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Geochemical changes in podzolic forest soil 17 years after deep tilling

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Mechanical site preparation, e.g. ploughing, is commonly used in connection with regeneration of forests after clear-cut. Ploughing causes disturbances in the properties of the original soil profile. The aim of this study was to determine changes in concentrations of elements in the podzolic soil horizons exposed to soil-forming processes such as weathering due to deep tilling in boreal forest soil located in southern Finland. The total concentrations of elements were determined by X-ray fluorescence (XRF) for the podzolic soil horizons collected from undisturbed soil, tilt, undisturbed soil below the tilt and furrow 17 years after clear-cut and deep tilling. Depletion of the elements by chemical weathering occurred in the topmost horizons of the furrow within 17 years after exposure of the B horizon to soil-forming processes caused by deep tilling. In the tilt horizons, the dominant factor affecting changes in concentrations was mixing of the original horizons as a result of deep tilling, which masked possible depletion due to weathering.

Introduction

Mechanical site preparation by e.g. ploughing is a common and, indeed, essential practice in regeneration of boreal coniferous forests after clear-cutting. Ploughing, however, disturbs the original soil profile. At northern latitudes, e.g. in the Nordic countries, the soil profile started to develop after the latest glaciation period when the glacial ice-sheet retreated (in Finland ca. 10 000 years ago) or soils emerged from the waters due to land uplift (Eronen 1983). Podzolisation has been a dominant process in the development of forest soils in Finland; and according to Tamminen and Tomppo (2008), ca. 50% of forest soils are classified as Podzols, followed by Histosols (25%), Arenosols (11%) and Leptosols (9%). A podzolic soil is typically composed of an acidic organic layer, weathered eluvial (E) horizon, illuvial (B) horizon enriched with secondary Al and Fe compounds and metal-humus complexes, and a parent material (C) horizon. Time is extremely important in the development of podzolic soils. It has been shown that poorly developed young Arenosols 300 to 1000 years old are less weathered than older Podzols 3000 to 5000 years old (Starr and Lindroos 2006), but the annual rate of weathering is higher in young soils due to the higher content of less weathered minerals. The effect of weathering on the geochemistry of forest soils can be seen in the enrichment of resistant minerals (zircon, quartz)

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and their elements (Zr, SiO_2) to the weathered layer as well as in the depletion of less resistant minerals (e.g. mafic minerals) and elements associated with them (Ca, Mg, K) (e.g. Olsson and Melkerud 1991, Starr *et al.* 1998, Olsson and Melkerud 2000, Klaminder *et al.* 2011, Starr *et al.* 2014). The K concentrations may behave differently than the Ca and Mg concentrations in the surface horizons of podzolic soil if K is associated with orthoclase feldspar which is resistant to weathering (Starr *et al.* 2014).

Ploughing used in procedures such as deep tilling cause the illuvial B and eluvial E horizons together with the humus layer to be turned over and deposited upside down on the original soil profile located alongside the furrow. Ploughing (deep tilling) was widely used in Finland in the 1960s and 1970s but nowadays it is not used anymore. It has been shown that significant amounts of Al from the earlier precipitated secondary minerals and compounds of the exposed B horizons after deep tilling are mobilized (Tanskanen and Ilvesniemi 2004). This mobilization is also reflected in the composition of the soil solution as elevated Al concentrations (Tanskanen *et al.* 2004). Although Al chemistry and the chemical balance between secondary minerals and soil solution composition have been studied, relatively little is known about the changes in geochemical total concentrations of many elements due to weathering processes taking place in the exposed soil horizons related to deep tilling. Weathering can be expected to be strong during the first years of soil development, as has been reported on the western coast of Finland for young soils that have emerged from the sea due to land uplift (Starr and Lindroos 2006). In deep tilled soils, the depletion of elements is probably even stronger than in young soils in coastal areas, because the horizons enriched with secondary precipitated minerals (B and BC horizon) are exposed to dissolution processes. These compounds can be considered more sensitive to dissolution processes than are primary minerals, which are dominant in the soils (C horizons) of the land uplift area on the western coast of Finland. About 7 million hectares of the total forest area in Finland have been deeply tilled by mounding or ploughing (Finnish Forest Research Institute 2001, Tanskanen *et al.* 2004), which means that the possible geochemical changes taking place in the exposed soil layers affect large areas of forest land, and current understanding about these processes is very limited.

We hypothesized that redistribution of elements in the soil horizons of podzolic soils disturbed by deep tilling could be observed even during a relatively short period of time as compared with time required for the original development of the soil, because the horizons in which secondary minerals had been accumulated during earlier soil development are exposed to direct leaching processes related to new development of the soil. We also hypothesized that changes in the elemental distributions will take place in the furrows in which the upper soil horizons have been removed and the deeper soil layers are exposed to soil-forming processes such as accumulation of litter as well as intensified and increased percolation of water through the soil matrix. The aim of this study was to determine the changes in concentrations of elements in the podzolic soil horizons exposed to soil-forming processes such as weathering due to deep tilling in boreal forest soil located in southern Finland.

Material and methods

The study site was located in Karkkila, southern Finland (Table 1). The forest was of the *Oxalis–Myrtillus* type which means that these species were dominant in the ground vegetation (Table 1). The soil type according to the FAO classification was Cambic podzol composed of glacial till. Based on grain counting of the parent material soil with a microscope (ca. 1000 mineral grains in a fraction 0.06–2 mm), the proportion of mafic minerals (‘dark’ minerals, e.g. pyroxenes, amphiboles) was relatively high, 25%, and the proportion of feldspars (orthoclase, plagioclase) was > 50%. The bedrock in the area is composed of gabbro and diorite (*see* Table 1 for basic characteristics of the sites).The site was originally a Norway spruce stand that had been clear-cut in 1979. After clear-cutting the forest soil was deep tilled, and the site was planted with Norway spruce (Table 1).

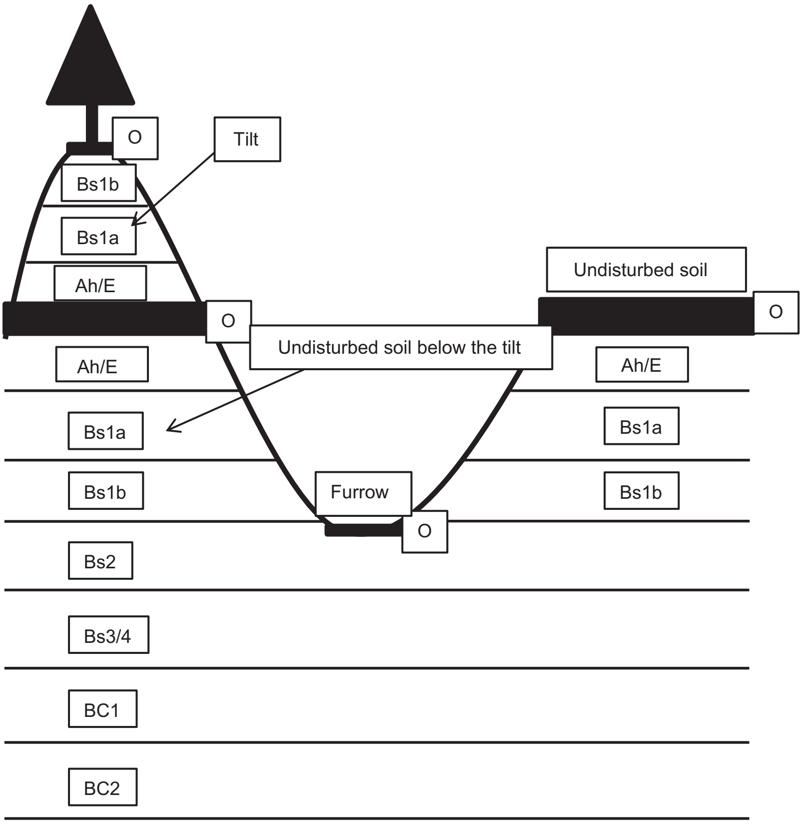

Fig. 1. Schematic presentation of deep tilled soil. The locations of the soil horizons are indicated in tilt, undisturbed soil below the tilt, furrow and undisturbed soil.

In order to study the total geochemistry of the soil layers, mineral soil samples were taken from different positions in the deep tilled soil. These samples were collected in 1996, i.e. 17 years after the clear-cut and deep tilling in 1979. Samples were taken from the undisturbed soil, the tilt, the undisturbed soil beneath the tilt and the furrow (Fig. 1). Soil horizons related to podzolic soil (*see* Fig. 1) were identified in the field at the time of sampling. From each soil layer 8–11 subsamples were taken randomly from the sample plot, which was 30 m × 30 m in size and located in the deep tilled area; and the subsamples were combined to give one composite sample for

Table 1. Some characteristics of the Karkkila study area.

Location (latitude, longitude)	60°32´N, 24°16´E
Mean temperature, January[1]	–5.6 °C
Mean temperature, July[1]	16.7 °C
Mean annual temperature	5.0 °C
Mean annual precipitation[1]	626 mm
Clear-cut and ploughing year	1979
Tree species (planted in 1980)	Norway spruce
Forest site type[2]	*Oxalis–Myrtillus* (OMT) type
Soil type[3]	Cambic Podzol
Soil texture	Glacial till
Mafic minerals in soil parent material	25% (fraction 0.06–2 mm)
Bedrock[4]	gabbro, diorite

[1] Drebs *et al.* (2002), [2] Cajander (1925), [3] FAO-Unesco (1990), [4] Geological Map of Finland (1953).

each layer in undisturbed soil, tilt, soil beneath the tilt and furrow. Due to the high costs of the total analyses of the soil, composite samples had to be used. Soil samples were taken with a steel auger (diam. 4.6 cm). The sampling points for subsamples were located on those spots on the sample plot where the soil horizons could be clearly identified in the tilt, the soil profile below the tilt and the furrow. Undisturbed soil profiles were located as near as possible to the tilts and furrows.

The mineral soil samples were air-dried and sieved (< 2 mm) immediately after collection and stored in a cool dry place before analysis. The samples were made into pressed powder pellets with micro wax (Hoechst wax C micro powder) in 2013 at the geochemistry laboratory of the Department of Geology, Oulu University. The total concentrations of MgO, SiO_2, Zr, FeO_{tot}, Al_2O_3, CaO, Na_2O, K_2O, Sr and V were determined with an X-ray fluorescence spectrometer (XRF, model S4 Pioneer of Bruker Analytical X-ray Systems GmbH) at the Center of Microscopy and Nanotechnology, Oulu University.

Based on the composite soil sample, including 8–11 subsamples, the average value for the studied horizon was determined and compared between the disturbed and undisturbed soil. In addition, the mean value for the whole tilt part of the soil was calculated based on the values for the three soil layers, each of which was based on the composite sample (Bs1b, Bs1a and Ah/E; *see* Fig. 1). This mean value was compared with the mean value that was calculated based on the corresponding three layers of undisturbed soil. The significance of the differences in the mean values of the tilt and undisturbed soil was determined using a non-parametric Mann-Whitney *U*-test. Similarly, the mean value for the whole furrow part of the soil was calculated based on the values of the four soil layers, each based on the composite sample (Bs2, Bs3/4, BC1 and BC2, *see* Fig. 1). This value was compared with the mean value that had been calculated based on the corresponding four undisturbed soil layers. Also in this case the Mann-Whitney *U*-test was used to test the differences between the mean values. The differences between the means were regarded as statistically significant at $p < 0.05$, and marginally significant at $p < 0.1$.

Results

The concentrations of MgO, CaO, Na_2O, Sr and V increased with depth, indicating weathering depletion of these elements in the topsoil during soil development (Fig. 2). Due their resistance to weathering processes, Zr, SiO_2 and K_2O were enriched in the topmost layers of the podzolic soils. Concentrations of FeO_{tot} and Al_2O_3 were lower in the upper layers but were enriched in the Bs and BC horizons.

The MgO, CaO, Sr and V concentrations were clearly lower in the individual horizons of the furrow as compared with those in the corresponding horizons of undisturbed soil. In general, the differences in concentrations between the furrow and the undisturbed soil were significant (Figs. 3 and 4) or marginally significant, whereas the difference between the tilt and the undisturbed soil was not significant (Figs. 3 and 4).

The concentrations of Zr, SiO_2 and K_2O were generally lower in the individual soil horizons of the tilt as compared with those in the corresponding soil horizons of the undisturbed soil, but the difference was statistically significant only for Zr (Fig. 5). However, the Zr, SiO_2 and K_2O concentrations clearly increased in the soil horizons of the furrow as compared with those in the undisturbed soil horizons. The mean value of all four furrow horizons was also significantly higher than that in the soil horizons of the undisturbed soil (Fig. 5).

In general, the difference in FeO_{tot} and Al_2O_3 concentrations between the furrow and undisturbed soil was significant, whereas the difference between these concentrations in the tilt and undisturbed soil was not significant (Fig. 6). The FeO_{tot} and Al_2O_3 concentrations were clearly depleted in the individual horizons of the furrow compared to the corresponding horizons of the undisturbed soil.

Discussion

According to our results, the weathering and soil-forming processes can cause surprisingly large depletion in total geochemical concentrations of many elements in the mineral soil in a relatively short period of time. Weathering depletion could

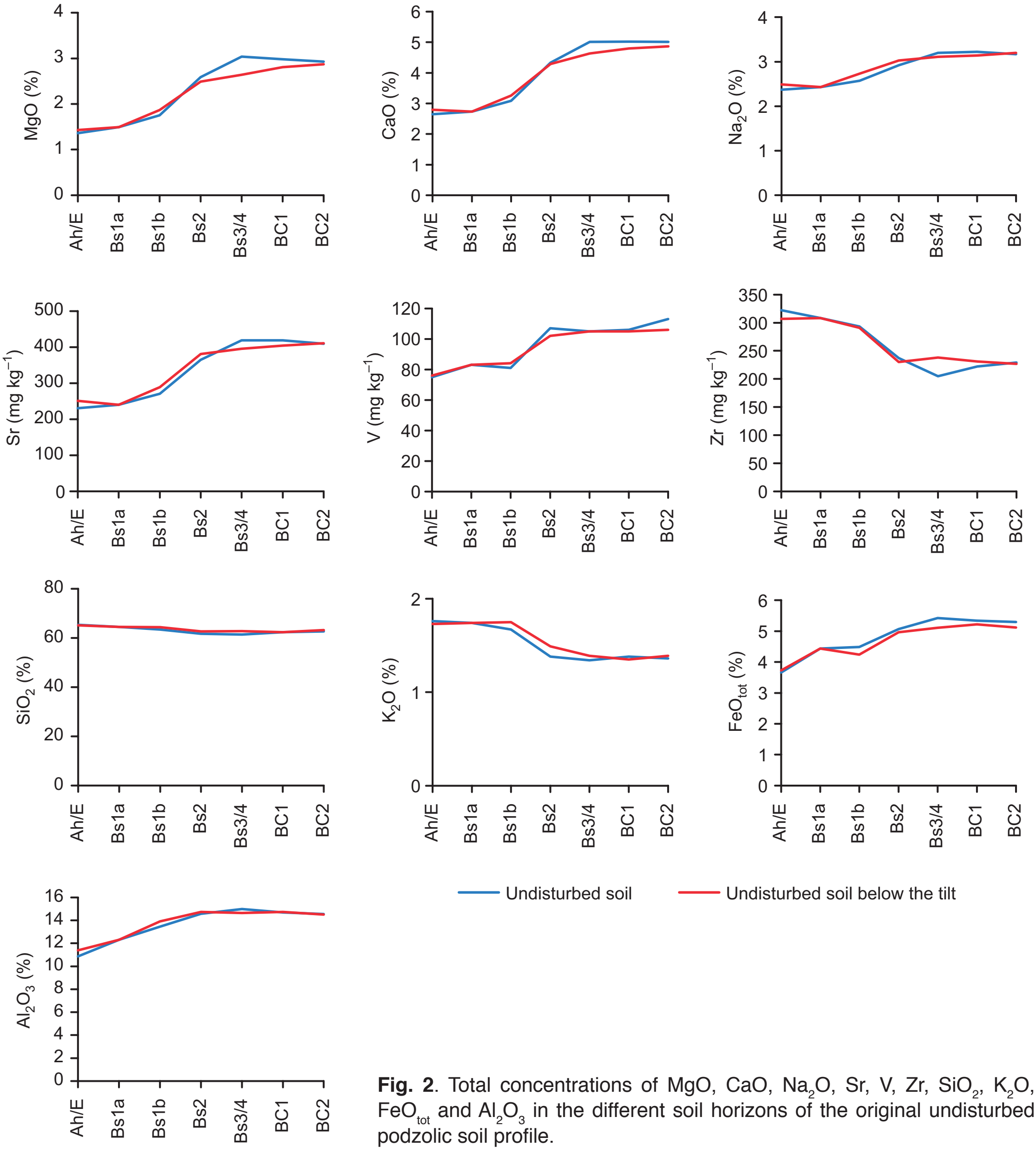

Fig. 2. Total concentrations of MgO, CaO, Na$_2$O, Sr, V, Zr, SiO$_2$, K$_2$O, FeO$_{tot}$ and Al$_2$O$_3$ in the different soil horizons of the original undisturbed podzolic soil profile.

be seen already 17 years after deep tilling in those locations with ploughed forest soil that were exposed to conditions known to enhance soil-forming processes and weathering. In the deep-tilled area, total concentrations of many elements were depleted in the upper soil layers of the exposed furrow horizons, undoubtedly due to the fact that via the furrows the percolation of water through the soil matrix is intensified. The role of water and organic solutes are known to be essential in the release of elements from the mineral grains (e.g. Pohlman and McColl 1988, Lundström and Öhman 1990, Raulund-Rasmussen *et al*. 1998, Giesler *et al*. 2000). Via the furrows, large amounts of water percolate downwards through the exposed Bs and BC horizons; and because the water runs through the layers rich in organic matter, the DOC concentration of the percolation water is highest in the uppermost soil layers (van Hees *et al*. 2000,

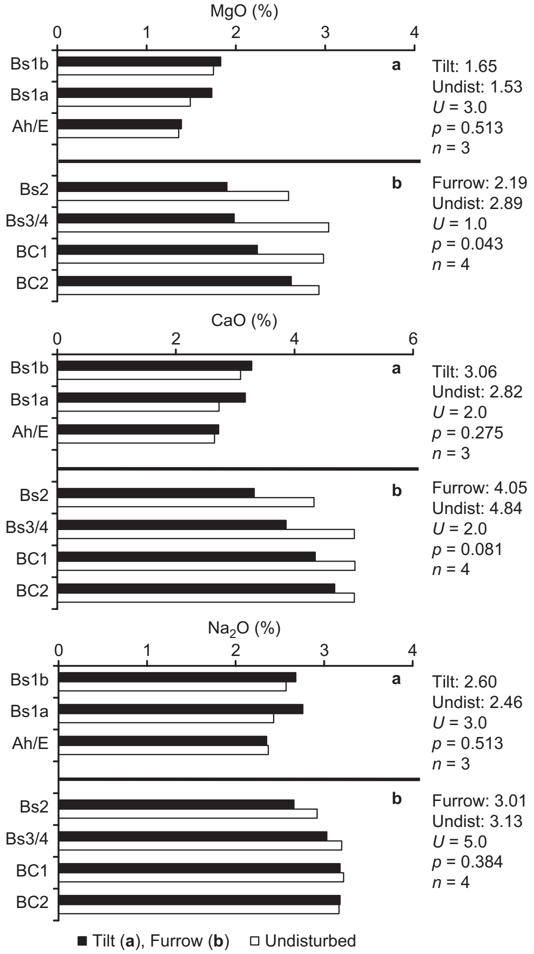

Fig. 3. MgO, CaO and Na_2O concentrations (% d.w.) in (**a**) the Bs and Ah/E horizons in tilt, and (**b**) the Bs and BC horizons in the furrow. For comparison, the concentrations in the corresponding undisturbed soil horizons (undisturbed in the non-ploughed area) for tilt and furrow horizons are also shown. Mean values for the whole tilt part of the soil containing the three soil layers and for the corresponding undisturbed soil layers are given before the test (Mann-Whitney *U*-test, asymptotic significances are shown) results next to the panels. For the location of the soil horizons in tilt, furrow and undisturbed soil *see* Fig. 1. To be comparable with the order of the horizons occurring in tilt after ploughing, the soil horizons in the undisturbed soil profile are presented in a reverse order as compared with in the natural situation.

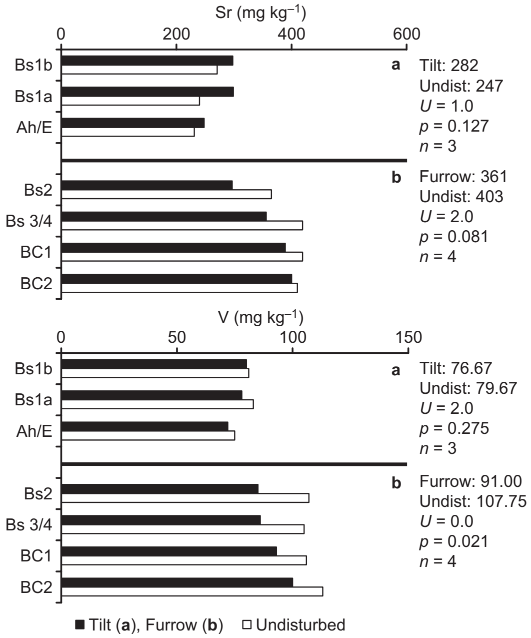

Fig. 4. Sr and V concentrations (mg kg^{-1} d.w.) in the Bs and Ah/E horizons in (**a**) the tilt and (**b**) the Bs and BC horizons in the furrow. For comparison, the concentrations in the corresponding undisturbed soil horizons (undisturbed in non-ploughed area) for the tilt and furrow horizons are also shown. Mean values for the whole tilt part of the soil containing the three soil layers and for the corresponding undisturbed soil layers are given before the test (Mann-Whitney *U*-test) results next to the panels. For further explanations *see* Figs. 1 and 3.

Lindroos *et al*. 2008). A new organic layer, including mosses and litter, is formed quite rapidly on top of the furrow horizons, which means that the input of dissolved organic compounds to the topmost mineral soil layers of the furrow is significant. Litter also accumulates more than average in the bottom of the furrow. Complex formation between dissolved organic matter and many metals in the minerals is suggested to be responsible for the increased rate of weathering (Lundström 1993). The bedrock in the area was composed of gabros rich in dark mafic minerals (pyroxenes, amphiboles) (Geological Map of Finland 1953); these minerals are also present in the soil matrix (proportion of mafic minerals in the sand fraction is 25%; Table 1). Dark minerals are especially susceptible to weathering, and therefore the favourable mineralogy, intensified percolation of water and dissolved organics can be considered to be the main factors responsible for rapid depletion of elements from the topmost furrow horizons.

Depletion of Mg, Ca, Sr and V in the topmost part of the furrow is related to weathering of, e.g.

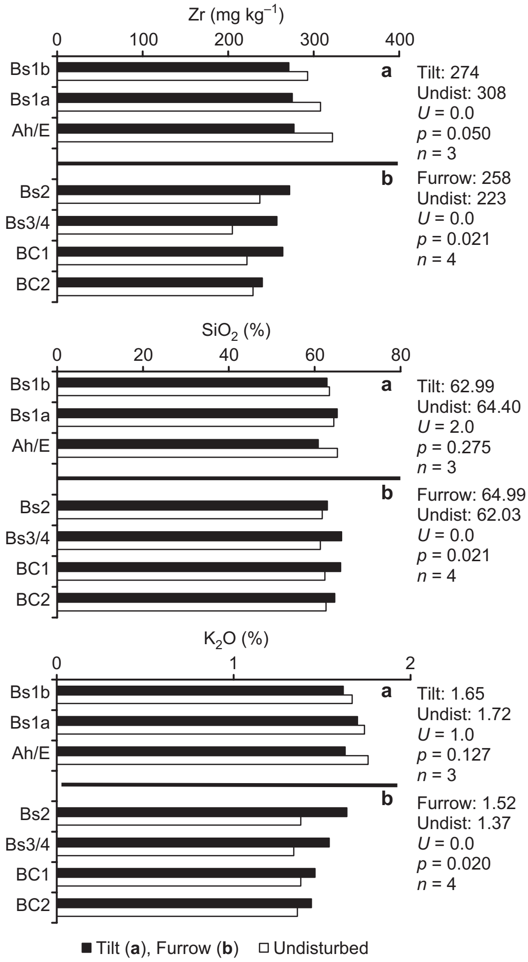

Fig. 5. Zr (mg kg^{-1} d.w.), SiO_2 and K_2O (% d.w.) concentrations in the Bs and Ah/E horizons in (**a**) the tilt and (**b**) the Bs and BC horizons in the furrow. For comparison, the concentrations in the corresponding undisturbed soil horizons (undisturbed in non-ploughed area) for the tilt and furrow horizons are also shown. Mean values for the whole tilt part of the soil containing the three soil layers and for the corresponding undisturbed soil layers are given before the test (Mann-Whitney *U*-test) results next to the panels. For further explanations *see* Figs. 1 and 3.

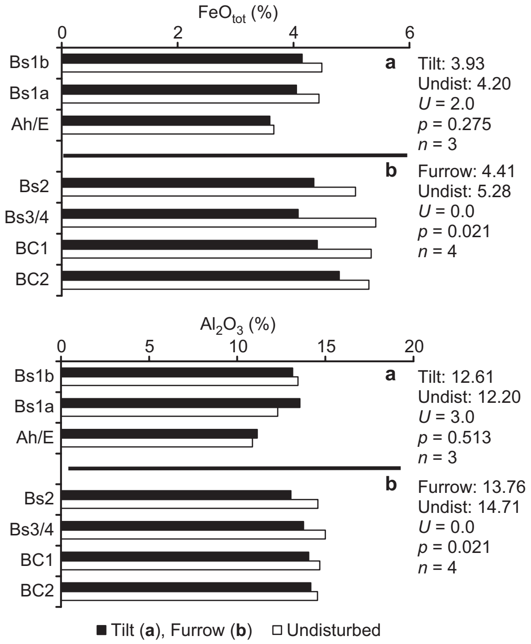

Fig. 6. FeO_{tot} (total iron) and Al_2O_3 concentrations (% d.w.) in the Bs and Ah/E horizons in (**a**) the tilt and (**b**) the Bs and BC horizons in the furrow. For comparison, the concentrations in the corresponding undisturbed soil horizons (undisturbed in non-ploughed area) for the tilt and furrow horizons are also shown. Mean values for the whole tilt part of the soil containing the three soil layers and for the corresponding undisturbed soil layers are given before the test (Mann-Whitney *U*-test) results next to the panels. For further explanations *see* Figs. 1 and 3.

mafic minerals. In the furrows, the topmost soil layers are Bs and BC horizons rich in secondary Al and Fe minerals, and the depletion of Fe and Al in the furrow horizons is undoubtedly related to the dissolution of the these compounds (Tanskanen and Ilvesniemi 2004). The weathering depletion of mafic and secondary minerals and their elements leads to the relative enrichment of the minerals and elements resistant to weathering (Olsson and Melkerud 1991). This fact was shown clearly in our results as an increase in Zr, SiO_2 and K_2O concentrations. Zr occurs in zircon, which is very stable in weathering environments (Tole 1985). In the short term, potassium feldspar is also relatively resistant to weathering. The increase in K_2O concentrations in the furrow horizons indicate that enrichment of this element is related to the presence of potassium feldspar (Starr *et al*. 2014).

It has been shown (e.g. Starr and Lindroos 2006) that in young, poorly-developed Arenosols that are 300 to 1000 years old, the annual weathering depletion of base cations is much greater than in older Podzols due to the fact that young soils contain more fresh, far less weathered, material compared with the older soils. A similar phenomenon undoubtedly takes place in the forest soil areas where deeper soil layers are exposed to soil forming processes such as in the furrows of the ploughed areas. In these furrows, the Bs and BC horizons of the podzolic soil are exposed to soil-forming processes, and this corresponds closely to the situation where the soil development begins, for example, after deglaciation or land uplift from below water level (Starr and Lindroos 2006).

The situation proved to be different in the tilts of the ploughed forest soil as compared with that in the furrows. No clear (Mg, Na) or even opposite changes in the total concentrations of elements (Mg, Zr, Al, Ca, Na, K, Sr, Na) in the individual horizons of the tilt as compared with those in furrow were detected even though the tilt horizons were also exposed to soil-forming processes. The Zr concentrations were lower in the tilt horizons than in the corresponding soil horizons of undisturbed soil. This could be due to the fact that tilt layers have probably been mixed during the ploughing operation even though visually they were still identifiable as separate horizons. The high Zr concentration in the original Ah/E horizon has decreased in the tilt Ah/E horizon because of the mixing effect of the lower values of the Bs horizons. Similarly, the mixing effect of ploughing is undoubtedly an important factor in the observed distributions of elements other than Zr in the tilt horizons. The mixing of the horizons due to ploughing probably masked the effect of weathering depletion for most of the elements and had even caused an opposite effect compared to weathering of the furrow soil (e.g. decrease in Zr).

In future studies related to ploughing of forest soils, it would be beneficial also to study the variation within each horizon and not only the average values (composite samples) since variation in the chemical parameters of forest soil can be expected to be large. This would help in generalization of the results. Additional mineralogical and chemical analysis would also be beneficial from the standpoint of interpreting the results. Such analyses include, e.g. mineralogical determination (especially clay minerals by XRD) and determination of oxyhydroxides.

In conclusion, element depletion by chemical weathering clearly occurred in the topmost horizons of the furrow within 17 years after exposure of the B horizon to soil-forming processes owing to deep tilling. In the tilt horizons, the mixing of the original horizons as a result of deep tilling was the dominant factor affecting the changes in concentrations, and it masked the depletion due to weathering.

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