (< 9000 yr, cal. BP) and old (> 9000 yr, cal. BP) soils (right).

3.2.3.4. Podzolization development index

Because the 3 indexes (Thickness, rubification, Al+Fe) are positively correlated with each other, the PDI – the sum of the 3 other indexes - was expected to show the strongest correlations with the continuous variables and differences among the categorical classes.

The PDI did not show a significant relationship with latitude, longitude and elevation (Figure 50 and 51), variables which describe climate (Table 2). The PDI increased eastwards and decreased northwards.

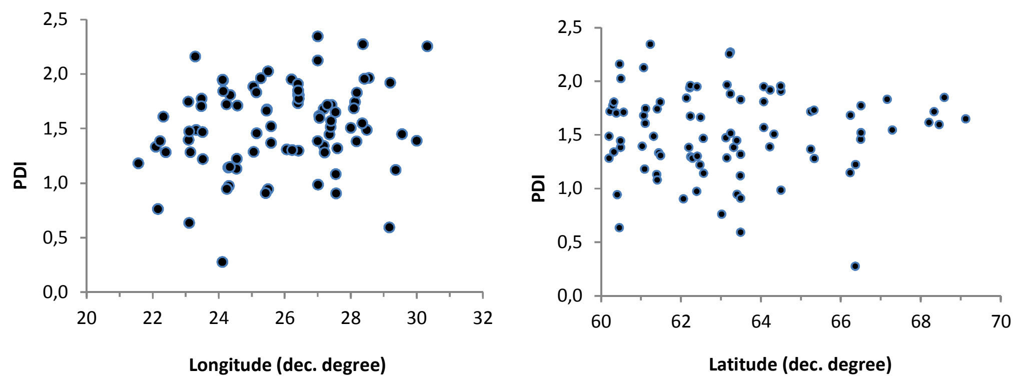

Figure 50. Relationship between longitude and latitude (decimal degree) and PDI.

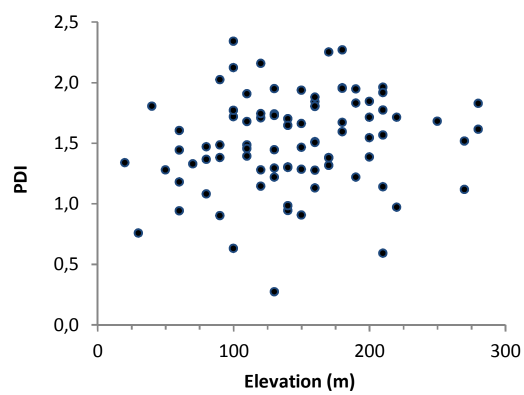

Figure 51. Relationship between elevation (m, asl) and PDI.

PDI was not significantly different among the three moisture classes, the nine slope aspect classes or slope position (Figure 52 and 53).

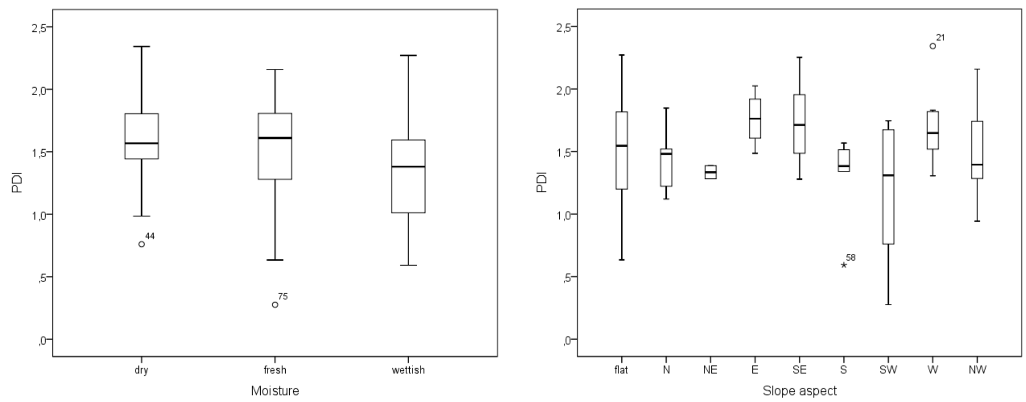

Figure 52. Variation in PDI values between different soil moisture classes and slope aspects.

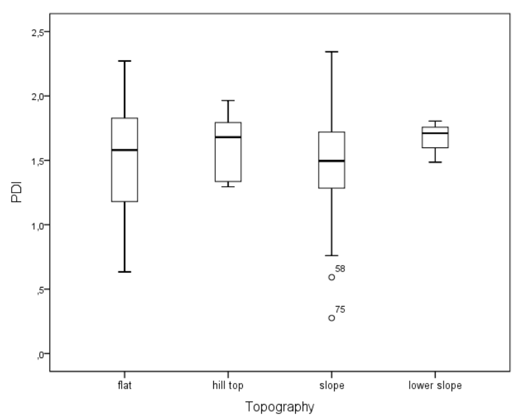

Figure 53. Variation of PDI means values in different slope positions.

The soil texture variables silt and sand, which describe the parent material soil formation factor, were significantly correlated to the PDI (Figure 54). Correlation coefficient was nearly significant with PDI and coarse fragments. However the podzolization development index (PDI) was significantly different in coarse fragment code classes indicating the influence of parent material soil formation factor. Tukey`s multiple comparison tests showed that the difference between coarse fragment classes 1 (1-5 %) and 3 (16-40 %) was significant (p = 0.017) and nearly significant different between classes 1 (1-5 %) and 4 (40-80 %) (p = 0.084) (data not showed). The Podzolization Development index (PDI) increased with silt and coarse fragment contents (%) but decreased with sand content (%).

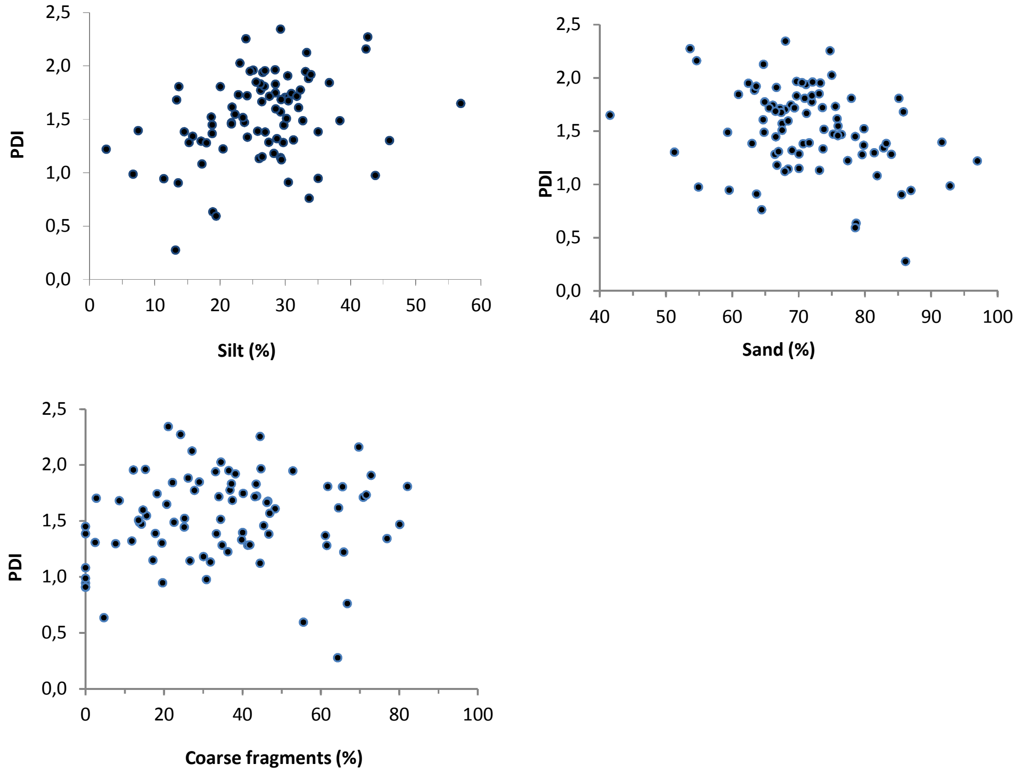

Figure 54. Relationships between the PDI and silt, sand and coarse fragment contents.

The PDI was not significantly different among bare rock cover and parent material classes (Figure 55).

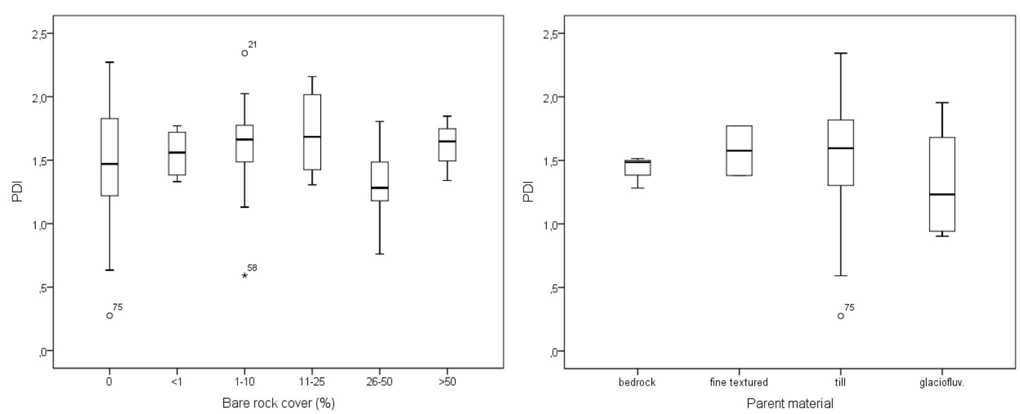

Figure 55. Variation in PDI values in bare rock cover (left) and parent material classes (right).

The PDI was not significantly different among site type or Sphagnum cover classes (Figure 56).

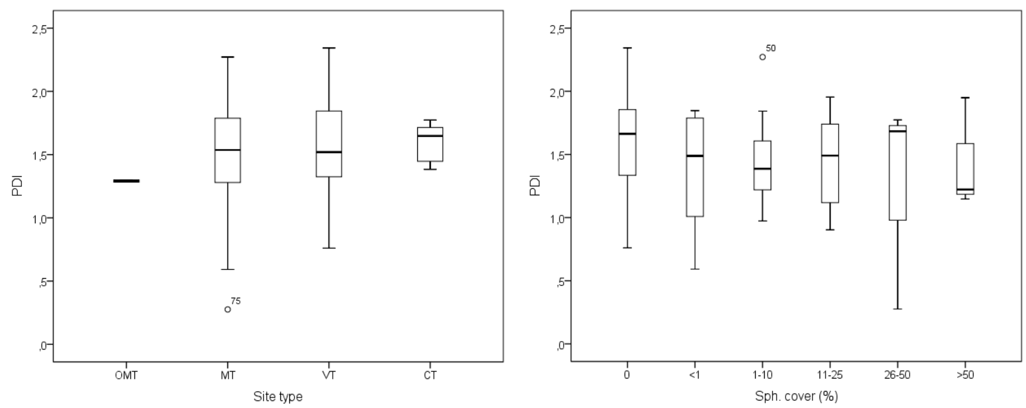

Figure 56. Variation in PDI values in site type (left) and Sphagnum cover class (right).

The PDI was significantly correlated with soil age (yr, cal. BP) (Figure 57).

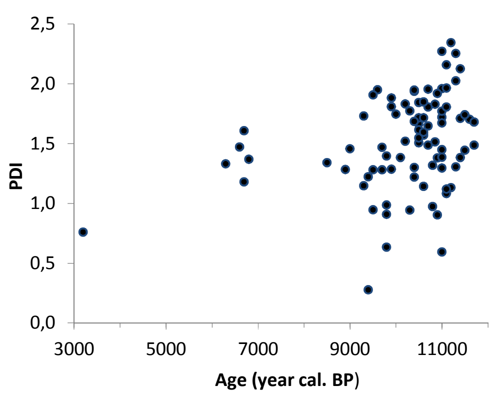

Figure 57. Relationship between PDI and profile age (yr, cal. BP).

The PDI was not significantly different in Supra/sub-aquatic or Young/old soils (Figure 58).

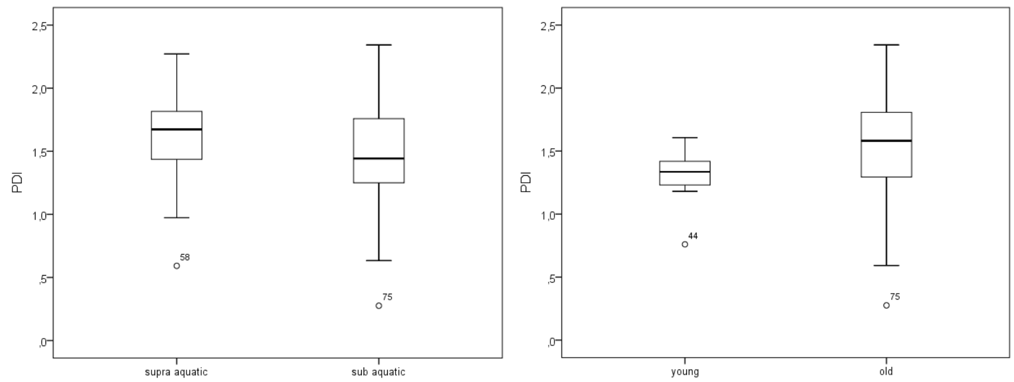

Figure 58. Variation in PDI values in Supra/sub-aquatic areas (left) and in young (< 9000 yr, cal. BP) and old (> 9000 yr, cal. BP) soils (right).

4. DISCUSSION

4.1. Diagnostic criteria of spodic B

Most of the profiles classified in the field as Podzols (91 %) had a B horizon that met the criteria for a diagnostic spodic horizon. The least problematic criteria were pH, organic C content and thickness of B horizon (Appendix III). The pH and thickness of B horizon criteria were fulfilled also in all 12 Finnish profiles studied by Mokma *et al.* (2004). Strand (1994) in Norway found only six spodic horizons out of 93 that failed to meet the pH criteria (too high values). Although these two studies used the Soil Taxonomy (1992 version) classification, it has same pH criteria as the WRB classification used in this study. In the study by Strand (1994) one profile had too low carbon content in B horizon. In Soil Taxonomy classification system the required carbon content of a spodic horizon differs (>0.6 %) from that in the WRB classification (>0.5 %).

In this study, the profiles met the colour criteria of the spodic horizon well. Especially, the colour defined in criterion 3aii was dominant. Soil colour due to soil formation is mainly affected by Fe content (rubification) and organic matter content (brunification). In profiles with a significant coarse fragment content soil colour is affected by the mineralogy (Barrett and Schaetzl 1993). Strand (1994) found 16 profiles out of 93 in Norway did not meet the colour requirements of Soil Taxonomy Spodosols, which have the same colour criteria as in the WRB classification. In the study by Mokma *et al.* (2004), all the studied Finnish profiles fulfilled spodic colour requirements, but interestingly did not meet the Al+Fe criteria.

In this study the amount of oxalate extractable Al+Fe and the eluviation-illuviation criteria was successful. By demanding that the B horizon must have higher oxalate Al+Fe contents than the overlying horizon is clearly getting at the classical concept of the podzolization process: weathering in the upper mineral soil and downward transport and accumulation of Al and Fe oxides to form an enriched B horizon (Gustafsson *et al.* 1995). Although the oxalate Al+Fe criterion can be replaced with the criteria for presence of cracked coating, cementation or Fe lamellae the determination of these criteria is considerably more demanding and subjective than determining oxalate Al+Fe contents and were not determined in BioSoil.

In the WRB classification an albic horizon is identified with soil colour and thickness of the horizon. In this study the albic colours of WRB (updated version 2007) were problematic. In selection of the profiles in this study, if an E horizon was not recognized in the field, the profile was rejected. However, the colour of E horizons in the remaining profiles were not developed enough, having too low values i.e. were too dark (both dry and moist). In contrast, Mokma *et al.* (2004) found the E horizon in all studied profiles in Finland to be albic using WRB criteria. Although they used WRB version 1998 the colour requirement for an albic horizon are the same is the updated version 2007 of WRB.

Problems with identifying albic horizon in Finnish forest soils are related to the presence of organic matter in the upper mineral soil. Organic matter lowers the value of soil colour (Evans and Cameron 1985) and masks of the albic colours of the mineral phase of the soil. The darkening of the B horizon due to the accumulation of organic matter however, does not affect the colour criteria for a spodic horizon. In requirements of albic colours in Finnish profiles should therefore be better considered. Soil colour and horizon thickness are easily determined in the field. However, if soil classification is made without the determination of oxalate Al and

Fe, then determining if a profile is Podzol or not using criteria 3a (presence of an overlying horizon having albic colour requirements) can cause problems in Finnish conditions.

Another problem with classifying profiles as Podzol based on the presence of an albic horizon is its thickness requirement. Implicit in the WRB classification (and US Taxonomy) is the assumption that the E horizon gets thicker (and whiter) with time (soil development). Although the correlation was weak, the thickness of the E horizon was found to be negative, i.e. the thickness of the E horizon decreased with age (time soil formation factor). The reason why the thickness index for the E horizon was calculated as 1-E thickness was just so that it positively correlated with the other podzolization indexes and thus added to the PDI value. An apparent thinning of the E horizon with time (i.e. upward migration of the E/B horizon) in Finnish Podzols was also found by Aaltonen (1952).

This study showed that soils classified as Podzols in the field (based on morphological properties of spodic horizon) generally do meet the WRB criteria to be classified as Podzols if oxalate Al and Fe extraction is used but would be less successful if only the colour criterion 3a for an overlying albic horizon has to be met.

It would be interesting to determine if other properties for defining a spodic horizon such as ODOE and cracked coatings would succeed in Finnish soils but these were not determined in BioSoil. Yli-Halla *et al.* (2006) used the presence of cracked coating to determine if cultivated soils were Podzols. They noticed clear increase of cracked coating in B horizons compared to E or C horizons.

Podzolization is predominating soil formation process in Finland and this should perhaps be considered the naming of lower orders of major soils types Arenosols, Cambisols and Regosols. Observation of profile photographs in the BioSoil Database suggested that some profiles classified in the field as Arenosols, Cambisols or Regosols were podzolized.

4.2. Soil formation factors and degree of podzolization

The forest soil profiles in the Finnish BioSoil database provide the best available data with which to evaluate podzolization and classification of Podzols according to international soil classification systems such as the WRB. The description and data for a large number of profiles distributed all over the country were available for this study.

In this study three indexes of podzolization based on both morphological and chemical properties within the soil profile and the sum of the indexes were used. The indexes were positively correlated with each other, the correlation between the Thickness index and Rubification index be significant and that between the Rubification index and the Al+Fe index nearly so. The Al+Fe index describes the eluviation-illuviation podzolization process chemically, while Thickness and Rubification indexes describe the podzolization process morphologically. As noticed in other podzolization studies carried out in Finland (Pohjola and Räisänen 1998) and northern latitudes (Gustafsson *et al.* 1995), the illuviation of aluminium oxides is greater than that of iron oxides. The Al+Fe index considers only ½ of the amount of illuviated oxalate Fe, however iron strongly influences rubification. Conversely, aluminium has a greater influence on the Al+Fe index, but aluminium oxides being colourless, has no influence on the Rubification index. Shaetzl and Mokma (1988) created a numerical index of soil development; POD, based on only morphological properties in United States. According to this index the E horizon turns whiter, B horizons redder and number of sub horizons increases as soil develops further.

The variables used in this study as proxies of the five soil formation factors to explain the degree of podzolization showed the strongest correlations (in the case of the continuous variables) and significant differences (in the case of the categorical variables) with the PDI, as would be expected since it is the sum of three other indexes. Given the complexity of soil formation, the many factors involved and their interactions, it is not surprising that the correlations and differences for individual variables were not generally strong. Development of a multi-variate model to explain the variation in the podzolization indexes would be more effective, but beyond the scope of this thesis.

Climate

Precipitation and temperature are important factors in podzolization (Lundström *et al.* 2000a). Correlations between Rubification, Al+Fe and PDI indexes on the one hand and latitude and longitude, which are proxies for climate, on the other indicate that podzolization decreases with lower temperatures and rainfall. Temperatures in Finland decrease northwards (Alalammi 1987), and thus soil formation processes are slower (Yli-Halla and Mokma 1998). Precipitation increases towards eastern parts when evapotranspiration decreases towards north and east (Alalammi 1987), resulting in increased humidity and infiltration to the soil from southern and coastal areas to northern and eastern Finland.

The Thickness index increased with both latitude and longitude. The thickness of the E horizon was greater in the moister sites. Development on E horizon is similar with the findings in Finnish soils by Aaltonen (1940). He also noticed that E horizons develop thicker from drier to moister sites. This indicates the importance of freely draining water in the development of E horizons.

The Rubification index was lower on moist sites. If soil water content is too high in moist sites, this can affect to oxidation of iron and therefore the accumulation of Fe in the B horizon and colour of the soil. Seibert *et al.* (2007) found that ferric Podzols predominate in dry sites in Sweden, and this would appear to be the same in this study. Ferric Podzols are dominated by accumulation of iron which would increase the Rubification index. However, this finding in contrast to that reported by Shaetzl and Mokma (1988) in the USA. They found Podzols were more developed in moist sites (somewhat poorly drained) than in drier sites. They measured the degree of development with POD index, which is based on only morphological properties of the soil.

The Al+Fe index was greater on moist sites. This index describes the illuviation between E and B horizon. Soil moisture assists the illuviation of the soil profile and hence the Al+Fe index. In the studies by Schaetzl and Isard (1996) in USA and Jauhiainen (1973) in Finland, the effect of snow cover was examined. They both found that thicker snow cover assist podzolization. Snow cover increases the amount of melting waters in spring that would infiltrate the soil. Snow cover is thickest in eastern parts of Finland (Alalammi 1987) and therefore helps explain the increase in podzolization intensity eastwards. Snow cover also tends to be thicker in shady slopes (Egli *et al.* 2006) and this may help explain the effect of aspect (topography) observed in this study. Slope aspect was found to influence to thickness of E horizon, which is dependent of water infiltration. Although southern slopes can receive more radiation accelerating soil processes, it can also affect to evapotranspiration and infiltration of soil water (Eger and Hewitt 2008). Aspect also has effect on weathering (Egli *et al.* 2006). Carter and Ciolkosz (1991) noticed slightly thinner E horizons in southwest slopes when compared to northwest slopes in USA. Because the leaching of weathering products are essential for podzolization (Lundström *et al.* 2000a), the degree of podzolization can be more intense on shady slopes in spite of being cooler. In the study of Podzols related to soil formation factors (vegetation, aspect, time) in South Wales, Crampton (1965) noticed that slopes in colder climate were more humid and acid in the past. However, relief is relatively small in Finland and this may explain the relatively small effect of the slope and aspect variables (climate soil formation factor) in this study.

Topography

Although slope and aspect had relatively little effect of podzolization, profile age and elevation are closely related in Finland. Thus profile age and elevation were found to be positively correlated to each other and to the podzolization indexes, although not always significantly. However, the local soil formation factor of slope position was found to have no effect on podzolization.

Elevation in Finland increases towards the north and east. According to Aaltonen (1940) podzolization is more intense in northern and eastern parts (old soils) of Finland when compared to coastal areas (young soils). Starr and Tamminen (1994) found that thickness of E horizon correlates negatively with longitude, latitude and elevation of the site and positively with temperature sum. In this study, the thickness of E horizon decreased towards the north, as also noticed by Starr and Tamminen (1994) who considered this as an age effect.

Aaltonen (1952) noticed that the thickness of Podzol E horizons decreased from young soils in coastal areas towards older (higher) soils. Although E horizons were thicker in younger soils, the horizons were still less weathered and leached, thus less developed than the thinner E horizons of older (higher) Podzols. Petäjä-Ronkainen *et al.* (1992) also observed that the thickness of E horizon started to decrease after certain soil age, although no explanation was given. This is notable, because normally thickening of a horizon is a sign of podzolization development, as discussed earlier.

Other than the Thickness index, the podzolization indexes indicated that the most intensive podzolization occurred at 150-200 m, asl. This may be because sites in this elevation class are older and therefore have been exposed to soil formation processes for longer, but it may also be related to the climate factor. According to Aaltonen (1952), the most podzolized areas in Finland are in eastern and northern parts in the same elevation class, 150-200 m (asl), as in this study (data not showed). This was also supported by the study by Starr and Tamminen (1994). In addition, the bedrock in this elevation class mostly consists of granitic and gneissic rocks (Alalammi 1986), which assist podzolization (Lundström *et al.* 2000a). Only the Al+Fe index showed a clear influence of slope position, with lower slope positions showing the most intense illuviation. Such sites would receive runoff and melt waters from upslope. Jankowski (2014) found that lateral podzolization in Poland is rather general in soils located on slopes. He noticed a higher accumulation of Al and Fe in lower hill areas, as in current study. This was explained not only by greater water supply and percolation but also related to higher soil pH values in downslope positions. A higher soil pH would result in more intense precipitation of Al and Fe organic complexes formed during podzolization. Seibert *et al.* (2007) found thicker E horizons in upslope areas in Sweden. No such a finding was noticed in current study. They also noticed that topography affects more the thickness of the O horizon.

Parent material

Soil texture has strong influence on water infiltration and percolation through the profile, and good drainage is essential for podzolization (Shaetzl and Isard 1996). Coarser soils are more leached and eluviation from E horizon in more intense (Aaltonen 1945). In this study most intensive development of podzolization was associated with till and soils having a high silt fraction.

Tills consist at least of some silt fraction because they are unsorted material. According to Lintinen (1995), tills rich in coarse silt fraction occur in east and southeast Finland while finer fractions of till material are more abundant in coastal areas. Tills in Finland are mainly sandy tills, where water can freely drain. However, tills in east Finland are rich in fines (<0.06) and contain a considerable amount of rocks (Räisänen (1990) and those in Ostrobothnia consist of fine textured fractions (Taipale and Saarnisto 1991). According to Lintinen (1995), supra- and sub-aquatic areas do not significantly differ concerning the fine and clay fractions of tills. Lintinen (1995) divided Finland into different provinces based on the content of fine fractions of till. In general tills in supra-aquatic areas are sandier than sub-aquatic tills, which are more enriched in clay material. A high clay content of the parent material was found to decrease podzolization (Jien *et al.* 2009). In this study, the thickness of the E horizon decreased with the clay content although the correlation was not significant. High clay content would prevent infiltration. It was also noticed that the old soils, which had a thinner E horizons, had low clay contents. Hawker *et al.* (1992) observed that Podzols in Africa had weaker E horizon development when having finer parent material.

High silt content, fine silt at least, can slow water movement in the soil profile and hence soil formation processes. In Canada it was found that podzolic soils occurred typically in loamy till, but that the degree of sorting affected podzolization (Evans and Manly 1983). This was also noticed in Norway (Strand, 1994), where podzolization was greater in tills having loamy sand texture**.** However, Mokma *et al.* (2004) and Yli-Halla *et al.* (2006) suggested that sandy rather than loamy parent materials have the strongest podzolization in Finland.

In this study, soil texture influenced to the Thickness index, Rubification index and PDI. The coarser and more sorted the parent material was, the thicker the E horizon.

The increase of the Rubification index in soils with fine material can be explained by the effect of texture on the illuviation of Fe oxides. Koutaniemi *et al.* (1988) found that soil Fe contents are greater in soils having a smaller particle size. Rubification is caused by the illuviation iron oxides. More intense rubification in fine soils is contrary to the findings of Evans and Cameron (1985). They found that rubification increases in sandier soil material because sand has less surface area to be coated when compared to loamy textured soils. Therefore sand requires less iron and carbon to develop as red soil colour than loamy material.

The Al+Fe index and PDI were found to be higher in till material than in glaciofluvial soils. Glaciofluvial material is more sorted, i.e. sandier and has been transported longer distances than till (Petäjä-Ronkainen 1992). Sandy material is usually dominated by quartz and feldspars, where the source of Al and Fe and weathering are limited. However, the fine material of till consists of minerals that can release Al and Fe in the soil. The rocky moraine hills in eastern Finland are rich in fine material containing K-rich micas and biotite, sources of Fe (Räisänen 1990).

Yli-Halla *et al.* (2005) suggested that higher amounts of biotite in the soil parent material results in stronger B horizon formation. Biotite is an easily weatherable mineral (Starr *et al.* 2014) and common in Finnish granitic rocks. Especially granitic rocks can be enriched in Fe (Mälkki 1998). In Scandinavia it is noticed that biotite is absent in E horizons but abundant in C horizon indicating that biotite is an important source of illuviated iron in soil profiles (Melkerud *et al.* 2000, Yli-Halla *et al.* 2006). According to Righi *et al.* (1997), smectite, which is abundant in E horizons, is derived the weathering of micaceous parent material and finally altered to amorphous oxides and hydroxides. Tevendal *et al.* (1990) suggested that as much as 90 % of the mica in Podzols in Norway has been altered to secondary minerals. According to Lundström *et al.* (2000a) Podzols are usually developed in acidic (Felsic) parent material, while parent material rich in mafic and ultramafic minerals can inhibit podzolization. However DÀmigo *et al.* (2008) found that podzolization occurs in soils consisting of mafic and ultramafic parent material if vegetation and climate conditions are favourable for podzolization. This illustrates the interaction of soil formation factors and the fact that they are often not independent.

Biotic

The biotic soil formation factor had more influence on the Thickness and Rubification indexes and less on the Al+Fe index and PDI. Biotic soil formation factors (variables) are often dependent on other soil formation factors such as climate, parent material and topography. The vegetation on fertile sites are usually more nutrient demanding and the soil of fertile site types may consist more of mafic minerals, i.e. having more easily weatherable Fe-minerals and greater rubification. More fertile sites can be assumed to have more fine-earth in the soil which would help retain soil moisture and so favour greater biomass production. Nevertheless too wet conditions, as indicated by >50 % Sphagnum mosses coverage, lowered the Rubification index presumably the result of limited oxidation.

But generally the E horizons were thicker in more fertile sites having wetter soil conditions. This was also noticed by Aaltonen (1940). The Al+Fe index, however, behaved in the opposite way, the index increasing in dryer sites. Dryer sites will tend to be dominated by coniferous trees, Scots pine in particular, and have less deciduous tree present. Coniferous trees produce more acidic litter and soil conditions than deciduous tree litter and therefore more weathering. According to Räisänen (1990), the solubility of Al increases in unfertile soils and Nikodem *et al.* (2013) found high intensity of podzolization under spruce forests. Van Breemen *et al.* (2000) noticed that podzolization is influenced by mycorrhizal fungi which occur under coniferous trees. Fungi speed up weathering as a result of the organic acids they exude. Fertile site types are assumed to have more deciduous trees thus creating a less acidic litter and less acidity to soil. Koutaniemi *et al.* (1988) in northern Finland found soil pH increased with site type productivity, presumably due to a greater deciduous tree component in the forests. Higher soil pH also increases the proportion of soil fauna, especially earthworms (Phillips and Fitzpatrick 1999), resulting in more mixing of soil horizons and formation of brown earth forest soils rather than Podzols.

Carter and Arocena (2000) found that moss cover and species composition affected podzolization in Canada. Soils under mostly *Ptilium* had more soil development compared to soils under *Pleurozium* cover, the difference in species reflecting a difference in soil moisture conditions. Both moss species are common in Finnish forests. Although podzolization is usually thought to occur under coniferous forests or shrub vegetation (Lundström *et al.* 2000a), Stutzer (1999) found strongly podzolized soils in Norway above the tree line where climatic conditions were unfavourable for development of Podzols. Those soils were formed under lichen mats where production of organic material was low. Thus podzolization can occur under various plant communities.

Time

The influence of time on soil formation is commonly studied using chronosequences where the influence of other soil formation factors is reduced. In Finland a strong relationships between soil age and podzolization have been recognized in several studies (Aaltonen 1952, Jauhiainen 1973, Koutaniemi *et al.* 1988, Starr 1991, Starr and Tamminen 1994, Mokma *et al.* 2004).

In this study the effect of time was studied looking at the correlation between profile age and the various podzolization indexes. All indexes were found to be affected by time, particularly the Al+Fe index. Mokma *et al.* (2004) also found strong positive correlation between oxalate Al+Fe concentrations and soil age in podzolized profiles. Also Sauer *et al.* (2008), working in Norway, found positive correlations between soil age and oxalate Al and Fe. Schwertmann (1973) found increasing oxalate Fe concentrations with podzolization development and that the depth of Fe concentrations moves downwards in the profile. Räisänen (1996) found that Podzols with various age in Finland had different depth of Fe and Al oxide maximum concentrations. The young Podzols had Fe+Al maxima in the B horizon while in old soils the Al oxide maximum was lower in BC horizon. Barrett and Schaetzl (1992) noticed the same behaviour of Al and Fe oxides in sandy soils of USA. In BioSoil the profile soil samples were only taken from the upper B horizon. In that case, the maximum Al concentrations may deeper and be better suited to the Al+Fe index. Nevertheless, the oxalate Al+Fe data from the upper B horizon worked both on terms of identifying the WRB spodic diagnostic horizon and in terms of the correlations of the Al+Fe index for the degree of podzolization.

The thickness of the E horizon slightly decreased with profile age. According to Buurman and Jongmans (2004), accumulation of sesquioxides in B horizon increases and thickness of the E horizon increase with time, especially during the first millennia. This was related to boreal Podzols where organic matter dynamics is fast and accumulation of metals in B horizon high. Based on the studies mentioned and the findings from this study, it can be assumed that rate of podzolization decreases with soil age. Starr (1991) found that the rate of podzolization decreased with soil age, podzolization being most rapid during the first 2500 years. In older soils processes starts to stabilize and changes in soil properties decreases. The E horizon becomes highly weathered and further release of elements slows down. At the same time accumulated sesquioxides in the B horizon protect the soil particles from weathering more (Yli-Halla *et al.* 2006) and prevents the E horizon from getting thicker. The accumulation of sesquioxides in the B horizon changes permeability

(Ritari and Ojanperä 1984, Mecke *et al.* 2002, Jankowski 2014) and the downwards movement of water in the soil profile deteriorates influencing the development of the E horizon. Aaltonen (1940) and Jauhiainen (1969) both noticed the same behaviour of E horizon thickness with soil age as in this study. However in the study by Koutaniemi *et al.* (1988) and Mokma *et al.* (2004), E horizon thickness increased with time.

4.3. Evaluation of errors

Although deglaciation and history of Baltic Sea has been widely studied, determination of soil age includes uncertainties. Areas under The Litorina Sea and supra-aquatic areas are fairly well determined in Hakku. This database does not include boundaries for areas under The Yoldia Sea and The Ancylus Lake however, hence profile dating in those areas is rather coarse. Soil ages in sub-aquatic areas were not available, hence information of soil ages were gathered from several sources and are rather rough. The influence of local ice lakes on soil profile ages was not considered in this study. However, only one BioSoil profile was located under ice lake according to data collected from Hakku service. In addition, Petäjä-Ronkainen *et al.* (1992) pointed out that podzolization anyhow would not have started before the spread of coniferous forest, some 8500 yr. BP.

Soil sampling and data collection was made by several people and this can be a significant cause variation in the data and influence to the strength of relationships. Soil sampling is crucial in this research. Mixing of material from different horizons can clearly affect the results. Nevertheless, the BioSoil data, which is the most comprehensive such data available, described the theoretical background of podzolization. Determination of soil colour is based on human eye and colour vision varies between individuals. Also the determination of soil texture class, topographical position of site, site type, soil moisture class in the field can vary among observers. Human activity as a soil forming factor was not considered in this study although activities such as fertilization, liming and ploughing affect podzolization (Yli-Halla *et al.* 2006). These actions can also disturb the boundaries between horizons, which can make the use of morphological properties in the field for classification problematic. On the other hand podzolization occurs after cultivation and afforestation, as shown by Olsson and Melkerud (1989) and Nikodemus *et al.* (2012).

5. CONCLUSIONS

- Field classification of Podzols, based on morphological features (colour and thickness of the E and B horizons, development of a hardpan), works well in Finnish soils.
- Most (91%) profiles classified as Podzols in the field meet the criteria of WRB (2007), indicating that the field based identification of Podzols is reasonably reliable. However, the colour criterion of albic horizon is problematic in Finnish soils. The Al+Fe oxalate extraction, which is relatively simple, is important for verification of field based classification.
- There was evidence that E horizon thickness and whitening decreases rather than increases with age
- Podzolization intensity is poorly explained by individual soil formation factor (variables). Soil processes occur simultaneously and there is much interaction among soil formation factors. In certain situations, indexes based on morphological or chemical properties acts opposite way to each other. Nevertheless, time and soil texture (parent material) were the most important factors. Topography was noticed to have only a minor effect on podzolization.
- Given the complexity of soil formation, the many factors involved and their interactions, it is not surprising that the correlations and differences for individual variables were not generally strong. Development of a multi-variate model to explain the variation in the podzolization indexes would be more effective, but beyond the scope of this thesis.

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8. APPENDICES

Appendix I. Field form used in BioSoil for soil profile description.

Appendix II. BioSoil categorical variables used in this study and their classes.

Appendix III. Criteria of diagnostic spodic B horizon. World Reference Base for Soil Resources (WRB 2007).

Appendix IV. Criteria of diagnostic albic horizon. World Reference Base for Soil Resources (WRB 2007).

Appendix I. Field form used in BioSoil for soil profile description.

PROFIILILOMAKE / VMI-pysyvät 1995

VMI- koord. Y	VMI- koord. X	Koeala	N.ottoala	Humuslaji	Maannos	FAO maannos	Kuopan syvyys, cm	Kerrosnro	Kiv.maa-näyte-koodi 1) 211 212 213	Horisontti	Paksuus, cm	Selvyys	Muoto	Keskiraekoko	Lajittuneisuus	Kivisyys, 10%	Kovuus	Rakenne	Ruostetäplät	Tuore väri hue	Tuore väri value	Tuore väri chroma	Huomautukset
								1															
Toissijaisesti								2															
								3															
								4															
								5															
								6															
								7															
								8															

1) vain näytekerroksille

HUMUSLAJI
0 puuttuu
1 kangashumus 1
2 kangashumus 2
3 mullas
4 multa
5 turve 1
6 turve 2

MAANNOS
0 turvemaannos
1 ruskomaa
2 pods. ruskomaa
3 rautapodsoli
4 humuspodsoli
5 gleimaannos
6 savimaannos
7 heikosti kehittynyt
8 häiriintynyt
9 kalliomaa

SALLITUT HORISONTTI-MERKINNÄT
OF, OH, OFH kgshumus mullas
H1, H2, H3 turve
- - - - - - - - - - - - - - - - - - - -
AH multa
AP muokkaus
E, EH huuhtoutumis
- - - - - - - - - - - - - - - - - - - -
B, BH, BS, BW
BHG, BHS, BSG, BWG
BC, BCG
- - - - - - - - - - - - - - - - - - - -
C, CG pohjamaa
G gleihorisontti
- - - - - - - - - - - - - - - - - - - -
R kallio
K isokivi
W pohjavesi
- - - - - - - - - - - - - - - - - - - -
1 ja 2 kaikkien kanssa

SELVYYS
0 määrittelemätön
1 jyrkkä
2 selvä
3 vähittäinen

MUOTO
0 määrittelemätön
1 tasainen
2 aaltoileva
3 epäsäännöllinen
4 katkonainen

KESKIRAEKOKO
1 savi
2 hiesu
3 hieno hieta
4 karkea hieta
5 hieno hiekka
6 karkea hiekka
7 sora

LAJITTUNEISUUS
1 lajittumaton
2 hiukan lajittunut
3 selvästi lajittunut
4 rapakivisora

KOVUUS
1 pehmeä
2 melko pehmeä
3 melko kova
4 kova
5 erittäin kova

RAKENNE
0 ei sekund. rakennetta
1 mururakenne
2 muu (levy, pylväs, prisma)

RUOSTETÄPLÄT
0 ei esiinny
1 heikkoja, pieniä tai vähän
2 melko selviä, keskikokoisia
3 selviä, isoja tai runsaasti

FAOn maannos
1 Dystric Gleysol
2 Umbric Gleysol
- - - - - - - - -
3 Eutric Regosol
4 Dystric Regosol
- - - - - - - - -
5 Dystric Leptosol
6 Lithic Leptosol
- - - - - - - - -
7 Haplic Arenosol
8 Cambic Arenosol
9 Gleyic Arenosol
- - - - - - - - -
10 Eutric Cambisol
11 Dystric Cambisol
12 Gleyic Cambisol
- - - - - - - - -
13 Haplic Podzol
14 Cambic Podzol
15 Ferric Podzol
16 Carbic Podzol
17 Gleyic Podzol

Appendix II. BioSoil categorical variables used in this study and their classes.

Variable	Classes
Young/Old	1= young soils (<9000), 2= old soils (>9000 years cal. BP)
Supra-/Sub-aquatic	1= supra-aquatic areas, 2= sub-aquatic areas
Elevation	1= <50, 2= 50–100, 3= 100–150, 4= 150–200 (m, asl)
Topography	0= flat, 1= hill top/upper slope, 2= slope, 3= lower slope/toe, 4= hollow, 5= other
Slope aspect	0= flat, 1= N, 2= NE, 3= E, 4= SE, 5= S, 6= SW, 7= W, 8= NW
Moisture status	1= very dry, 2= dry, 3= fresh, 4= wettish, 5= wet, 6= very wet
Sphagnum cover	0= 0, 1= <1, 2= 1-10, 3= 11–25, 4= 26–50, 5= >50 (%)
Bare rock cover	0= 0, 1= <1, 2= 1-10, 3= 11–25, 4= 26–50, 5= >50 (%)
Site type (in order of increasing fertility)	1= grove (OMaT), 2= grove-like heath forest (OMT), 3= mesic heath forest (MT), 4= sub-xeric heath forest (VT), 5= xeric heath forest (CT)
Coarse fragments	0= 0, 1= 1-5, 2= 6-15, 3= 16–40, 4= 40–80, 5= >80 (%)
Mean grain size	1= fine (clay & fine silt), 2= medium-coarse (silt & fine sand), 3= coarse (coarse sand & gravel)
Parent material	1= bedrock, 2= water-lain clay/fine sediments, 3= till, 4= glaciofluvial, 5= aeolian, 6= peat

Appendix III.

Diagnostic criteria

A spodic horizon:

1. Has a pH (1:1 in water) of less than 5.9 in 85 % or more of the horizon, unless the soil is cultivated; and
2. Has an organic carbon content of 0.5 percent or more or an optical density of the oxalate extract (ODOE) value of 0.25 or more, at least in some part of the horizon; and
3. Has one or both of the following:
   a. an albic horizon directly overlying the spodic horizon and has, directly under the albic horizon, one of the following Munsell colours, when moist (crushed and smoothed sample):
      i. a hue of 5YR or redder; or
      ii. a hue of 7.5 YR with a value of 5 or less and a chroma of 4 or less; or
      iii. a hue of 10 YR or neutral and a value and a chroma of 2 or less;or
      iv. a colour of 10 YR 3/1;or
   b. with or without an albic horizon, one of the colours listed above, or a hue of 7.5 YR, a value of 5 or less and chroma of 5or 6, both when moist (crushed and smoothed samples), and a one or more of the following:
      i. cementation by organic matter and Al with or without Fe, in 50 percent or more of the volume and very firm or firmer consistency in the cemented part; or

      ii. 10 percent or more of the sand grains showing cracked coatings; or

      iii. 0.50 percent or more Al_{ox}+½Fe_{ox} [26] and an overlying mineral horizon which has a value less than one –half that amount in an overlying mineral horizon; or

      iv. an ODOE value of 0.25 or more, and a value less than one-half that amount in an overlying mineral horizon; or

      v. 10 percent or more (by volume) Fe lamellae[27] in a layer 25 cm or more thick; and
4. Does not form a part of a natric horizon; and
5. Has a C_{py}/OC[28] and a C_f/C_{py} [4] of 0.5. or more if occurring under tephric material that meets the requirements of an albic horizon; and
6. Has a thickness of 2.5 cm or more

Explanations:

Al_{ox} and Fe_{ox}: acid oxalate-extractable aluminum and iron, respectively, expressed as percent of the fine-earth (0-2 mm) fraction on an oven-dried (105° C) basis (Blakemore, Searle and Daly, 1981).

Iron lamellae: non-cemented bands of illuvial iron less than 2.5 cm thick.

C_{py}, C_f and OC: pyrophosphate-extractable C, fulvic acid C and organic C, respectively, expressed as percent of the fine earth (0-2 mm) fraction on an oven-dried (105° C) basis (Ito et al. 1991).

Appendix IV.

Diagnostic criteria

An albic horizon has:

1. a Munsell colour (dry) with either:
   a. a value of 7 or 8 and a chroma of 3 or less; or
   b. a value of 5 or 6 and a chroma of 2 or less; and
2. a Munsell colour (moist) with either:
   a. a value of 6, 7 or 8 and a chroma of 4 or less; or
   b. a value of 5 and a chroma of 3 or less; or
   c. a value of 4 and a chroma of 2 or less[2]. A chroma of 3 is permitted if the parent materials have a hue of 5YR or redder and the chroma is due to the colour of uncoated silt or sand grains; and
3. a thickness of 1 cm or more.