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The effect of clear cutting on podzolisation and soil carbon dynamics in boreal forests (Middle Taiga zone, Russia)

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Abstract

Boreal forests are one of the most important terrestrial carbon sink, and a large portion of C is allocated in soil for long-term storage. However forest harvesting may quickly affect soil carbon stocks and dynamics, especially where organic substances drive the soil-forming processes, such as in Podzols. To evaluate the effects of clear cutting on carbon dynamics and podzolisation process over a short time period, a pristine boreal forest (Komi Republic, Russian Federation) and a recently clear cut site (5 year-old) were selected. Soils are polygenic: podzolisation occurs within the clay-depleted eluvial horizon, formed by a previous lessivage process. Because podzolisation can start only after the eluvial horizon has reached a sort of threshold, bisequal soils allow to individuate comparable pedogenic conditions prior to anthropogenic disturbances.

Harvesting increased C storage in the upper part of the soil profile (organic layer and podzolic sequum) from 2.2 to 5.0 kg m⁻². The abundance of recalcitrant woody materials on the forest floor together with an increase in soil water saturation, discernible by the vegetation survey and iron fractionation, prevented litter degradation and allowed organic matter accumulation at the soil surface. Fulvic acids (FA) in the organic layer of the pristine site showed a low incorporation of polysaccharide and proteinaceous moieties, confirming a higher degradation of the humified fraction than at the clear cut site. The lack of disturbances allowed a selection of FA with the more oxidised and mobile fractions accumulating in the deeper horizons, as currently observed in Podzols. Almost no differences were instead found in the chemical composition of FA along the profile from the clear cut site. A larger portion of FA have migrated through the profile after clear cutting even below the Bhs horizon (Cfulvic acid/C-humic acid >1) with a marked increase in the FA-carbon stocks with respect to the pristine forest soil (0.66 and 0.30 kg m⁻² down to 30 cm, respectively).

Clear cutting also affected Al and Fe dynamics. The reducing conditions acted upon soil mineral surfaces and enhanced Fe mobilisation probably both in the ionic form and complexed with organic matter. The Al dynamics was instead more related to short term transformations of the layer silicate phases. Traces of a poorly crystalline chlorite were detectable in the Bhs in the pristine forest, but at the clear site only hydroxy-interlayered vermiculite was present. The high amounts of organic acids that migrated through the Bhs after clear cutting may have partially complexed the Al from pedogenic chlorite, giving rise to hydroxy-interlayered behaviour, as normally occurs in Podzol eluvial horizons from where the organic Al-complexes migrate.

If this dynamics proceeds further the bisequal soil may partially lose its present characteristics, with the migration downwards of the whole podzolic sequum. This may have important implication on C budget, as organic carbon will be transferred deeper in the soil profile limiting its losses at least over a short time period.

Introduction

Worldwide boreal forests and woodlands provide a total sink for 0.6-0.7 Pg of C per year, of which 0.13 Pg C yr⁻¹ are in the forest floor and soil organic matter (Goodale et al., 2002). Carbon accumulation in soil is thus an important part of the carbon cycle in forest ecosystems, and a number of efforts has been made in the last years to evaluate the effects that several kinds of disturbances have on soil carbon stocks and dynamics.

Russian pristine spruce forests are currently subjected to anthropogenic disturbances, especially in the form of timber harvesting by clear cutting: 77% of 809 million ha of forest area are designated primarily for production functions (FAO, 2006). Forest harvesting affects organic matter dynamics in soil through removal of above-ground tree biomass, alteration in the proportion of plant residues returned into soil, and shift in the under-storey vegetation and microflora associations. The coniferous forest litters consist mainly of needles, and woody debris represent 20-40% of the total above-ground litterfall (Kögel-Knabner, 2002), whereas in logging residues woody materials are approximately 70% (Smolander et al., 2008) with a consequent higher abundance of lignin and cellulosic components. These changes are expected to affect organic matter decomposition rate, because recalcitrant biocompounds are selectively preserved during the initial phases of litter degradation (Von Lützow et al., 2006) and can accumulate in the short period after clear cutting. As a consequence, soil may be affected in term of biogeochemical processes and pedogenesis, specifically where organic substances drive the soil-forming processes, such as in Podzols and podzolic soils (Nave et al., 2010).

The soils of the Middle Taiga develop in a cold continental region at the interface between the area of Podzols and that of Albeluvisols (Driessen et al., 2001). In this ecotonal condition, soils with two eluvial-illuvial sequa are often found. Such polygenic soils have typically an E-Bs sequum overlying an E²-Bt sequum. According to several pedogenic theories (reviewed by Schaetzl, 1996), bisequal soils form through a two-step process that follows cation leaching. First, lessivage (clay

translocation) starts in the cation desaturated soil, and the E-Bt sequum develops. Next, as the E horizon has become clay-depleted and increasingly acidic, podzolisation begins and Fe and Al are chelated by organic acids and translocated downward, thus producing E-cheluviated and Bs-chilluviated horizons within what was previously the E horizon of the sequum formed by lessivage. As the podzolic sequum is closer to the surface, and podzolisation is a much faster process than lessivage (e.g. Burt and Alexander, 1996; Hallmark and Franzmeier, 2000; Mokma and Evans, 2000), the upper soil part should be the most sensitive to small changes and disturbances, and thus bisequal soils may record variations in pedogenic processes and pathways (Schaetzl, 1996). Several papers have documented changes in podzolisation following forest disturbances. Barrett and Schaetzl (1998) reported depodzolisation 100 years after clear cutting in Michigan. Mossin et al. (2001) found a lack of immobilisation of Al in Bs horizons after 70 years Sitka spruce plantation on former heathland. However, some changes may occur even more rapidly, as observed in a Norway spruce dominated boreal forest, where an increase in carbon and nitrogen in E and B podzolic soil horizons was observed after only 3 years since clear cutting (Pirainen et al., 2002). The increase of carbon in the mineral horizons may derive from C depletion of the organic layers, as observed by Olsson et al. (1996) in a podzolic soil 15-16 years after Norway spruce harvesting. Different results were obtained in a hardwood forest 15 years after clear cutting, where a severe decrease of carbon pools was found: Ussiri and Johnson (2007) reported in fact a reduction of the concentration of humic and fulvic acids by more than 40% in Oa, but also in E and Bh mineral horizons. The transformation and dynamics of C after clear cutting in podzolic ecosystems are therefore still not straightforward; part of the uncertainties may be linked to the effects that slight site condition variations have on soils where fluxes of organic carbon naturally occur to a great extent. In this context, bisequal soils represent an optimal situation to understand the effects of anthropogenic disturbances, because they have a double environmental significance: (i) if the development of the lower sequum is comparable, then “undisturbed” podzolisation should have proceeded with the same intensity in the upper part of profiles; (ii) podzolic sequum would be extremely sensitive to

the environmental changes. Thus, present tendencies in the podzolisation process would be the results of recent disturbances. We evaluated therefore the effects of clear cutting on organic matter in bisequal soils, to provide some insight into the changes in the dynamics of carbon and the consequences on pedogenic processes during the first years after harvesting operations.

Materials and methods

The study area is located in the Ust'-Kulom region (Figure 1a), Komi Republic (Russian Federation). It belongs to the Middle Taiga ecological subzone, and is located at the Southern end of the Timan ridge, which is basically composed of paleozoic sediments: quartzites, sandstones, limestones, dolomites, marls, and clays, covered by quaternary glacial and outwash sediments (Andreicheva, 2002). Soils develop in clay loams overlying moraines and fluvio-glacial deposits. The mean air temperature is +0.3°C, and the length of the frost-free period is approximately 90-100 days. Mean annual precipitation is 514 mm. The thickness of the snow cover is, on the average, 85 cm.

Two sampling areas, comparable for all pedogenic factors with the exception of present plant cover, were chosen: an undisturbed site (or pristine forest), and a recently clear cut site, harvested 5 years before sampling. At the undisturbed site the forest is dominated by Norway spruce and the volume of the standing biomass was 233 m³ ha⁻¹. In the recently disturbed forest all trees with diameter ≥10 cm were cut in the winter 2001-2002, when the snow cover prevented physical disturbance to the soil surface. About 200 m³ ha⁻¹ of stem biomass was harvested and logging residues were left on the site. Before clear cutting the forest composition was the same at the two sites and made by 80% Norway spruce and 20% of *Abies sibirica* and *Betula pendula*, with a canopy density of 90% at both sites (Bobkova and Galenko, 2006).

A vegetation survey was carried out on 5 rectangular plots (I to V) of 100 m² at each site to obtain an overview of the ecological conditions of the sites. The specie names were given according to

Tutin et al. (1993) for vascular plants and to Ignatov and Ignatova (2004) for bryophytes. An index of abundance-dominance was given to each species in the shrub, herb and moss layers, according to the standard procedure of the Zurich-Montpellier school (Braun-Blanquet, 1964; Westhoff and Van der Maarel, 1973).

At each site, a topographic survey was performed on an area of about 0.5 ha and morphology maps were obtained on the basis of clinometric classification after contour line digitalisation each 10 cm (Figures 1b and 1c). At the undisturbed site, a first soil investigation was performed by approximately 100 observations either by pit opening or auger drilling. Soil morphology indicated that all soils were Podzolic according to the Russian soil classification system (Shishov et al., 2004) that basically identifies this soil type with the presence of the eluvial horizon. Bisequal soils dominated the area. With the exception of some small depressions, where the upper part of soil had a thick organic horizon and redoximorphic features in mineral material (Peaty-gleyic Podzolic soils, in the Russian soil system, 4% of total area according to Simonov et al., 2007), the other bisequal soils were well drained, with thin organic layers, reddish-brown coloured illuvial horizons rather close to the surface and top E horizon more or less depleted in organic matter (i.e. Iron-illuvial and Humus-leaked podzolic soils). Thus, a soil profile was described near to the summit position and taken as reference of the pristine forest soil (Profile 1, Figure 1b). To study the effect of clear cutting, in the recently clear cut site a profile was open in a similar and comparable topographic position on the basis of the morphology map (Profile 2, Figure 1c). Samples were taken from each genetic horizon of the profiles. The samples were air-dried, sieved and the soil analyses were carried out on the fine earth fraction of mineral and organic soil horizons. In all horizons, the coarse fraction (>2 mm) was absent. The POD index, which reflects podzolisation strength, was computed according to Schaetzl and Mokma (1988) as:

$$POD\ index = \sum \Delta V \cdot 2^{\Delta H} \quad (1)$$

where ΔV is the Munsell colour value (moist) difference between the E and Bs horizons and ΔH is the number of Munsell pages different in hue.

The pH was determined potentiometrically in a 1:2.5 or 1:20 soil:deionised water suspension for mineral or organic horizons, respectively (Van Reeuwijk, 2002). The total soil organic carbon (C_T) and total nitrogen (N_T) contents were measured by dry combustion (CE Instruments NA2100). The texture was determined by the pipette method after oxidation of the organic matter using H_2O_2 and dispersion of the sample with a sodium hexametaphosphate solution (Gee and Bauder, 1986). Amorphous iron (Fe_o) and aluminium (Al_o) forms were estimated through extraction with acid-ammonium oxalate (Schwertmann, 1964), and Fe and Al in the extracts were measured by atomic absorption spectrometry (AAS, Perkin Elmer 3030). Pedogenic iron oxides (Fe_{DCB}) were estimated through extraction with Na-dithionite-citrate-bicarbonate (Mehra and Jackson, 1960). The bulk soil composition was determined by HF- HNO_3 , following the method of Arinushkina (1970), and the elements in the extracts were analysed by AAS.

For each horizon the stocks of C_T on a volume basis were calculated by taking into account the thickness and using the following pedotransfer function to estimate the bulk density in each horizon (Bonifacio et al., 2008):

$$BD = 1842 - 267 \ln(C_T) \quad (2)$$

where BD is bulk density [$g\ dm^{-3}$] and C_T the content of organic carbon in the horizon [$g\ kg^{-1}$ fine earth].

The clay fraction ($<2\ \mu m$) was separated by sedimentation, Mg saturated with $MgCl_2$, washed until free of Cl^- , and freeze-dried for the mineralogical investigations. The X-ray diffraction (XRD) analyses were carried out using a Philips PW 1710 diffractometer (40 kV and 20 mA, Co- $K\alpha$ radiation, graphite monochromator) on Mg-saturated (Mg), ethylene glycol (EG) solvated, and heated ($550^\circ C$) oriented mounts. Scans were made from 3 to $35\ ^\circ 2\theta$ at a speed of $1.5\ ^\circ 2\theta\ min^{-1}$. The identification of clay minerals was made according to Thorez (1975), by evaluating the variations in peak positions and intensities in all XRD patterns. The presence of Al-hydroxopolymers in the interlayers was ascertained, and their thermo-stability assessed, by K saturation and heating the

samples at 110, 350 and 550°C. The X-ray diffractograms were routinely smoothed and the background was subtracted using Powder-X (Dong, 1999).

The total extractable organic fraction (TE) was obtained with NaOH using the procedure described by Schnitzer (1982). An aliquot of the extract was used to quantify C forms. Humic (HA) and fulvic acids (FA) were operationally separated by acidifying the alkaline extract to pH 1 with HCl. The supernatant containing FA was separated from the precipitate (HA) by centrifugation, and FA further purified through a PVP resin. The C and N contents of the TE, FA and HA solutions were determined using a TOC analyser (Vario TOC Elementar). The non-extractable carbon (C_{NE}) and nitrogen (N_{NE}) were determined from the difference between C_T or N_T and the TE carbon or nitrogen content, respectively.

Another aliquot of the TE extract was used to isolate the HA and FA for their characterisation. After acidification and centrifugation, humic acids were demineralised by shaking overnight with a 0.1M HCl:0.3M HF solution (solid:liquid ratio 1:1), then washed with deionised water until the solution pH was 3. Fulvic acids were purified by using XAD-8 and IR-120 resins. Both HA and FA solutions were freeze-dried. The elemental composition (C, N, H, S) of HA and FA was determined with an elemental analyser (CE Instruments NA 2100); the O content was calculated by difference. The Fourier-Transform Infrared (FT-IR) spectra of fulvic acids were recorded using pellets prepared by pressing 1 mg of fulvic substances with 400 mg of KBr. Spectra were acquired from 4000 to 400 cm^{-1} , at 4 cm^{-1} resolution and 16 scans were averaged (Nicolet Impact 410).

The stocks of C in TE, HA, FA (C_{TE} , C_{HA} , C_{FA}) were determined as described for total C stocks.

Results

Vegetation

Only a few species were present in the shrub and herb layers (Table 1). In the pristine forest *Vaccinium myrtillus*, *Dryopteris carthusiana*, *Maianthemum bifolium* and *Oxalis acetosella* prevailed, while at the clear cut site *Carex globularis* and *Equisetum sylvaticum* dominated and

indicated moister conditions. *Agrostis gigantea*, typically connected with wetland communities, was also present but only at the clear cut site.

In the moss layer, a lower number of species at the disturbed site was observed. In addition, *Dicranum scoparium*, *Hylocomium splendens* and *Pleurozium schreberi*, typical species of mesic conditions, were less present in the clear cut area, while at the pristine forest they were recorded in all survey plots, and dominated the moss layer.

Soil morphology and chemical characteristics

In the upper part of both soil profiles, below the litter layer, organic material was at different stages of decomposition and therefore Oa or Oe/Oa horizons were present, followed by E and Bhs horizons (Table 2). Below the spodic horizons, the clay-depleted horizons (E' or EB) reached the same depth in both profiles (46-48 cm), which indicated the lowermost boundary of clay eluviation. Below them, E/Bt or Bt/E with well developed albeluvic tongues were found. The deepest horizons were Bt. Both profiles were therefore bisequal. In the upper part, the texture of the podzolic sequum ranged from loam to silty-loam, whereas in the deeper luvic sequum it varied from silty-loam to clay-loam (Table 2). Clay migration evidenced in the field from clay cutans on the ped faces was confirmed by textural data meeting the criteria for diagnostic argic horizons. In the clay-depleted E' or EB horizons overlying the albeluvic tongues the amount of clay was rather similar in the two profiles. In the argic horizons the clay content was again almost identical in the two profiles.

In both soils the podzolic sequum was dominated by the eluvial horizon, being it at least twice as thick as the Bhs horizon. The POD index of podzolisation, which takes into account the differences in colour between eluvial and illuvial horizons (Table 2), was 1 for both soils. In the soil profile of the pristine forest (Profile 1), the Bhs horizon was too shallow for allowing this soil to be classified as a Podzol. The soils were thus classified according to the WRB (ISSS Working Group WRB, 2007) as Cutanic Albeluvisol and Albic Podzol at pristine forest and at the clear cut site,

respectively; whilst according to the Soil Taxonomy (Soil Survey Staff, 2010) as Typic Glossocryalf and Typic Haplocryod, respectively.

Both soils were acidic at the surface and pH values increased downward the profile (Table 2). The total organic carbon (C_T) content in the organic layers was 269 and 338 g kg⁻¹ in Profile 1 and 2, respectively. In both profiles a vertical translocation of C_T was visible as indicated by its accumulation in the Bhs horizons (Table 2). Conversely to what occurred in the organic layers, Profile 1 had higher C_T contents than Profile 2 in the podzolic sequum.

The typical trend of Fe and Al forms arising from the podzolisation process was visible (Table 3): an eluvial, Fe and Al-depleted horizon overlaid an illuvial, Fe and Al-enriched Bhs. In the E and Bhs horizons of Profile 1 the Fe_O content was 0.19 and 0.74%, respectively, and lower than in the corresponding horizons of Profile 2 (0.26 and 1.17%). The Al_O content was instead similar: 0.12-0.21% and 0.16-0.26%, respectively in Profile 1 and 2. Poorly crystalline Fe forms constituted almost the totality of pedogenic iron oxides in the podzolic sequum of both profiles, as evident from the Fe_O/Fe_{DCB} ratio close or equal to 1 (Table 3). Below the spodic horizons the content of Fe_O and Al_O decreased, as well as the proportion of poorly crystalline Fe oxides (Fe_O/Fe_{DCB} ≤ 0.50). In the luvic sequum of Profile 1 the E' horizons were depleted in Al_O, while in Profile 2 the distribution of aluminium was more homogeneous. The total SiO₂ content decreased with depth as a result of residual enrichment of Si in the upper part of the profiles (Table 3). The ratio between Si and Fe_T sharply decreased from the top to the bottom horizons in both profiles, while the Si to Al_T ratio showed less pronounced variations (Table 3). The high Si/Fe_T ratio in the E horizon of Profile 2 suggested higher reducing conditions at the surface of the clear cut site than in the pristine forest.

Mineralogical soil properties

The argic and E/Bt or Bt/E horizons of both profiles showed the presence of a wide peak at 1.4 nm that moved to 1.7 nm after EG solvation, and partially collapsed at 1.0 nm when the sample was heated to 550°C (Figures 2a and 2b). The 1.0 nm peak in the heated samples was however rather

wide and asymmetrical in all horizons. At 1.0 nm a peak was detectable in the Mg-saturated sample as well as a peak at 0.7 nm that disappeared after heating at 550°C. Upon EG-solvation a small peak at 1.4 nm became visible and was more pronounced in the horizons with albeluvic tongues. A broad asymmetric diffraction band, from 1.0 nm towards the low-angle side was always present after heating the samples. The clay fraction of these horizons was therefore composed by smectite, vermiculite, illite and kaolinite. Smectite and/or vermiculite were also present as mixed layer minerals with illite, as deduced from the broad diffraction band (1.4-1.0 nm) in the Mg-saturated samples. The pronounced asymmetry of the 1.0 nm peak after heating the samples at 350°C (Figure 2c) was indicative of Al polymers in the interlayers, and the lack of complete collapse even at 550°C indicated that Al intercalation has proceeded to such an extent to give rise to a chlorite-vermiculite irregular mixed layer mineral.

The E' horizons of Profile 1 and the EB of Profile 2 showed the presence of kaolinite, illite, vermiculite and smectite-illite mixed layers and traces of chlorite (Figure 3). A relatively narrow and symmetrical peak at 1.0 nm was obtained after heating the samples at 550°C, but only a partial collapse was obtained at 350°C. Al-interlayering was therefore present in the clay-depleted horizons of the two profiles, with a similar degree of filling, and/or a similar thermal stability of the Al-polymers. With respect to the underlying horizons, swelling minerals were less abundant and were present only as mixed layers. The luvic sequa of the two Profiles were therefore rather similar in mineralogical composition.

In the podzolic sequum, the E horizons showed the presence of a very broad peak around 1.2 nm that decreased in intensity upon EG-solvation and partially shifted towards 1.6 nm (Figure 4). A diffraction band between 1.4 and 1.0 nm was however still present after solvation in both samples. Both clay samples showed the complete collapse to 1.0 nm at 550°C, and no chlorite was identified. The eluvial horizons of the podzolic sequum were therefore composed of smectite-illite mixed layers, vermiculite, illite-vermiculite, illite and kaolinite. The Mg-saturated XRD pattern of the Bhs horizon from Profile 2 was dominated by a broad asymmetric diffraction band that extended from

1.4 nm to 1.0 nm (Figure 4). Upon EG-solvation, part of the 1.4-1.0 nm diffraction band moved towards the low-angle side. The Bhs from Profile 1 showed a similar behaviour although the shape of the 1.4-1.0 nm diffraction band was different. In both samples however swelling minerals were present as randomly interstratified smectite-illite mixed layers, but they were more abundant in Profile 2. The two Bhs horizons also differed in the degree of collapse after heating the K-saturated samples. In Profile 1 progressive changes were visible between 110 and 350°C, a complete collapse was obtained at 550°C but a small peak at 1.4 nm was still visible. In Profile 2, some materials collapsed when the sample was heated to 350°C, but no further changes were visible at higher temperature. Al-interlayering was therefore more complete in Profile 2, although other minerals with Al-polymers of low thermal stability were also present. Illite was present in both soils; vermiculite, interstratified illite-vermiculite minerals, kaolinite, and traces of a poorly crystalline chlorite, visible only in Profile 1, completed the clay mineralogical composition.

Carbon stocks and organic matter characteristics

The total stocks of carbon were 4.5 and 7.4 kg m⁻² in Profile 1 and 2, respectively (Table 2). The difference was mainly caused by higher amounts stored in the upper part of the profiles. The C_T stocks were similar in the luvic sequa (2.2 and 2.5 kg m⁻² in Profile 1 and 2), whereas in the podzolic sequa 1.3 and 3.5 kg C m⁻² were found, respectively.

In the organic layers, the C concentration in the TE fraction was 174 g kg⁻¹ in Profile 1 and 186 g kg⁻¹ in Profile 2, and accounted therefore for 65 and 55% of C_T (Table 4). Consequently, the amount of C_{NE} was 95 and 152 g kg⁻¹, respectively. As expected from the morphological characteristics (Oa in Profile 1 and Oe/Oa in Profile 2), a higher amount of carbon in the non-extractable fraction was found in the litter of the clear cut site. The HA content was lower in the O horizon of Profile 2, while the FA content was similar at both sites. Total nitrogen was higher in Profile 1 than in Profile 2 and indicated that the organic material at the clear cut site was N-poorer. Nitrogen deficiency was confirmed by the C_T/N_T, C_{TE}/N_{TE} and C_{NE}/N_{NE} ratios (Table 5), but was

not related to the humic fraction (HA+FA) as in this fraction the C/N ratio was similar, or even slightly lower in Profile 2.

The elemental analysis showed the similarity in HA of the two profiles (Table 6). The FA had a higher H/C ratio in the organic layer of the clear cut site indicating a larger proportion of the aliphatic component. This could be related to a greater contribution of saccharide residues, as evinced by the more pronounced band at 1070 cm^{-1} (polysaccharide C-O stretching) in the FT-IR spectrum of the organic layer in Profile 2 (Figure 5). In contrast, the FA of Profile 1 had a higher O/C ratio and the more pronounced band at 1720 cm^{-1} (C=O stretching of COOH) indicated that this was likely due to an appreciable content of carboxyl groups.

In the mineral horizons, the amount of carbon and nitrogen in the TE fraction followed the C_T and N_T trend, with an accumulation in the Bhs horizons, and with higher values in Profile 1 than in Profile 2 (Table 4). As a consequence, C_T/N_T decreased along the profiles and was higher in Profile 2 (Table 5).

In both soils, HA decreased with depth, whereas FA accumulated in the Bhs horizons. The C_{FA}/C_{HA} ratio indicated a marked translocation of FA into the Bhs of Profile 2, where, in addition, a C_{FA}/C_{HA} ratio > 1 was found also in the clay-depleted horizon.

The FT-IR spectrum of FA (Figure 6) showed a peak at 2940 cm^{-1} , due to aliphatic C-H stretching, in the E horizon of Profile 1 that became less pronounced in the Bhs and E'1 horizons, in agreement with the H/C ratio trend as visible in the Van Krevelen diagram (Haumaier and Zech, 1995; Figure 7a). Conversely, the intensity of the band at 1720 cm^{-1} increased progressively from the E to the E'1, parallel to the higher O contents (Table 6). The highest O/C ratio was found in the clay-depleted horizon (Figure 7a), while the C/N ratio increased with depth (Table 6). The data thus indicated a dominance of aliphatics at the surface and pointed to a selective translocation of fulvic material enriched in highly acidic compounds and depleted in N downwards the profile. The FA chemical composition of Profile 2 was more homogenous with depth. No trends were present either in the O/C or H/C ratios (Figure 7a), the bands at 1720 and 1070 cm^{-1} had similar intensities in all

mineral horizons, and the band at 1640 cm^{-1} (C=C stretching) was slightly weaker but only in the EB horizon (Figure 7).

Conversely, humic acids had a similar composition in the two profiles, and showed in general more differences with depth than FA. The C content ranged from 52 to 60%, clearly decreasing along the profile, and N followed the opposite trend (Table 6). As a consequence, in both profiles the C/N molar ratio decreased from top to bottom. An increase in the aromatic component was observed with depth in both soils, while the O/C ratio indicated the presence of more oxidised materials in the deeper horizons (Figure 7b).

The C_{TE} stocks confirmed the richness in organic matter of the upper part of Profile 2 (organic layers and podzolic sequum) already observed with total C stocks (Figure 9). In the O layer of Profile 1 the C_{TE} stock was 0.61 kg m^{-2} while in the Profile 2 it was 0.80 kg m^{-2} and in the podzolic sequum 0.94 and 2.26 kg m^{-2} . The stocks of HA and FA were higher in Profile 2 than Profile 1, but only in the E and Bhs horizons. Thus, all carbon fractions increased after clear cutting in the podzolic sequum, and the stocks of TE and FA doubled. This was confirmed also by considering all mineral horizons down to a fixed depth (Figure 8).

Discussion

Undisturbed pedogenic processes

In both soils, clay translocation was evident in the deeper part of the profile and podzolisation in the upper. The formation of the luvic sequum has occurred with similar intensity in the two profiles: the clay concentration in the argic horizons was similar, as was the lower limit of the clay-depleted horizons. The mineralogical analyses pointed towards the same intensity of transformations, supporting the hypothesis of similarity in the pedogenic processes that originated the luvic sequa. As the main driver of pedogenic processes for Luvisols is the amount of water percolating through the profile (e.g. Chesworth, 1992), similarity at the two sites entails comparable local hydrologic conditions during the formation of the luvic sequa. In both profiles smectite was more abundant in

the Bt than in the other horizons, thus it probably derived from a selective enrichment caused by translocation from the clay-depleted horizons, where only a mixed layer swelling phase was found. The presence of vermiculite, of HIV and of chlorite-vermiculite mixed layers indicated that weathering has occurred through the intercalation of Al-polymers into the interlayers of the vermiculite. This transformation is rather common in Luvisols and Albeluvisols (e.g. Bonifacio et al., 2009); the pH of the bottom horizons may have favoured the incorporation of Al in the interlayer of vermiculite, according to the data reported by Xu et al. (1990), thus explaining the lower degree of Al-interlayering found in the clay-depleted horizons of both profiles. No differences in the present mineralogical composition of the luvic sequa of the profiles were visible, indicating that the eluvial clay-depleted part, in which podzolisation has started, was comparable, and suggesting that also undisturbed podzolisation should have proceeded with similar intensity in both profiles.

In the upper sequa, podzolisation gave rise to an eluvial Fe and Al-depleted layer overlying an illuvial Fe and Al-enriched Bhs horizon. The process of podzolisation was clearly discernible from the increase in organic carbon, Fe and Al in the illuvial horizons. Both soils were characterized by thicker E horizon than Bhs, indicating that the cheluviation has prevailed over the chilluviation process. The POD index was identical among the profiles and suggested that intensity of podzolisation was similar in the two soils from the morphological point of view.

Below the E horizons, fulvic acids prevailed over humic acids with higher C_{FA}/C_{HA} ratio in Bhs, as observed in many Podzols (e.g. Andreux, 1996). Although humic and fulvic acids are not characterised by distinct types of molecules (Sutton and Sposito, 2005), their separation based on the different amount of dissociable groups gives useful information on their relative mobility in soil. Consequently, in Profile 1, before disturbances, the migration of FA involved the most acidic and oxidised, aromatic compounds (Lündstrom et al., 2000).

The mineralogical data showed that in both profiles the typical clay transformations of Podzols eluvial horizons have occurred: swelling phases have developed and the stability of Al-polymers in

the interlayers has decreased (Righi et al., 1999; Egli et al., 2003). The high acidity and the complexing capacity of low molecular weight compounds and fulvic acids led to a destabilisation of the Al-hydroxopolymers (Drever and Stillings, 1997), and accounted for the disappearance of HIV minerals from the E horizons. In addition, the formation of smectites has occurred, increasing the amount of swelling mixed layers with respect to the clay depleted horizons.

Any difference in the dynamics of Al, Fe and organic matter between the podzolic sequa of the two profiles was therefore likely to be caused by clear-cutting giving indications about the consequent disturbance to pedogenic processes.

Clear cutting effect on pedogenic processes and soil organic matter

Clear cutting had two immediate and macroscopic consequences, that in turn may have affected pedogenic processes in the upper sequum: i) the increase in soil moisture evidenced by vegetation; ii) the increase in total carbon in organic horizons.

Loss of trees changes soil climate conditions by reducing evapotranspiration and leading to increased soil moisture, and in some cases causes anaerobic conditions within the rooting zone (Prescott et al., 2000). This was clearly evinced at the clear cut site by the presence of *Carex globularis* and *Equisetum sylvaticum*, which are good indicators of hydromorphism (Barkman, 1951; Niippola and Carleton, 1991). The species recorded in the moss layer further stressed the increase in humidity, with a higher abundance of more hydrophilic species, and the decrease or disappearance of the most mesophilic ones. These results strongly confirm the findings by Tseplyaev (1965) who described the development of hydromorphic conditions after clear cutting on wide areas in Russia. Changes in the lower layers of forest communities due to intensive exploitation of forest is a common phenomenon in the Middle Taiga zone of the Komi Republic, as reviewed by Degteva (2003). In more humid forest, the effect of the clear cutting is visible already after 3 year on the regeneration of tree species that show lower growth rate due to the changing hydrological conditions (Roy et al., 2000).

The presence of logging residues on the forest floor induced an increase in poorly decomposed organic matter in soil organic horizons, which was markedly visible both as C_T and C_{NE} content and C_T stocks. At the clear cut site, both bulk organic matter and the non-extractable fraction had a higher C/N ratio than at the pristine forest, as expected from the larger abundance of woody tissues (Smolander et al., 2008). Upon changes in the composition of biomass inputs, a selective decomposition of litter residues according to their biochemical composition should have occurred, thus inducing an accumulation of inherently more slowly decomposing compounds in the non extractable organic fraction at the soil surface. Another factor that probably contributed to the accumulation of C_T and C_{NE} was also the increase in soil water saturation after clear cutting, which could change microbial activity and consequently organic matter decomposition rate (e.g. Pennanen et al., 1999; Chauvat et al., 2007).

Fulvic acids showed a low incorporation of polysaccharide and proteinaceous moieties in the pristine forest, suggesting that the humified material was decomposed, and the more oxidised and mobile fractions selectively migrated into the deeper horizons. Five years after clear cutting, the process of migration was enhanced, as a larger portion of FA was found in the Bhs and the clay-depleted EB horizon and the FA to HA ratio increased compared to Profile 1. Such change has been reported by Abakumov et al. (2010), who observed a higher proportion of the most mobile fraction of humic substances already in the youngest terms (10 and 20 year-old) of a podzolic soil chronosequence, both in mineral and organic horizons. The role of FA and organic acids in the podzolisation process is largely acknowledged (e. g. Dawson et al., 1978, Lundström et al., 2000), but along Profile 2 the FAs were chemically homogenous indicating that no chemical selection of FA during migration along the profile has occurred. A simple enhancement of the cheluviation-chilluviation process, although favoured by an increase in soil moisture (e.g. Schaetzl and Isard, 1996; Egli et al., 2007), is however not sufficient to explain the variation in the chemical properties of the podzolic sequum after clear cutting. In Profile 2 a remarkable depletion of Fe has occurred from the primary phases in the E horizon, as shown by the 50% higher Si/Fe_T ratio than in Profile 1.

Only small variations in the Si to Al ratio were instead visible, indicating that iron mobilisation differed from that of aluminium. Because of the increase in moisture after clear cutting, Fe mobilisation from the eluvial horizon may have occurred both in ionic form, or as Fe^{2+} complex with organic matter released into the soil by the logging residues. In fact, iron reduction in absence of oxygen is a rapid process when coupled with suitable reductants, as organic matter (Chen et al., 2003). However, only little precipitation of metal-organic complexes occurs for Fe^{2+} (Nierop et al., 2002), and the soluble complexes should thus represent a high proportion, or dominate, even at the highest Fe/C ratios (Jansen et al., 2003). This mechanism may account for the increase of Fe_O and the relative content of FA also below the Bhs horizon.

Short term transformations in the layer silicate phase may account for the increase of Al_O concentration below the Bhs in Profile 2. The Bhs horizon of Profile 1 had traces of a poorly crystalline chlorite, while this mineral was not present in the corresponding horizon of Profile 2, where instead, a higher degree of Al intercalation in the silicate layers was found. The high amounts of organic acids that migrated into the Bhs and below, after clear cutting, could have partially complexed the Al from the poorly crystalline pedogenic chlorite, giving rise to hydroxy-interlayered behaviour. This is the mineralogical transformation that normally occurs in Podzol eluvial horizons from where the organic Al-complexes migrate (Righi et al., 1999; Egli et al., 2003). In this case the migration of Al seems to have involved the Bhs, and the accumulation has actually taken place in the clay-depleted horizons of the luvic sequum. Mineralogical transformation may occur rather quickly in the presence of organic ligands (e.g. Kelly et al., 1998) and in situ experiments have demonstrated that in three years significant dissolution of feldspars occur in field conditions (Nugent et al., 1998; Augusto et al., 2000). The transformations we observed five years after clear-cutting were apparently striking, but they actually have involved only the interlayer of phyllosilicates, with the displacement and reprecipitation of Al species. Variations in interlayer cation species have been reported even after only three years from clear-cutting tree (Ranger et al., 2008) and the intercalation of Al hydroxides into the interlayer space of vermiculites has been

observed after three years of in-field incubation (Augusto et al., 2001). If the transformations we have observed would proceed further, additional Al and organic carbon may be transferred deeper in the soil profile with the migration downwards of the whole podzolic sequum. In fact in Profile 2, the stocks of C_T calculated in the luvic sequum were already slightly higher than those found in Profile 1.

Conclusions

Bisequal soils are sensitive systems and anthropogenic disturbances have affected their evolution also in the short-time period. Harvesting operations changed vegetation composition and soil moisture conditions: the presence of logging residues on the forest floor increased soil carbon stocks, both in organic and mineral horizons, and moister soil conditions promoted the release of Fe from solid phases. As a consequence the podzolisation trend was enhanced and migration of organo-metal complexes seemed to have occurred even below the Bhs horizon. The stocks of carbon markedly increased after clear cutting also in deeper mineral horizons, thus limiting carbon losses in the short-time and enhancing the mineral transformations which are typical of podzolic soils. This tendency may have important implication on C budget, although it may be limited to the first years after clear cutting and should stop when the density of the tree canopy and drier moisture regime in the upper part of soil will be restored.

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Table 1. Indexes of abundance-dominance of shrub, herb and moss species at the two sites (five plots).

	<i>Pristine forest</i>					<i>Clear cut site</i>				
	I	II	III	IV	V	I	II	III	IV	V
Shrub and herb layers										
<i>Rosa acicularis</i>	0	+	0	0	0	2	1	0	0	0
<i>Rubus arcticus</i>	0	0	0	+	0	+	1	+	0	0
<i>Rubus chamaemorus</i>	0	0	0	0	0	0	2	1	0	0
<i>Rubus saxatilis</i>	+	1	0	2	1	+	+	1	+	0
<i>Vaccinium myrtillus</i>	3	3	0	2	1	+	+	+	1	+
<i>Vaccinium vitis-idaea</i>	0	0	0	0	0	+	0	1	0	1
<i>Agrostis capillaris</i>	0	0	0	0	0	1	0	0	0	0
<i>Agrostis gigantea</i>	0	0	0	0	0	1	+	0	1	+
<i>Carex globularis</i>	0	0	0	0	0	4	3	4	3	3
<i>Deschampsia flexuosa</i>	0	0	0	0	0	0	+	0	0	0
<i>Dryopteris carthusiana</i>	2	2	4	3	2	0	0	0	0	0
<i>Epilobium angustifolium</i>	0	0	0	0	0	1	1	+	+	1
<i>Equisetum sylvaticum</i>	1	1	+	+	+	1	3	1	3	1
<i>Festuca gigantea</i>	0	0	0	0	0	0	+	+	0	0
<i>Gymnocarpium dryopteris</i>	+	+	2	2	1	+	1	+	+	0
<i>Linnaea borealis</i>	1	+	+	2	2	+	+	0	+	+
<i>Luzula pilosa</i>	+	+	+	+	+	0	0	0	0	0
<i>Lycopodium annotinum</i>	1	+	+	1	+	+	0	0	+	0
<i>Maianthemum bifolium</i>	2	0	1	2	2	+	+	0	0	0
<i>Melampyrum sylvaticum</i>	1	+	1	+	+	0	0	0	0	0
<i>Milium effusum</i>	0	0	1	0	+	0	0	0	0	0
<i>Minuartia stricta</i>	0	0	0	0	0	0	+	0	0	0
<i>Oxalis acetosella</i>	1	2	2	2	3	+	1	+	1	+
<i>Streptopus amplexifolius</i>	0	0	+	0	0	0	0	0	0	0
<i>Trientalis europaea</i>	+	+	+	+	+	+	+	+	+	1
Moss layer										
<i>Aulacomnium palustre</i>	0	+	0	+	+	+	+	0	+	+
<i>Dicranum polysetum</i>	0	0	0	+	0	0	0	0	0	0
<i>Dicranum scoparium</i>	2	1	2	1	2	+	0	0	+	0
<i>Eurhynchium praelongum</i>	0	0	2	0	0	0	0	0	0	0
<i>Fissidens taxifolius</i>	0	0	0	0	0	0	0	0	0	+
<i>Hylocomium splendens</i>	2	2	2	2	2	+	1	+	2	+
<i>Mnium stellare</i>	0	+	0	+	0	0	0	0	0	0
<i>Plagiothecium laetum</i>	0	0	0	0	0	0	0	0	+	0
<i>Pleurozium schreberi</i>	2	3	1	2	3	2	1	1	3	2
<i>Polytrichum commune</i>	2	1	2	1	1	+	1	0	0	+
<i>Polytrichum juniperinum</i>	0	+	0	0	+	1	0	+	2	1
<i>Polytrichum piliferum</i>	2	0	0	0	0	0	0	0	0	0
<i>Ptilium crista-castrensis</i>	+	1	+	+	1	+	+	0	+	+
<i>Rhythidiadelphus triquetrus</i>	0	0	0	0	1	0	0	0	0	0
<i>Sanionia uncinata</i>	+	0	0	+	+	0	0	0	0	0
<i>Sphagnum girgensohnii</i>	0	0	0	1	0	0	0	+	+	+

4: 50-75%; 3: 25-50%; 2: 5-25%; 1: <5%; +: rare

Table 2. Selected chemical and physical properties of the soils

	Depth	Colour [§]	Sand	Silt	Silt	Clay	pH	C _T	BD	C _T
	cm		%	coarse %	Fine %	%		g kg ⁻¹	Mg m ⁻³	kg m ⁻²
<i>Profile 1- pristine forest</i>										
Oa	1-0	-	-	-	-	-	4.1	268.8	0.35	0.94
E	0-2/8	10YR 6/2 d; 5YR 4/3 m	25.0	38.1	25.3	11.6	4.0	20.4	1.04	1.06
Bhs	2/8-3/9	10YR 5/3 d; 5YR 3/3 m	29.5	28.2	26.2	16.1	4.3	24.6	0.99	0.24
E'1	3/9-23/34	10YR 7/3 d	30.8	35.5	26.2	7.5	4.6	1.2	1.80	0.48
E'2	23/34-35/46	10YR 7/3 d	31.2	30.2	26.6	12.0	4.9	2.2	1.63	0.43
E/Bt	35/46-47/58	10YR 6/4 d	22.5	28.1	19.8	29.6	5.4	1.2	1.80	0.17
Bt	47/58-130+	10YR 5/6 d	22.5	26.9	19.2	31.4	5.6	0.8	1.90	1.15
<i>Profile 2 – clear cut site</i>										
Oe/Oa	1.5-0	-	-	-	-	-	4.1	337.7	0.29	1.46
E	0-11/15	10YR 7/2 d; 7.5YR 5/3 m	37.8	22.5	26.7	13.0	4.4	13.1	1.15	1.97
Bhs	11/15-19/22	10YR 6/4 d; 7.5YR 4/3 m	32.4	24.0	26.3	17.3	4.4	19.4	1.05	1.53
EB	19/22-48	10YR 6/4 d	40.2	21.4	24.2	14.2	5.1	2.0	1.66	0.92
Bt/E	48-73/83	10YR 5/6 d	32.4	19.6	20.4	27.6	5.6	1.1	1.82	0.59
Bt	73/83-130+	10YR 5/6 d	24.8	18.3	25.4	31.5	5.6	1.0	1.84	0.96

C_T: total organic carbon; BD: estimated bulk density

[§]d: dry Munsell soil colour; m: moist Munsell soil colour

Table 3. Al and Fe extraction and total SiO₂ contents in the soil profiles

	Al _O	Fe _O	Fe _{DCB}	Fe _T	Fe _O /Fe _{DCB}	Fe _{DCB} /Fe _T	SiO ₂	Si/Fe _T	Si/Al _T
	%	%	%	%			%		
<i>Profile 1- pristine forest</i>									
E	0.12	0.19	0.21	1.43	0.91	0.14	82.05	106.38	15.10
Bhs	0.21	0.74	0.78	1.76	0.95	0.44	82.53	87.04	14.93
E'1	0.08	0.15	0.34	1.69	0.45	0.20	80.76	89.06	14.52
E'2	0.10	0.24	0.50	2.08	0.49	0.24	81.03	72.27	14.37
E/Bt	0.15	0.20	0.75	3.08	0.27	0.24	74.82	45.19	10.46
Bt	0.14	0.18	0.86	3.40	0.21	0.25	74.46	40.72	9.86
<i>Profile 2 – clear cut site</i>									
E	0.16	0.26	0.26	1.00	1.00	0.25	83.66	155.49	15.70
Bhs	0.26	1.17	1.17	2.64	1.00	0.42	78.78	55.39	12.23
EB	0.15	0.28	0.55	2.30	0.50	0.24	79.02	63.73	11.27
Bt/E	0.13	0.26	0.84	2.89	0.31	0.29	75.39	48.46	9.70
Bt	0.13	0.28	0.76	3.15	0.37	0.24	73.91	43.56	9.16

Table 4. Chemical fractionation of soil organic carbon

	C_{TE}	C_{HA}	C_{FA}	C_{NE}	C_{TE}/C_T	C_{FA}/C_{HA}
	$g\ kg^{-1}$	$g\ kg^{-1}$	$g\ kg^{-1}$	$g\ kg^{-1}$		
<i>Profile 1- pristine forest</i>						
Oa	173.7	101.0	22.5	95.1	0.65	0.22
E	14.5	6.0	2.3	5.9	0.71	0.38
Bhs	19.5	5.2	6.2	5.1	0.79	1.19
E'1	1.0	0.3	0.3	0.2	0.83	1.00
<i>Profile 2- clear cut site</i>						
Oe/Oa	186.0	68.0	23.0	151.7	0.55	0.34
E	7.3	3.0	1.7	5.8	0.56	0.57
Bhs	14.8	2.3	4.4	4.6	0.76	1.91
EB	1.6	0.3	0.4	0.4	0.80	1.33

TE: total extractable fraction; HA: humic acids; FA:fulvic acids; NE: non-extractable fraction; C_T : total organic carbon

Table 5. Chemical fractionation of soil nitrogen and C-to-N ratios

	N_T	N_{TE}	N_{HA+FA}	N_{NE}	C_T/N_T	C_{TE}/N_{TE}	C_{HA+FA}/N_{HA+FA}	C_{NE}/N_{NE}
	$g\ kg^{-1}$	$g\ kg^{-1}$	$g\ kg^{-1}$	$g\ kg^{-1}$				
<i>Profile 1- pristine forest</i>								
Oa	14.5	10.4	7.3	4.1	18.5	16.7	16.9	23.2
E	1.0	0.9	0.5	0.1	20.4	16.1	16.6	59.0
Bhs	1.4	1.1	0.8	0.3	17.6	17.7	14.3	17.0
E'1	0.1	0.1	0.1	-	12.0	10.0	6.0	-
<i>Profile 2- clear cut site</i>								
Oe/Oa	11.2	7.1	6.8	4.1	30.2	26.2	13.4	37.0
E	0.5	0.4	0.3	0.1	26.2	18.2	15.7	58.0
Bhs	0.9	0.8	0.6	0.1	21.6	18.5	11.2	46.0
EB	0.2	0.2	0.2	-	10.0	8.0	3.5	-

N_T : total nitrogen; C_T : total organic carbon; TE: total extractable fraction; NE: non-extractable fraction ; HA+FA : humic and fulvic acids

Table 6. Elemental content and atomic ratios of purified, ash and moisture-free humic and fulvic acids

		C	N	H	O	C/N	H/C	O/C
		%	%	%	%			
<i>Profile 1- pristine forest</i>								
<i>Humic acids</i>	Oa	60.1	3.94	6.54	28.9	17.8	1.29	0.36
	E	58.9	3.68	6.48	30.6	18.7	1.31	0.39
	Bhs	57.6	4.66	5.06	32.3	14.4	1.05	0.42
	E'1	53.2	6.23	4.42	35.5	10.0	0.99	0.50
<i>Fulvic acids</i>	Oa	51.0	1.37	3.83	43.6	43.2	0.89	0.64
	E	50.8	1.87	4.43	42.6	31.7	1.04	0.63
	Bhs	49.8	1.20	4.08	44.7	48.5	0.98	0.67
	E'1	49.0	1.11	3.81	45.7	51.5	0.93	0.70
<i>Profile 2- clear cut site</i>								
<i>Humic acids</i>	Oe/Oa	56.9	3.17	6.02	33.5	20.9	1.26	0.44
	E	59.8	3.60	7.12	29.1	19.4	1.42	0.37
	Bhs	57.7	4.56	5.92	31.4	14.8	1.22	0.41
	EB	52.0	5.67	3.19	38.5	10.7	0.73	0.56
<i>Fulvic acids</i>	Oe/Oa	56.3	1.42	5.12	36.8	46.1	1.08	0.49
	E	50.9	1.27	4.20	43.4	46.8	0.98	0.64
	Bhs	50.8	1.33	4.08	43.6	44.4	0.96	0.64
	EB	50.4	1.56	4.23	43.4	37.5	1.00	0.65

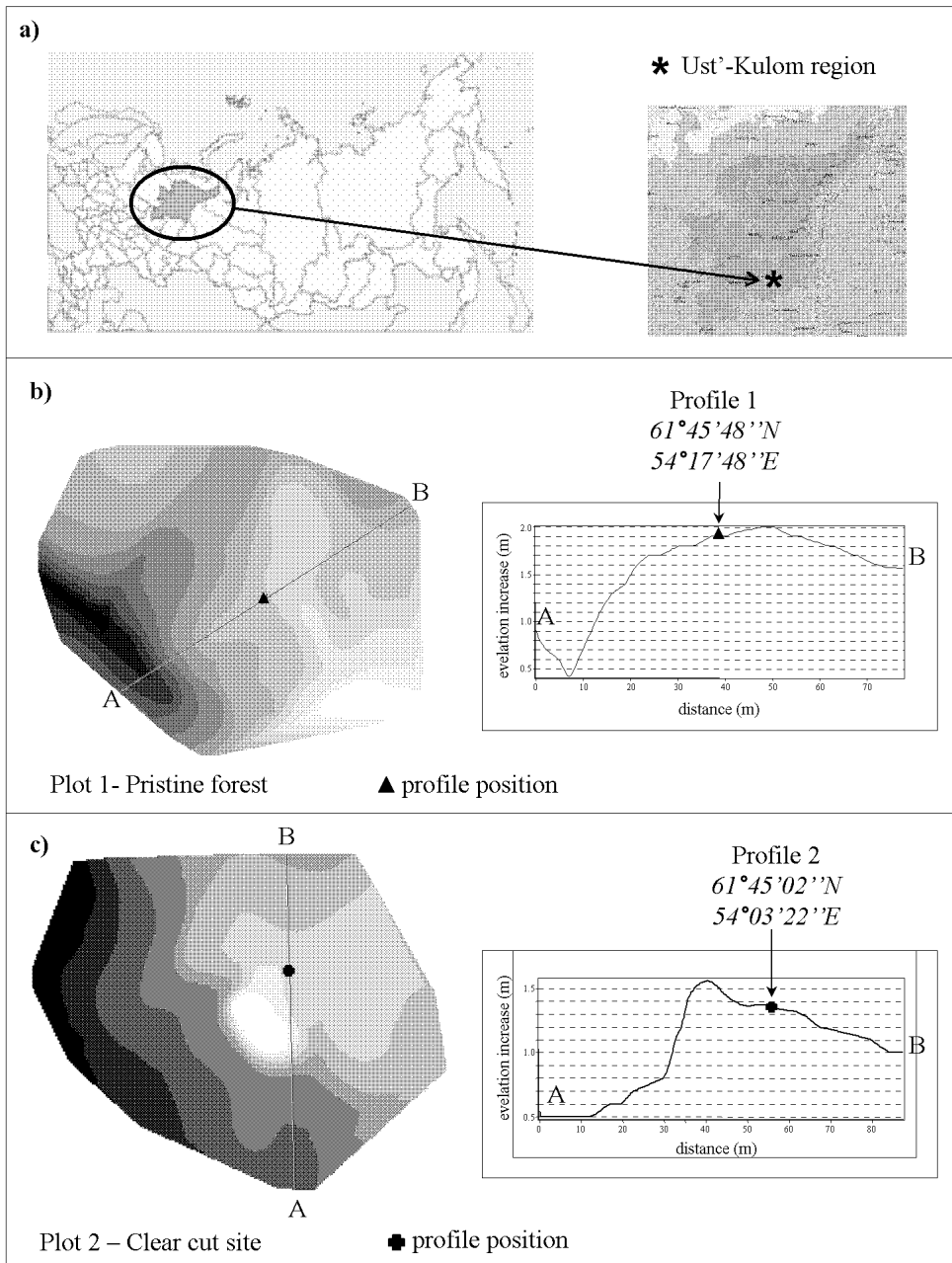


Figure 1. Localisation of study area (a); morphology map and topographic profile of the pristine forest site (b); morphology map and topographic profile of the clear cut site (c). In morphology maps the darkest the colour, the lowest the elevation. The topographic profile represents the variation in elevation along the A-B transect. The equidistance in the morphology map is 0.2 m

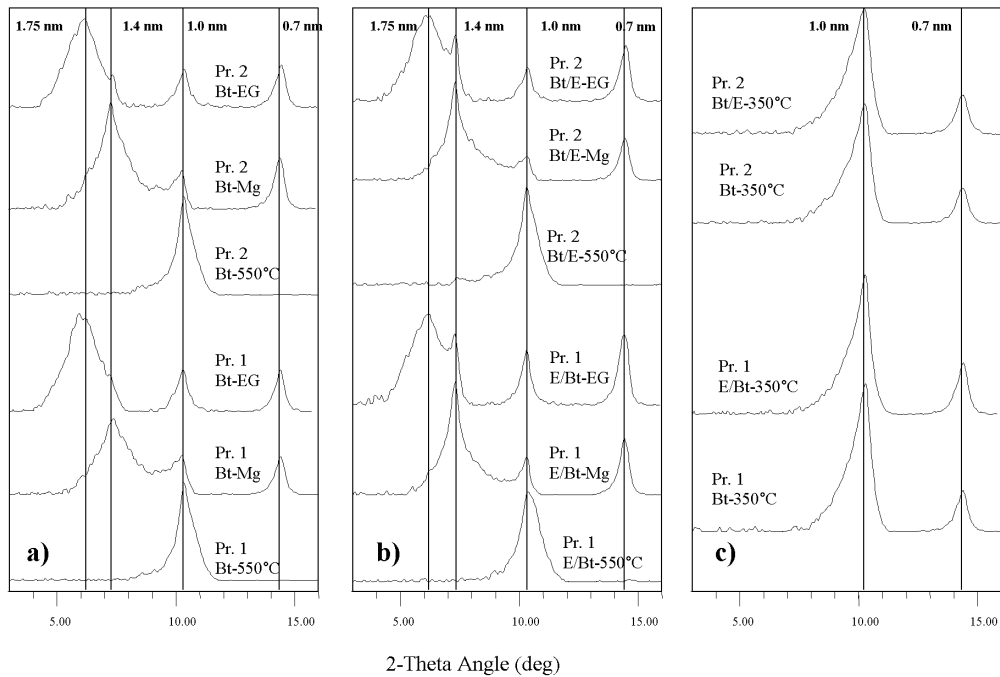


Figure 2. XRD patterns of the clay fraction from deeper horizons of the profiles: a) Bt horizons after Mg saturation (Mg), ethylene-glycol solvation (EG) and heating at 550°C (550°C); b) E/Bt and Bt/E horizons after Mg saturation (Mg), ethylene-glycol solvation (EG) and heating at 550°C (550°C); c) E/Bt, Bt/E and Bt horizons after K saturation and heating at 350°C (350°C)

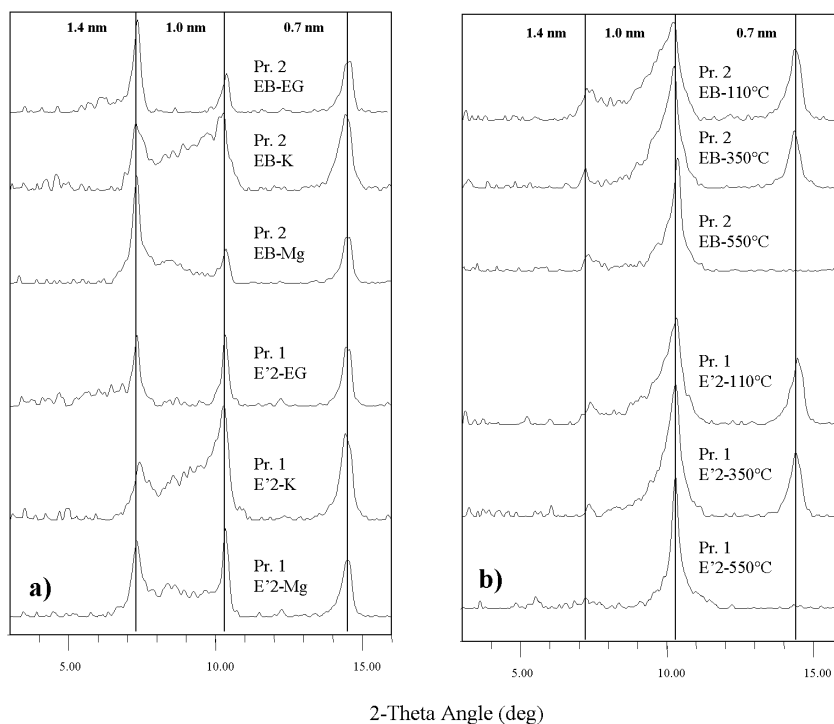


Figure 3. XRD patterns of the clay fraction from the clay-depleted horizons of the profiles after Mg saturation (Mg), K saturation (K), ethylene-glycol solvation (EG) and heating at 110, 350 and 550°C (110°C, 350°C and 550°C, respectively)

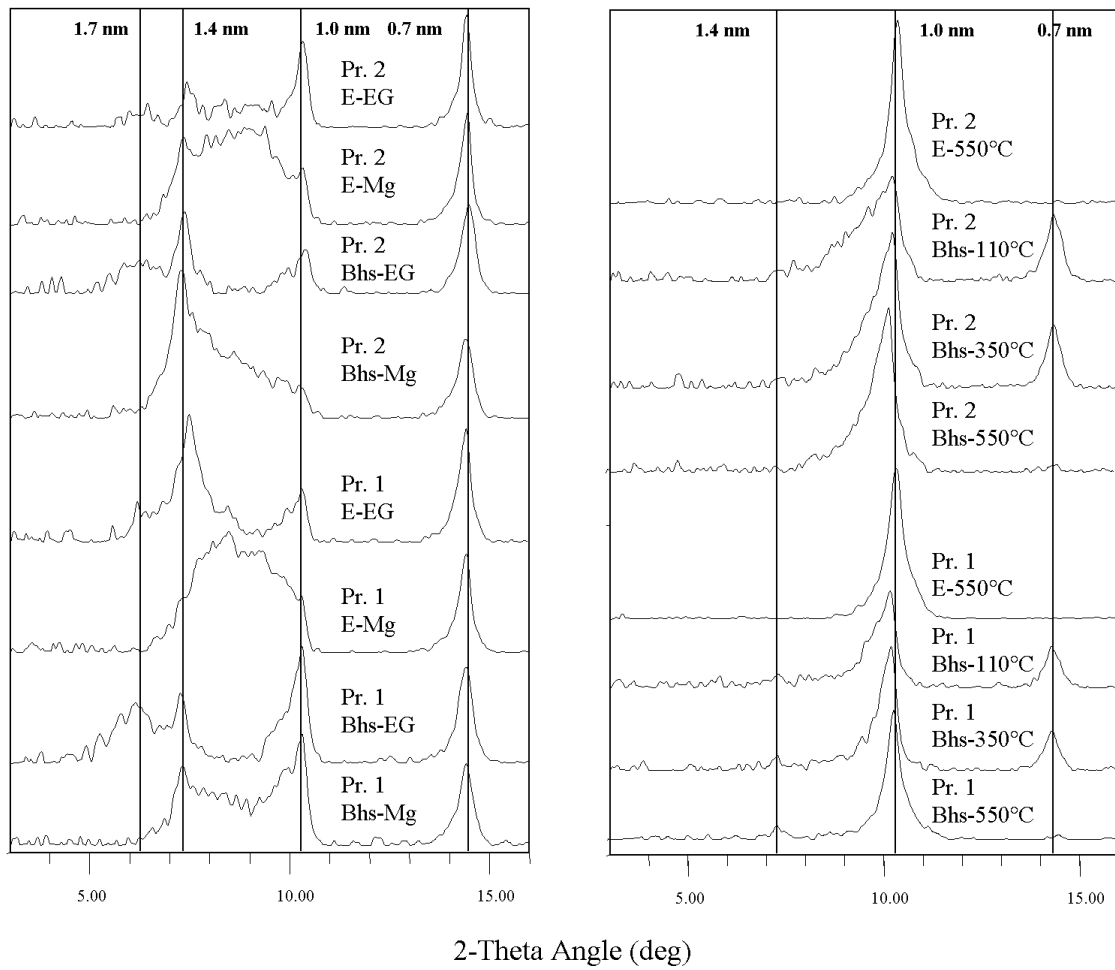


Figure 4. XRD patterns of the clay fraction from E and Bhs horizons of the profiles after Mg saturation (Mg), ethylene-glycol salivation (EG) and heating at 110, 350 and 550°C (110°C, 350°C and 550°C, respectively)

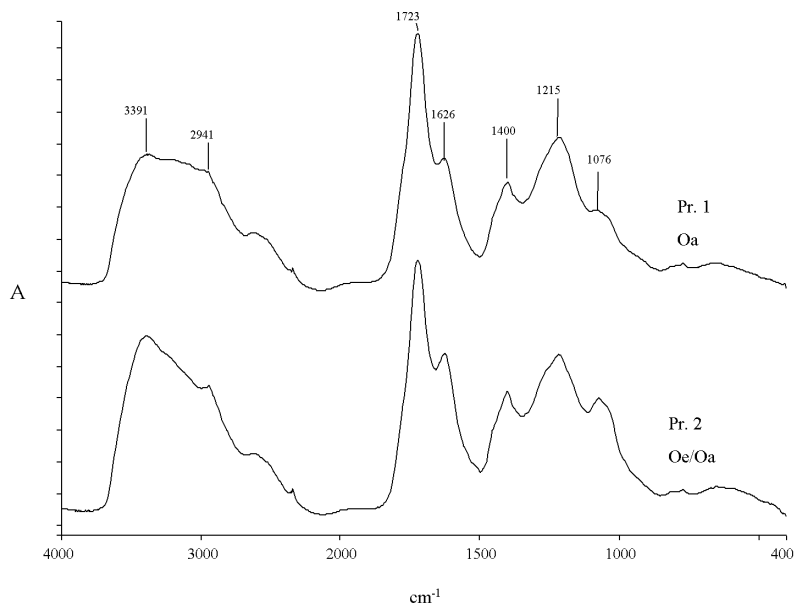


Figure 5. FT-IR spectra of fulvic acids from the organic layers of the profiles

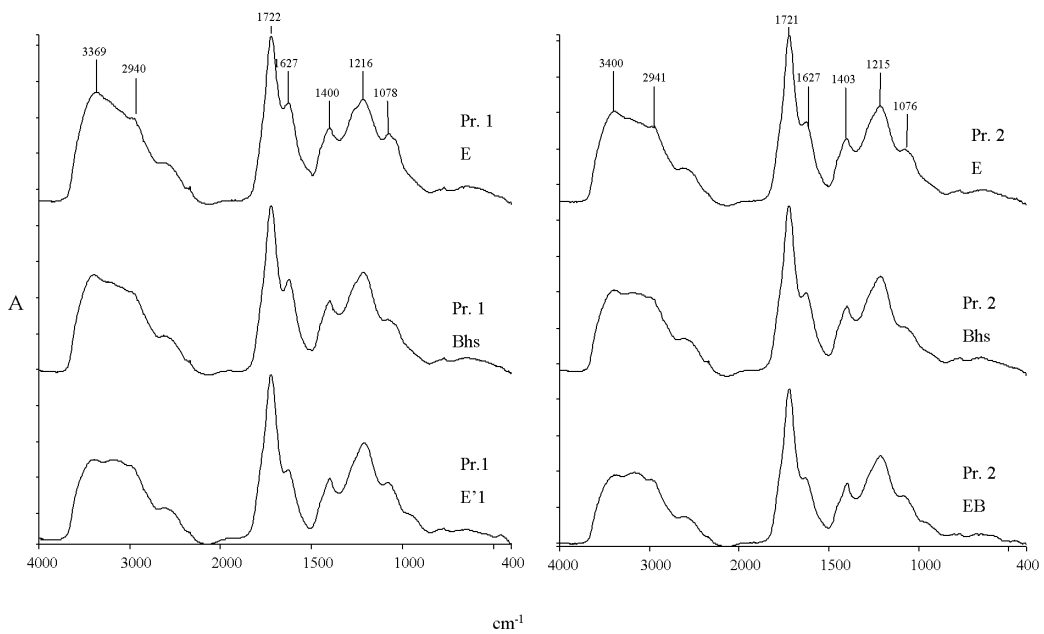


Figure 6. FT-IR spectra of fulvic acids from the mineral horizons of the profiles

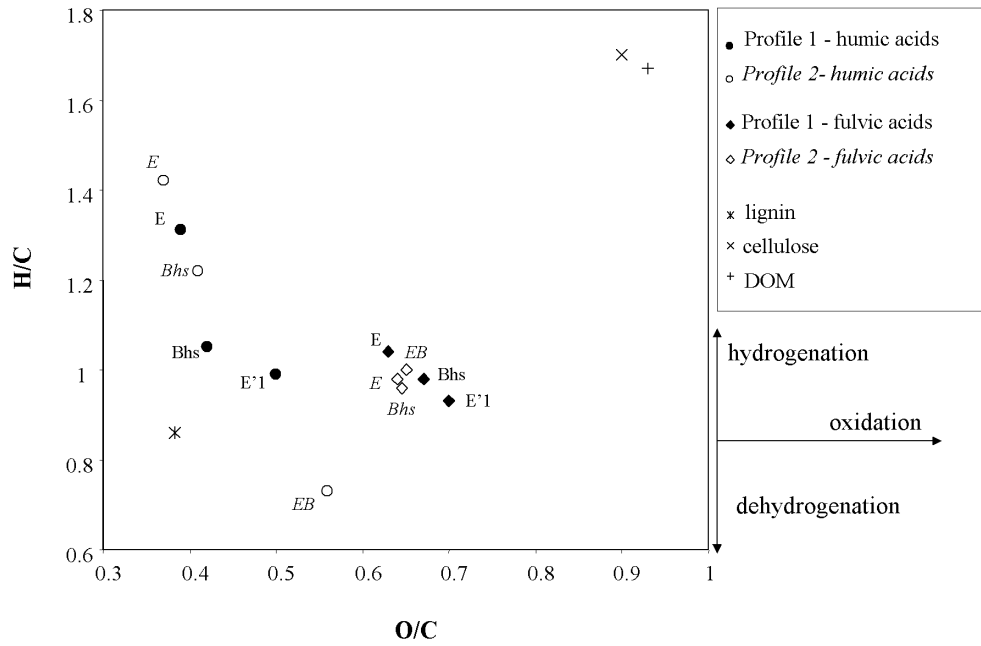


Figure 7. Van Krevelen diagrams for humic acids and fulvic acids extracted from the mineral horizons of the profiles used in this study, lignin and cellulose (Haumaier and Zech, 1995), DOM (Martin et al., 2006)

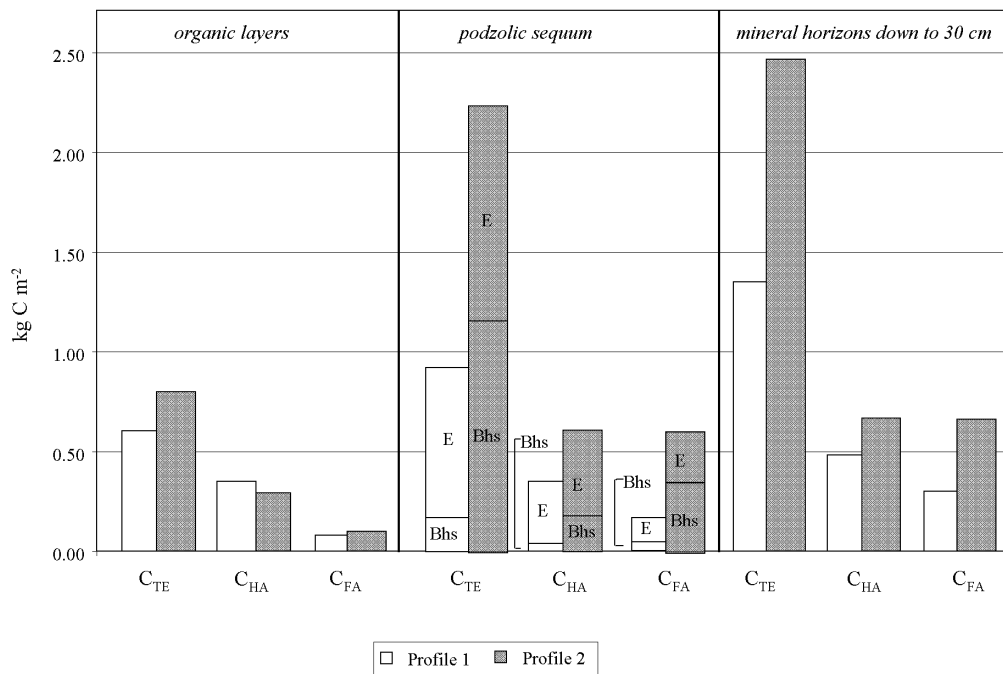


Figure 8. Stocks of total extractable carbon (C_{TE}), humic acids (C_{HA}) and fulvic acids (C_{FA}) in the organic layer, in the podzolic sequum (E and Bhs horizons) and in the mineral horizons down to 30 cm of the profiles