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Soil properties and trace elements distribution along an altitudinal gradient on the southern slope of Mt. Everest, Nepal

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Abstract

The absence of significant local inputs of pollution makes remote mountain ecosystems suitable to assess the atmospheric deposition of contaminants, such as trace elements, which can derive from both natural and anthropogenic sources. The Himalayan range is a potential target for the atmospheric deposition of pollutants because of the regional monsoon climate and the presence of contaminant source regions in its vicinity (e.g. Kathmandu Valley). Studies of elevation gradients of trace elements in topsoils and soil profiles in the Himalaya are very limited. The main goal of this study was to determine the distribution of trace elements (Co, Cd, Cu, Zn, Cr, Pb, Ni, and Mn) in soils on the southern slope of Mt. Everest as a function of elevation, soil depth, and pedogenic properties. Trace elements were measured in 30 topsoils along an altitudinal gradient (3570-5320 m a.s.l.) and in 11 different soil profiles opened under different land uses and topographical settings. The contents of Co, Zn, Cr, and Ni in the topsoil were found positively correlated with the altitude, and on average reached a peak at 4900-5000 m a.s.l.. The results showed a limited contamination, similar to the one measured in soils from other high mountain regions. Differently from the expectations, both soil depth and organic carbon, which significantly decreased with the altitude, were not found significant factors controlling the altitudinal distribution of trace elements. Pedogenic processes were associated with different depth trends of trace metals along the elevation gradient, with depletion in surface and accumulation in illuvial horizons where podzolization was active; at higher altitude, a weaker leaching resulted in higher surface concentrations.

Key Words: Himalaya, Depth distribution, Inorganic contaminants, Pedogenesis, Toposequence.

1. Introduction

Mountain soils are a fragile ecosystem, and their high spatial variability derives from their strong dependency on factors such as parent materials, climate, relief, biosphere, and human impact, which are particularly striking in high-elevation areas (Florinsky, 2012; Zanini et al., 2015).

Soil parent material is a primary source of trace elements particularly in weakly developed soils (D'Amico et al., 2015). However, additions may occur from atmospheric deposition from both natural and anthropogenic sources. The long-range transport of trace elements from centers of human activity to the biosphere has been recognized in the past years (e.g. Elgmork et al. 1973, Zoller et al. 1974). Trace elements occur in the atmosphere as, or adsorbed to, airborne particles, and these atmospheric aerosols can travel long distances before being redeposited, reaching remote areas such as the Arctic (Camarero et al., 2009), and high elevations such as the Himalayan Mountains (Yeo and Langley-Turnbaugh, 2010; Cong et al., 2015). The deposition degree of air-borne trace elements is related to several factors. These include distance from potential sources, intensity and frequency of precipitation and wind, and the aerosol capture by intercepting surfaces (Reiners et al., 1975; Bacardit and Camarero, 2010). Their deposition is especially influenced by precipitation and wind, particularly in regional convergence zones, such as mountain ranges, that trap atmospheric contaminants because of cold condensation and enhance atmospheric deposition (the so-called "orographic effect") (Lovett and Kinsman 1990; Loewen et al. 2005; Wegmann et al. 2006; Cong et al., 2015). Since precipitation tends to increase with altitude until a specific elevation limit and then tends to decrease (Salerno et al., 2015), total deposition might be expected to increase accordingly (Reiners et al., 1975). In addition, the soil trace elements content is susceptible to chemical (e.g. weathering, pedogenesis, leaching) and biological (e.g. microbial decomposition or organo-metal chelates) post-depositional processes. It is well known that soil characteristics are closely related to trace elements retention, uptake by plants and mobility into the ecosystem with potential negative effects on living organisms and water sources (Navas and Lindhorfer, 2005). According to USEPA (2008), one-tenth of the world’s population is using high mountain water every day, emphasizing the importance of a more detailed knowledge of elemental contents in high altitude areas.

Few studies, with contrasting results, have examined the soil trace elements distribution in high-elevation soil profiles, whose characteristics and pedogenic properties were less studied compared to lower altitude soils (e.g. Magnani et al., 2017a). Mountain soils are strongly influenced by elevation and local topographical settings (Zanini et al., 2015) and at higher elevation, terrain features (e.g. concavities and convexities) may influence the amount of water, the accumulation of sediments and the snow cover duration (Magnani et al., 2017b), with significant effects on soil development. Soil physicochemical properties, such as organic matter content, oxides, pH, and redox reactions determine trace elements mobility along the profile and the more so in extreme settings such as a high mountain range (Navas and Lindhorfer, 2005). A valuable opportunity to study both the soil development and the associated trace elements distribution is offered in the Himalayan range, which presents both a wide altitudinal range and a traditionally considered pristine environment, and thus is suitable for studying the effects of remote pollution sources. It is known that the orographic effect is quite pronounced in the Himalayan range because of dramatic elevation temperature and precipitation gradients relative to contaminant source regions in its vicinity, and because of the regional monsoon climate that has been shown to deliver air pollutants to higher altitudes (Loewen et al., 2005). The Kathmandu Valley, which is widely recognized as an area characterized by a severe air pollution due to high concentrations of airborne particulate matter (Gurung and Bell, 2012), can be considered a potential regional source of contamination for the southern slope of Mt. Everest, especially during the monsoon period when the prevailing direction of the wind is S-N and SW-NE (Ichiyanagi et al., 2007).

Following these considerations, this study was designed along an elevation transect in remote areas in the Sagarmatha National Park (central southern Himalaya) to test these hypotheses: 1) The soil pedogenic properties would change along the altitudinal gradient and on a natural high-elevation toposequence; 2) Trace element contents would increase with elevation, but would then decline above the treeline due to a decline in rainfall and interceptive vegetative surfaces; 3) Trace element contents along the profiles would be influenced by organic matter dynamics and differential leaching associated with pedogenic processes.

Soil characteristics and trace element contents were analyzed on topsoil samples and in soil profiles across a wide altitudinal gradient (from 3700 to 5320 m a.s.l.), and on one high-elevation toposequence (5055 – 5070 m a.s.l.) in order to point out background values, external additions and possible local contamination due to the increasing touristic pressure. A special attention was given to factors and pedogenic trends, which may influence trace elements distribution, such as elevation, topography, land cover, and local or remote sources of contamination.

2. Material and Methods

2.1. Study area

The study area is located in the Mt. Everest region in the Sagarmatha National Park and Buffer Zone (SNPBZ) (27.75° to 28.11° N; 85.98° to 86.51° E), which lie in eastern Nepal in the southern part of the central Himalaya (Fig. 1). The park area (1148 km^2) extends in elevation from 2845 to 8844 m a.s.l. covering the upper Dudh Koshi Valley, and represents the highest protected area in the world (Amatya et al., 2010).

Carosi et al. (1999) described the geology of the Higher Himalayan Crystallines, while Searle et al. (2003) summarized the main lithological units in the SNP. The Khumbu Valley substratum is dominantly made up of crystalline rocks (e.g. sillimanite gneisses calc-silicates, amphibolites and K-feldspar augen gneisses) and leucogranites that intrude the metasediments as dykes, sills and bodies. The overlying Everest series (weakly metamorphosed shales and pelites with limestone bands), the Yellow band unit (limestones, marbles and calc-silicates), and the Ordovician limestones are only present in the eastern part of the study area. Extensive glacial till of different ages, alluvial and glaciofluvial deposits, host sub-surface aquifers in close connection with the hydrographic network (Tartari et al., 1998; Salerno et al., 2016).

According to Nepal and Nepal (2004), the soils in the high valleys are primarily Regosols. Below 4000 m a.s.l., Podzols have developed in forested areas, which are mainly located in the north-facing slopes. The extensive grassland and shrubland areas in the southern slopes below 3750 m a.s.l. were characterized by Cambisols and Regosols.

The SNPBZ can be divided into three vegetation zones based on altitude. The lower altitudinal belt (below 3800 m a.s.l.), consisting of temperate forests and woodlands, the middle zone (3800 to 4200 m a.s.l.) of subalpine forests and shrublands, and the upper zone (above 4200 m a.s.l.) of alpine tundra vegetation (Nepal and Nepal, 2004). Shrubs, grasslands and diverse varieties of herbs characterize the vegetation from 3600 to 4000 m a.s.l. on the southern slope. The alpine zone from 4200 to 5500 m a.s.l. is divided into a lower area characterized by moist alpine shrubs of dwarf rhododendrons (*Rhododendron setosum* D. Don, *Rhododendron nivale* Hook. f., *Rhododendron lepidotum* Wall. ex G. Don, *Rhododendron anthopogon* D. Don) and prostrate junipers (*Juniperus recurva* Buch.-Ham. Ex D.Don, *Juniperus indica* Bertol.*)*, and an upper area dominated by *Kobresia pygmaea* (C.B.Clarke) C.B.Clarke mats and cushion plants such as *Anaphalis cavei* Chatterjee and *Leontopodium monocephalum* Edgew. (Byers, 2005).

Glaciers are located above 4300 m a.s.l., with more than 75% of the glacier surfaces lying between 5000 and 6500 m a.s.l. (Thakuri et al., 2014; 2016). The climate is characterized by monsoons, with a prevailing S-N direction. During the 1994-2013 period, the mean annual precipitation at the Pyramid meteorological station (5050 m a.s.l.) was 446 mm, with a mean annual temperature of -2.45 °C. In total, 90% of the precipitation falls between June and September. The probability of snowfall during these months is very low (4%) but reaches 20% at the annual level. Precipitation linearly increases to an elevation of 2500 m a.s.l. and exponentially decreases at higher elevations (Salerno et al., 2015; Derin et al., 2016).

The SNPBZ, which represents one of the most attractive mountain sites in the world, reports an exponential increase of tourists trekking in the last thirty years, reaching even 30,000 visitors in 2008 (Salerno et al., 2013). Nepal and Nepal (2004) reported soil erosion on trails, while Byers (2005) showed how erosion processes were exacerbated by harvesting of soil-binding shrub juniper for fuel wood, primarily used in tourist lodges. Salerno et al. (2010) reported a 20% decrease of forest cover since 1992 in order to sustain the tourism demand for fuel. Furthermore, the increasing number of visitors caused the localized buildup of litter and pollution from human waste and the necessity to manage solid waste that is usually collected and burnt in specific areas (Stevens, 2003; Manfredi et al., 2010). Local sources of contamination could therefore contribute to an increase of trace elements in soil, whose distribution has been studied extensively in sites that are close to human activity centers (Li et al., 2009; Biasioli et al., 2012), in agricultural areas (Wilcke, 2000; Liu et al., 2014) and in forest soils (Hernandez et al., 2003).

In our study area, at low elevations (agropastoral zone below 4000 m a.s.l.), the farming activities of Sherpa people has contributed to the development of soils rich in organic matter by leveling, stone removal and manure distribution. Forests are an important part of village life and provide fuel wood, structural timber, litter, and grazing areas (Stevens, 1993). The main impacts that tourism has had on local vegetation are the forest thinning in the Khumbu temperate and subalpine forests, which was more intensive and extensive in Pharak, and the loss of alpine shrub juniper in some areas of eastern and central Khumbu (Stevens, 2003). The forest is preserved in many sacred sites near the monasteries, such as in the Kathmandu Valley, and appears as vegetative islands in an intensively used landscape, like spiritual oases (Hamilton, 2002).

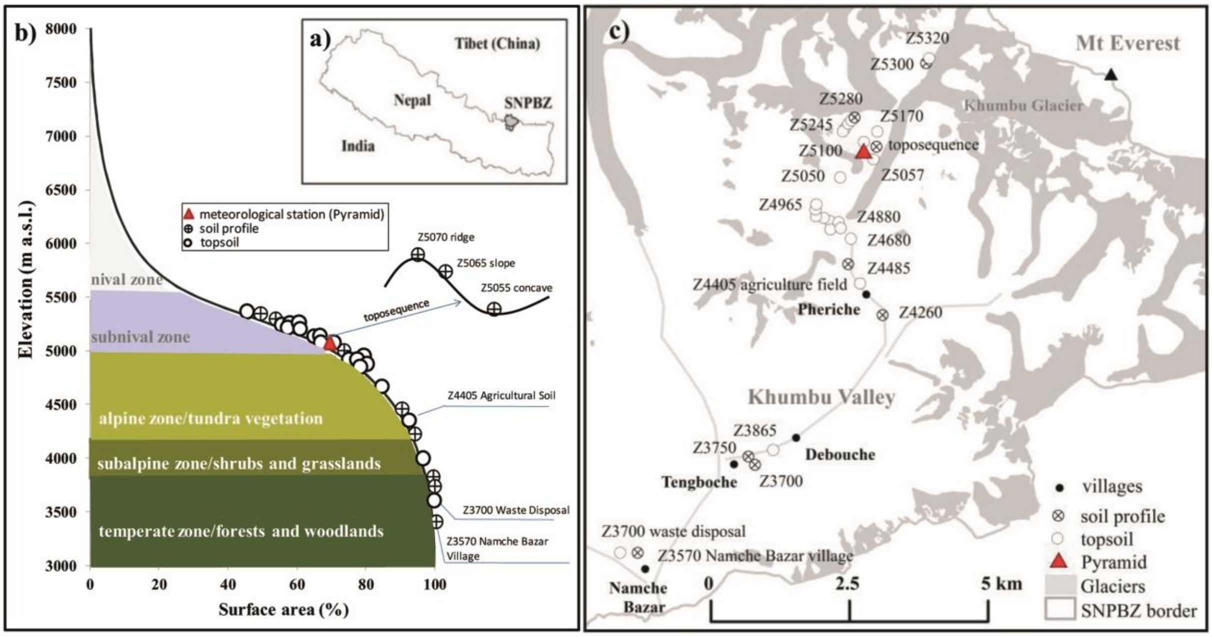

Fig. 1. a) Location of the study area (SNPBZ) in Nepal (southern Himalaya); b) Hypsometric curve, bioclimatic zones and location of the sampling sites in the study area; c) Spatial distribution of soil sampling sites along the Khumbu Valley.

2.2. Soil sampling

Soil samples were collected in July 2012 from 30 sites in the Dudh Koshi Valley along an altitudinal gradient that started from the village of Namche Bazar at the elevation of 3570 m a.s.l., and ended in the proximity of the Khumbu Glacier at 5320 m a.s.l. (Fig. 1). At 11 of these 30 sites, complete soil profiles were described according to IUSS Working Group WRB (2015) and each genetic horizon was sampled, chosen because of the representativeness of land cover and topography, in order to observe the soil forming processes that might influence the accumulation or leaching of trace elements in soil profiles. In order to better investigate the topography as soil forming factor, 3 soil profiles were opened close to the Pyramid Laboratory, at an elevation of about 5100 m a.s.l., along a toposequence characterized by concavities, gentle slope and convexities (ridge), in an “old” hummocky moraine (Hambrey et al., 2008). A different vegetation cover corresponded to different catena positions, represented by sparse *Rhododendron* and herbaceous species in the concave site, by a dense *Rhododendron* cover on the gentle slope and by a biological crust (bryophytes and algae) on the ridge. In the other cases, due to logistic constraints, only topsoil samples were collected (0-10 cm depth). Among these topsoils, one was sampled in the Namche Bazar Village (3570 m a.s.l.), one was collected close to a waste disposal site at 3700 m a.s.l., near the same village, and one was collected in an agricultural area, around the village of Pheriche (4405 m a.s.l.) (later named as village, waste disposal, and agricultural soil, respectively).

Approximately 0.5-1 kg of soil material was collected from each sampled horizon or topsoil. Undisturbed samples were collected with core cylinders for the measurement of bulk densities.

At each soil sampling site, a temperature sensor with a data logger (I-button) was placed at 10 cm depth in July 2012 to measure the hourly soil temperature till October 2013.

2.3. Soil chemical and physical analysis

The soil chemical and physical analyses were performed according to standard methods (Colombo and Miano, 2015). All samples were air-dried and sieved to separate the fine earth (<2 mm) from the coarse fraction. The pH was measured in water (soil:water=1:2.5). Total carbon (corresponding to the total organic carbon, TOC, given the absence of carbonates) and nitrogen (TN) were analyzed by dry combustion with a CN elemental analyzer (CE Instruments NA2100, Rodano, Italy). The cation exchange capacity (CEC) was measured with ammonium acetate (pH 7) and the exchangeable bases were measured by FAAS (Flame Atomic Absorption Spectrometer, Analyst 400, Perkin Elmer, Waltham, MS, USA) in the ammonium acetate extracts. The particle size distribution was determined by the pipette method. The pseudo-total contents of Co, Cd, Cu, Zn, Cr, Pb, Ni, Mn and Fe were measured with FAAS after a microwave-assisted *aqua regia* (3:1 $HCl:HNO_3$) digestion (MILESTONE Start D Digester). Cd contents were always below detection limits so they were not used in the elaborations.

Pedogenic Fe-oxides (Fed) were extracted by dithionite-citrate-bicarbonate (DCB) solution. Non-crystallized or poorly crystallized Fe-oxides, hydroxides, and associated gels (Feo) were extracted by acid ammonium oxalate solution (Van Reeuwijk, 2002).

2.4. Statistical analysis

Initially, the degree of correlation among the data was verified through the Pearson correlation coefficient (r) and the normality of single variables and residuals were tested using the Shapiro–Wilk test (Shapiro and Wilk, 1965; Hervé, 2015). We found that the altitude of the sampled soils did not follow a normal distribution and even after the log-transformation, the requirements for normality were not reached (Venables and Ripley, 2002), so the non-parametric Spearman's correlation test was performed in order to test the significance of the relationships. Although the majority of variables and relationships were normally distributed, we preferred to apply the non-parametric test to all data set and comparisons. Results are summarized in the Spearman's correlation matrix of Fig. 2. This analysis was performed using the "cor.test" function selecting "spearman" as method (R Development Core Team, 2010). Generally, the non-parametric tests are more robust than the parametric ones (Venables and Ripley, 2002). The Spearman's test showed similar correlations among the variables, but with a lower significance level. Therefore, the correlations presented and discussed in this work are more precautionary than the ones that include parametric assumptions.

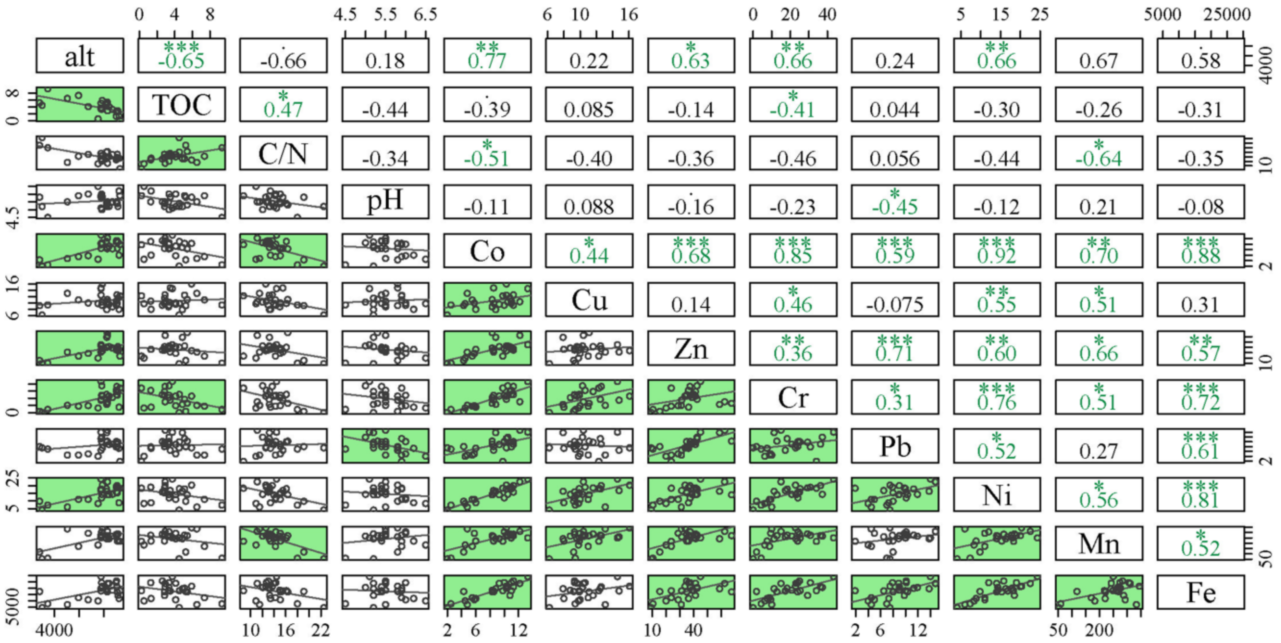

Fig. 2. Spearman's correlation between altitude (alt), TOC, C/N, pH, trace elements, and Fe in topsoils (n=27) along the altitudinal gradient. Village, Waste Disposal and Agricultural Soil sites were excluded from the analysis. * Indicates significant correlation at p<0.05; ** at p<0.01; *** at p<0.001. A single dot indicates slightly significant correlation at p<0.1.

Moreover, we conducted a principal component analysis (PCA) in order to obtain information on the relationships among altitude, soil characteristics, and trace elements. This analysis was performed using the "prcomp" and "biplot" functions (e.g. Salerno et al., 2014; Salerno et al. 2016). All tests were implemented in the software R (R Development Core Team, 2010) with a significance level at $p<0.05$. All data were normalized and autoscaled before implementing the PCA. As widely discussed by Jolliffe (2002) and Wilks (2006), the PCA is a purely geometrical technique and therefore there is no need for a statistical hypothesis: multivariate normality is not a critical assumption. This assumption is required only when inferential statistics are to be derived from the principal components.

3. Results

3.1. Soil properties and trace elements distribution along the altitudinal gradient

Most soils were developed in sandy or sandy loamy materials, almost free of coarse fragments, which however became abundant in the deepest horizons (Table 1). The most common soil types changed with altitude as normally observed in mountain areas. Podzols were common below subalpine forest and *Rhododendron* sp., below 4500 m a.s.l., and were characterized by a strong Fe-Al oxi-hydroxide redistribution from the bleached eluvial to the illuvial Bs/Bhs horizons. The Feo/Fed ratio was relatively high along the soil profiles, in particular in the A horizon. TOC redistribution with depth was not always visible, but a particularly high C/N characterized these soils. Other soil types were the less developed Arenosols, Umbrisol, and Regosols (Table 1). Arenosols were mostly observed below sparse high altitude vegetation or under cryoturbated hummocks.

In the agricultural land the topsoil was characterized by the highest TOC (16.6%). The pH and the percentage of rocks were similar to the other topsoils. The topsoil sampled close to the landfill, where the solid wastes are burnt in an open disposal, was characterized by high pH and TOC values. The characteristics of the topsoil sampled close to Namche Bazar village (3570 m a.s.l.) were in general similar to the other topsoils (Table 1).

There was no clear altitudinal trend of topsoil pH values, while topsoil TOC was inversely correlated with elevation (i.e. from subalpine forest to alpine tundra, *rho*=-0.65; p<0.001) (Fig. 2). Topsoil trace elements showed a significant increasing trend with the elevation, except for Cu, Pb, Mn, and Fe (Fig. 2), and a peak in trace elements was measured at 4900-5000 m of altitude. TOC was not correlated to most trace element contents in the topsoils, and a significant negative correlation between TOC and Cr was observed (*rho*=-0.41; p<0.05) (Fig. 2). No significant positive correlations were observed between the considered trace elements and C/N, and only Co and Mn presented significant, but negative correlations (*rho*=-0.51; p<0.05 and *rho*=-0.64; p<0.05, respectively) (Fig. 2). The soil pH did not show any significant correlation with trace element contents as well, except with Pb (*rho*=-0.45; $p<0.05$) (Fig. 2).

Concerning the soil profiles, in subalpine podzolic soils many trace elements showed very low contents in the surface E horizon, and higher ones in the underlying illuvial Bs and Bhs horizons (particularly Co, Cu, Ni, Table 2). The increasing trend of trace elements with soil depth was generally not observed above about 4400 m of altitude, where non-podzolic soils showed higher contents in surface A and lower in subsurface layers. The largest difference between trace element-"rich" surface horizons and subsurface ones was measured in profile Z4955, where contents of most trace elements were almost doubled in the surface. Above this altitude, the difference between surface and subsurface horizons tended to disappear (Table 2).

Trace elements in the waste disposal showed a content of the selected elements below the critical limits for contaminated soils reported by USEPA (2006) and only Cu, Zn, and Pb showed values closer to the lower limit reported by this guideline. In both village and agricultural soils, trace element contents were similar or even lower than in the other topsoils (Table 2).

In the PCA biplot shown in Fig. 3, PC1 (explaining 56% of the variance) was highly positively associated with altitude and trace element contents, negatively with TOC and C/N (Table 3), and it can thus be interpreted as an altitudinal gradient. Siderophile elements, such as Fe, Co, Ni, Cr, Mn, with the addition of Zn, were very closely associated among them along the gradient described by PC1, while Cu and Pb were less strongly related. PC2 (explaining 20% of the variance) was strongly associated with soil pH and negatively with TOC, C/N and Pb; it showed the strong Pb bind with TOC in surface horizons. The peculiarity of Cu content variations along the altitudinal gradient was evidenced by axis 3, which was associated with this element and, weakly, with Pb (Table 3).

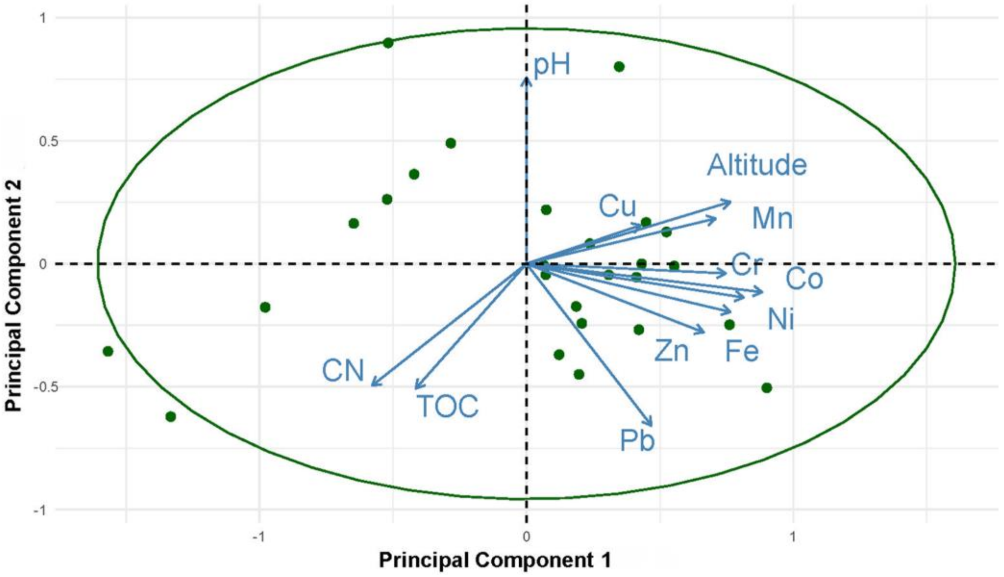

Fig. 3. PCA analysis biplot performed between altitude (alt), TOC, C/N, pH, trace elements, and Fe recorded in the topsoil along the altitudinal gradient (n=27). Village, Waste Disposal and Agricultural Soil sites were excluded from the analysis. Topsoil samples scores are identified by their position, and the length of the arrows refers to the factor loadings. The ellipse represents the 95% confidence interval for the data.

3.2. Soil properties and trace elements distribution in the high-elevation toposequence

The soil depth in the high-elevation toposequence ranged between 30 and 85 cm, revealing a high variability, and all soils showed well-developed sandy Bw horizons (Table 4). In all topographic positions, the proportion of stone fragments in the upper soil horizons was negligible. The sand and coarse silt fractions dominated with more than 80% in all horizons. The soil texture was sandy loam in the highest horizons of ridge and concave sites, while it was loamy sand in the slope site. Stone rich layers appeared at depths of about 40, 80, and 21 cm in the concave, slope, and ridge sites, respectively (Table 4).

At all sites the content of TOC decreased regularly along the soil profile. The mean TOC was higher in the concave and slope sites than in the ridge, as does the C/N (Table 4).

There were no significant differences in mean trace element contents among the three sites of the toposequence. However, their depth distribution showed different patterns for the different elements (Table 5). In all soils, the maximum values of Pb were recorded in subsurface horizons (AB horizons). Cu, Zn, Cr and Ni content in the ridge zone were the highest in the upper soil horizons, and in the slope and concave sites the Zn recorded the maximum values in the subsurface soil horizons, with a decreasing trend at greater depths. In the latter sites, the maximum values of all the other trace elements were recorded at greater depths, showing an accumulation in the subsoil. A relative enrichment of trace elements in the surface horizons was not measured (Table 5).

4. Discussion

4.1. Topsoils and soil profiles along the altitudinal gradient

A pedogenic trend with altitude was observed from podzolic soils below subalpine forest and *Rhododendron* sp. to Umbrisols, Regosols and Arenosols above the treeline (Righi and Lorphelin, 1987; Bäumler and Zech, 1994). The relatively high Feo/Fed ratio along most soil profiles revealed the dominance of poorly crystalline Fe oxides and metal-organic complexes. A decreasing weathering degree with altitude was shown, as expected (Table 1), by the decreasing Fed/Fet ratio; it showed the highest values in subalpine Podzols and the lowest values in the other soil types (Arenosols, Umbrisols, and Regosols), and it was associated with a weaker Fe and Al redistribution with depth. The almost total absence of coarse fragments in the soil profiles can be considered as evidence of a widespread presence of wind-blown loess-like materials, as already reported for high-elevation soils in Eastern Nepal by Bäumler (2001) (Table 1).

The ecosystem gradient from subalpine forest to alpine grassland and tundra was associated with a decreasing trend in topsoil TOC and an increase in the C/N ratio of the organic matter (Fig. 2), in agreement with various studies showing an increasing trend with altitude from the montane to the subalpine belt, followed by a strong decrease in the alpine one (e.g. Egli et al., 2008). The differences along the altitudinal gradient reflected a changing balance of soil C inputs and soil C losses that are potentially related to changes in both abiotic (e.g. temperature) and biotic (e.g. litter quality) factors (Garten and Hanson, 2006; Egli et al., 2008). TOC was low at high altitudes (Table 1), as a result of harsh climate and short growing seasons limiting net primary productivity and C inputs to the soil above the treeline (Garcia-Pausas et al., 2007). In fact, we observed that the mean topsoil winter temperature drops below 0°C at elevations higher than 4000 m, with values close to -5°C at elevations above 5000 m (Fig. 4). Soil freezing and the consequent cryoturbation are strong limitations to plant growth (Körner, 2003).

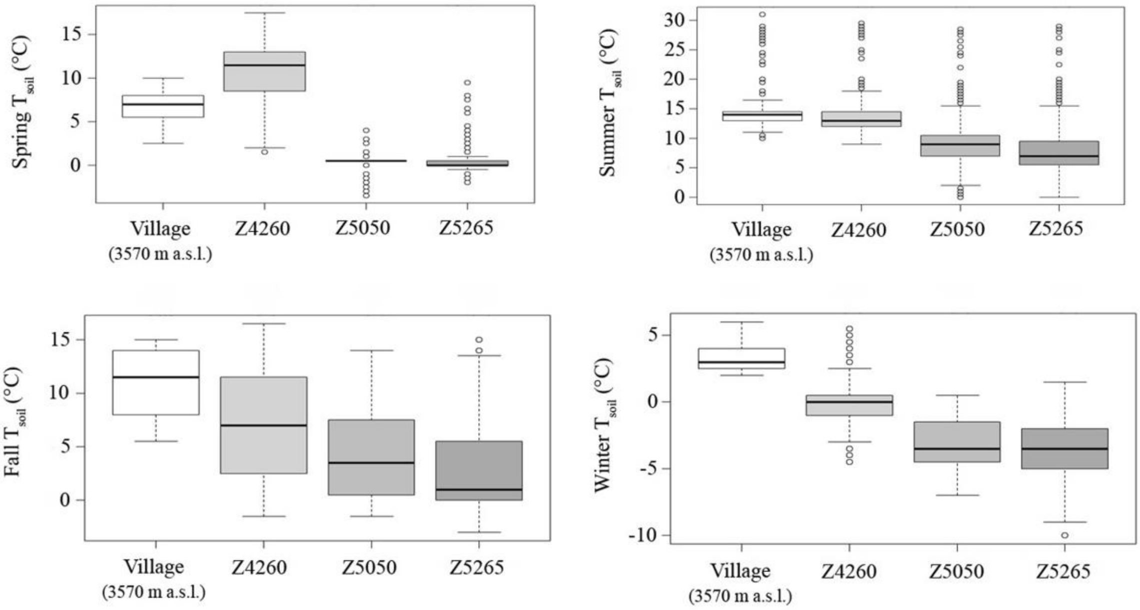

Fig. 4. Topsoil mean temperature (T_{soil}, °C) during the different meteorological seasons (Spring, Summer, Fall, Winter) along the altitudinal gradient (from 3570 to 5265 m a.s.l.). Data recorded every four hours from July 2012 to October 2013.

Most of the limited available information on the distribution of trace elements in the Himalayas has been determined only in topsoil samples (e.g. Loewen et al., 2005; Li et al., 2008; Yeo and Langley-

Turnbaugh, 2010). In particular, trace element contents in topsoils measured in the southern side of Mt. Everest (Table 2) were similar to those recorded in soils from other remote areas, such as the Tibetan Plateau (Li et al., 2008) and the northern side of Mt. Everest (Yeo and Langley-Turnbaugh, 2010), and were below the critical limits for contaminated soils reported by USEPA (2006) at all altitudes. Only the soil sampled close to the waste disposal showed element contents close to these critical limits; trace elements released from the uncontrolled open burning of electronic waste could penetrate the soils where vegetables and crops are grown by contaminating irrigation water and through direct deposition by air (Luo et al., 2011).

Considering the larger number of topsoil trace elements data, we can see a peak in trace element contents measured at 4900-5000 m of altitude. This peak did not correspond to the peak of precipitation observed at 2500 m in this area (Salerno et al., 2015). We did not observe the hypothesized vegetation interceptive effect (Reiners et al., 1975), since the forest sites showed the lowest values of trace elements (Table 2). Our data agreed with those measured by Bergamaschi et al. (2002), who found a slight increase of the enrichment factor for Br, Sb, Zn and Pb in foliose lichens between 3800 and 5090 m in the same area. They supposed that some of these elements were associated to the finest airborne particles and could be subjected to long transport phenomena in the higher tropospheric layer.

Although organic matter is an efficient scavenger of trace elements (Reiners et al., 1975), TOC was not correlated to most topsoil trace elements; only Pb was well associated with organic matter content in PCA axis 2, while Cu was weakly negatively correlated with TOC, despite its high measured contents in A horizons (Fig. 3). Soil organic matter with low C/N is usually considered to decompose more rapidly than organic matter with high C/N (Finzi et al., 1998), and the fast turnover of organic matter may cause a rapid loss of trace elements (e.g. Pb) from soils (Watmough et al. 2005). The absence of significant positive correlations between trace elements and C/N, and between trace elements and pH (Fig. 2), revealed that the sorption potential determined by the organic matter content and quality, and soil pH as factors influencing the mobility of trace elements, were not generalized causes of the differences in elemental contents in the topsoils, and their influence was different on each trace element, as also reported by Bacardit and Camarero (2010). Pedogenic processes, on the contrary, have a strong impact on trace element content in topsoils, and the leaching caused by cheluviation in subalpine podzolic soils can explain the low values below treeline.

The depth trend of trace elements throughout the soil profile is less known. Depth trends can be used to detect possible surface contamination or to assess their mobility in the soil profile, associated with soil properties such as structure or with pedogenic processes (Li et al., 2014). In general, the relative enrichment of trace elements in the upper soil horizons implies the contributions of anthropogenic inputs (Li et al., 2014). Our results showed that, in subalpine podzolic soils, most siderophile elements (i.e. Ni, Cr, Co, Mn), but also Cu and Zn, were subjected to leaching in podzolic soils (e.g. D'Amico et al., 2008). The lowest values observed in topsoils of podzols can be ascribed to cheluviation processes. Cu often showed the highest values in A horizons, in line with the capacity of organic matter to bind this element (Alloway, 2013), or possibly with anthropogenic enrichment. In other soil types, no significant increase in deep layers was observed (Table 2).

The trace element depth trend in alpine soils, showing the highest values in surface horizons, particularly around 5000 m of elevation (Table 2), could be caused by air-borne contamination. In fact, air-borne contamination cannot be excluded, and is maybe driven by particular micro-climatic or topographic conditions (e.g. Bergamaschi et al. 2002; Cong et al., 2015). An increase in Pb content with altitude has been recorded in other high-elevation areas such as in soils across the Pyrenees (McGee and Vallejo, 1996) and on northeastern United States mountains in New Hampshire (Reiners et al., 1975). Several studies in the European Alps suggested that there is generally an increase in deposition as altitude increased (Camarero et al., 2009), but other studies (e.g. Kang et al., 2007) found no obvious trends in trace element accumulation with altitude. Thus, these pristine ecosystems can undergo long-range atmospheric contamination (Bacardit and Camarero, 2010; Cong et al., 2010). Soil trace element deposition levels are especially influenced by precipitation amounts and high mountains are regional convergence zones that trap atmospheric contaminants as a result of cold condensation and enhanced atmospheric deposition (Zechmeister, 1995; Wegman et al., 2006). A stronger air born contamination (possibly associated with higher rainfall) could however be masked in lower altitude soils, where pedogenic processes lead to leaching from surface layers.

4.2 High-elevation toposequence

Soil development in high mountain regions is strongly controlled by processes of weathering and cryoturbation, which in turn are significantly influenced by the topographic conditions associated with different humidity, wind, snow cover depth, and duration (Fig. 5). In fact, rugged surfaces shape snow deposition and translocation patterns on slopes, affecting the freeze-thaw cycles and melt-water runoff (Stres et al., 2013), thus influencing soil development degree and chemical properties.

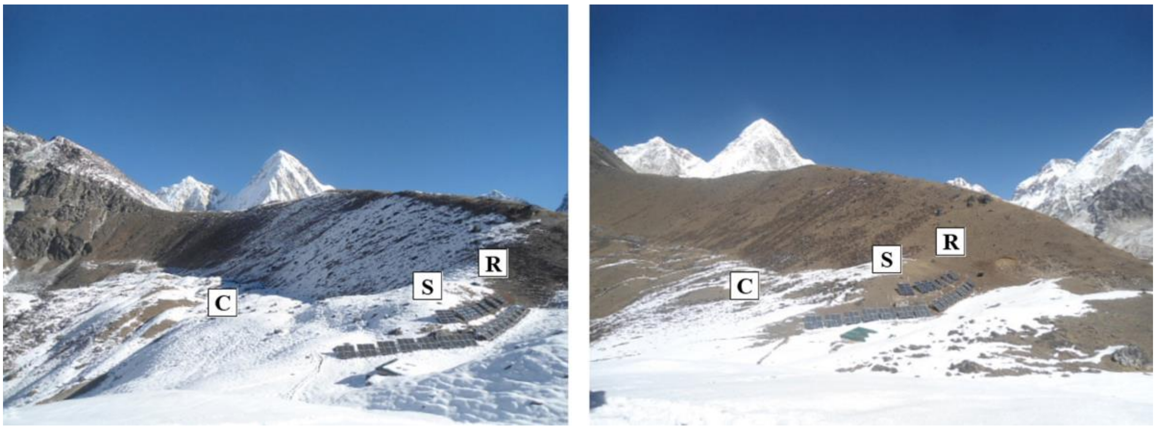

Fig. 5. Snow distribution patterns in the high-elevation toposequence (R: ridge; S: slope; C: concave). On the left: October 24th, 2013. On the right: November 11th, 2013.

All soils were characterized by well-developed sandy Bw horizons (Table 4), in contrast with that reported by Bäumler and Zech (1994), who indicated the prevalence of shallow Regosols in the alpine mountain zone above the forest line and in the zone of alpine turf vegetation. The presence of stone-rich bottom layers at all sites evidenced a depositional discontinuity explained by a widespread presence of wind-blown materials (Bäumler 2001). The clear increasing trend in pH values with soil depth (Table 4) could imply a multi-layer stratigraphy of the solum (Bäumler, 2001), but could be easily explained also by leaching during the monsoon season and to the acidifying effect of *Rhododendron* shrubs (Guggenberger et al., 1998). The Fed/Fet ratio evidenced a higher weathering degree at the slope and concave sites than at the ridge one, probably because of the greater erosion intensity in the latter site (Table 4). In the ridge site, the Fed/Fet decreased with increasing soil depth, while in the other two sites local maxima were located in the subsoil. The greater Feo/Fed ratio in the AB and B horizons at all sites revealed a weathering trend leading to the formation of amorphous and poorly crystalline iron oxides. According to Bäumler (2001) the Fed, which ranged between 1 and 7 g kg^{-1}, reveals how the deposits are of Late Pleistocene origin or younger, since older soils of interglacial origin have much higher amounts of well-crystallized iron oxides up to 40 g kg^{-1} in eastern Nepal.

The TOC and C/N were higher in the concave and slope sites than in the ridge, revealing a higher degree of organic matter mineralization in the ridge site or a lower TOC input associated with a sparser vegetation cover devoid of *Rhododendron* shrubs (Table 4).

Water fluxes are also important in element leaching or accumulation through the soil. In particular, snowmelt or monsoon precipitation can cause high water contents in soils and rapid water flow in preferential pathways, with a potential reduction of retention by sorption (Bacardit and Camarero, 2010). Thus, the observation of trace element contents in soils developed across a toposequence characterized by different snow accumulation and wind processes can give insights on their behavior in these high-elevation Himalayan soils. In fact, the coarse-texture of these soils could facilitate the downward migration of trace elements resulting in an accumulation at greater soil depth (Li et al., 2014). Water is the vehicle for transport of solutes, including trace elements, through soil. The always lower content in the stone rich deep horizons is likely associated with a mineralogical discontinuity caused by the thick aeolian layer (Table 5) (Guggenberger et al., 1998).

5. Conclusions

Soils types and pedogenic processes change along the altitudinal gradient in the Dudh Koshi Valley. At elevations higher than 4000 m a.s.l. soil temperatures below 0°C were reported, which caused soil freezing and consequent cryoturbation. Thus, the plant growth was limited at high elevations and it was reflected in the negative correlations found between altitude and TOC.

Trace element contents along the altitudinal gradient were similar to those recorded in soils from other remote areas, with the exception of the area close to the open waste disposal where higher values were recorded, but still below the USEPA (2006) thresholds, revealing a potential localized source of contamination. Contents of Co, Zn, Cr, and Ni, in the topsoil were positively correlated with the altitude, as reported in other mountain areas, a phenomenon potentially ascribable to the orographic effect on trace element deposition and/or to different biogeochemical processes leading to leaching at lower altitudes. Among the soil characteristics influencing the mobility of trace elements along the altitudinal gradient, both organic matter and pH seemed not to be determinant of the differences in elemental contents in the topsoils. The degree of weathering and pedogenesis influenced the distribution of trace elements through the soil profiles. In the lower elevation podzolic soils, low surface concentrations of trace elements were measured, with higher contents in the illuvial Bs and Bhs horizons. The difference between surface and subsurface horizons tended to disappear among soil profiles with the increase in elevation. No significant differences in mean trace element contents were found in the high-elevation toposequence despite the observed different patterns of depth distribution.

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Sample	Altitude	Classification	Horizon	Depth	Color	Stones	TOC	C/N	pH	Fed	Feo	Feo/Fed	Fed/Fet	Alo	IS
	m a.s.l.	IUSS 2015		cm		% vol	%			g kg^{-1}	g kg^{-1}			g kg^{-1}	
Z3700	3700	Albic Podzol	A1	0-7	7.5 YR 2/3	5.0	7.6	19.0	5.4	12.6	12.0	1.0	0.7	9.5	1.6
			A2	7-11	7.5 YR 4/3	5.0	2.9	29.0	6.2	8.4	6.4	0.8	0.7	3.7	0.7
			E1	11-18	7.5 YR 5/2	5.0	2.6	26.0	6.1	4.0	2.7	0.7	0.6	2.0	0.3
			Bs	18-25	10 YR 5/6	5.0	2.4	24.0	5.9	17.1	15.1	0.9	0.9	4.9	1.3
Z3750	3750	Ortsteinic Albic Podzol (Arenic)	A	3-9	10 YR 5/3	0.0	4.5	22.5	5.2	3.5	3.3	0.9	0.8	0.6	0.2
			E	9-17	10 YR 5/4	0.0	1.5	15.0	5.0	3.4	1.8	0.5	0.6	0.8	0.2
			Bhs	17-43	10 YR 4/6	0.0	4.5	45.0	5.3	21.9	14.2	0.6	0.8	18.4	2.6
			BC	43-60+	10 YR 5/4	0.0	1.4	14.0	5.6	7.0	4.6	0.7	0.4	7.8	1.0
Z3865	3865		A	0-10	10 YR 3/3	1.5	9.4	18.0	4.5						
Z4260	4260	Brunic Dystric Arenosol	A	0-10	7.5 YR 2/2	0.0	6.5	10.8	5.5	2.5	2.3	0.9	0.4	1.3	0.3
			AB	10-20	10 YR 6/4	0.0	0.7	7.0	5.8	1.1	0.6	0.6	0.1	0.6	0.1
			Bw	20-30	7.5 YR 6/6	0.0	0.7	7.0	5.9	1.1	0.9	0.8	0.1	0.9	0.1
Z4485	4485	Brunic Dystric Arenosol	A	0-7	10 YR 3/4	5.0	7.4	14.8	5.9	3.9	3.2	0.8	0.3	1.5	0.3
			Bw	7-10+	10 YR 5/3	0.0	1.9	19.0	5.1	2.5	1.9	0.8	0.2	1.3	0.3
Z4680	4680		AC	0-10	10 YR 4/3	37.9	4.1	15.1	6.0						
Z4880	4880		AC	0-10	10 YR 7/2	38.5	0.5	10.9	6.5						
Z4940a	4940		A	0-10	10 YR 4/3	0.0	3.7	14.4	5.1						
Z4940b	4940		A	0-10	10 YR 4/3	0.9	5.1	13.2	5.9						
Z4940c	4940		A	0-10	10 YR 5/4	6.4	3.5	15.5	5.8						
Z4950	4950		A	0-10	10 YR 4/3	0.4	3.3	14.3	6.0						
Z4955	4955	Dystric Arenosol	A	0-7	10 YR 4/2	10.0	3.4	11.3	5.0	2.5	1.1	0.5	0.1	0.8	0.1
			C	7-20	10 YR 5/2	10.0	0.1	4.7	5.6	0.6	0.2	0.4	0.1	0.2	0.0
Z4960	4960		A	0-10	10 YR 5/3	0.0	0.1	4.9	6.0						

Z4965	4965		A	0-10	10 YR 3/3	3.3	5.9	12.6	5.8						
Z5050	5050		A	0-10	10 YR 2/3	0.0	4.5	16.1	5.4						
Z5100	5100		A	0-10	10 YR 3/3	0.0	4.1	14.0	5.2						
Z5170	5170		A	0-10	10 YR 4/3	0.0	3.3	15.0	5.5						
Z5245	5245		A	0-10	10 YR 5/3	0.0	1.3	12.7	5.5						
Z5250	5250		A	0-10	10 YR 4/3	1.5	2.6	13.0	5.5						
Z5260	5260		A	0-7	10 YR 2/2	5.8	2.9	13.7	5.4						
Z5265	5265		A	0-10	10 YR 3/4	20.0	2.8	15.1	5.4						
Z5280	5280	Haplic Umbrisol (Arenic, Turbic)	A1	0-7	10 YR 2/3	20.0	2.9	14.5	5.2	5.2	2.6	0.5	0.4	1.7	0.3
			A2	7-20	10 YR 3/3	0.0	2.3	11.5	5.5	6.3	2.6	0.4	0.2	0.2	0.2
			AB	20-30	10 YR 3/3	0.0	2.0	20.0	5.9	6.9	3.8	0.6	0.4	0.3	0.2
Z5300	5300	Brunic Dystric Arenosol	A	0-10	10 YR 5/3	0.0	1.3	13.0	6.2	1.3	0.5	0.4	0.1	0.7	0.1
			AB	10-20	10 YR 6/3	0.0	0.7	7.0	5.9	1.2	0.6	0.5	0.0	0.8	0.1
			Bw	20-25	10 YR 6/3	10.0	0.6	6.0	6.4	1.5	0.6	0.4	0.1	1.0	0.1
Z5320	5320		A	0-7	10 YR 6/1	28.1	0.2	8.8	5.9						
Village	3570	Dystric Regosol	A	0-10	7.5 YR 3/3	2.0	6.7	13.4	5.8	15.5	8.2	0.5	0.5	9.9	1.4
			AC	10-30	10 YR 3/4	2.0	4.6	15.3	5.7	19.0	12.0	0.6	0.6	15.3	2.1
Waste disposal	3700		A	0-10	10 YR 4/2	0.0	5.3	22.1	8.3						
Agricultural soil	4405		A	0-10	10 YR 2/3	1.7	16.6	11.9	5.7						

Table 1. Topsoil and soil profile characteristics along the altitudinal gradient. IS: index of spodicity (1/2*Feo + Alo). Stone content (% vol) was estimated qualitatively in the field.

Sample	Altitude	Horizon	Co	Cu	Zn	Cr	Pb	Ni	Mn	Fe
	m a.s.l.					mg kg^{-1}				g kg^{-1}
Z3700	3700	A1	4.3	9.2	15.5	1.8	8.0	9.8	118.0	17.4
		A2	2.5	5.2	8.0	0.0	10.5	4.3	81.0	12.3
		E1	2.6	6.3	11.0	3.8	11.4	4.8	92.3	6.8
		Bs	2.9	8.7	10.0	5.9	18.5	5.4	83.0	18.3
Z3750	3750	A	2.0	6.2	9.3	0.0	7.5	4.0	53.0	4.4
		E	1.7	1.8	9.7	5.4	29.7	0.5	54.0	6.1
		Bhs	7.0	7.9	35.0	23.9	29.2	17.5	163.0	29.0
		BC	7.6	7.7	37.9	21.4	25.9	20.0	218.1	19.5
Z3865	3865	A	2.5	9.4	10.5	4.3	7.0	7.3	59.4	7.5
Z4260	4260	A	3.5	6.4	16.3	5.8	3.5	9.9	90.0	7.0
		AB	4.9	5.1	20.1	6.6	7.8	8.2	98.0	8.5
		Bw	5.5	5.4	20.4	7.1	7.9	8.6	120.0	8.6
Z4485	4485	A	5.5	11.0	23.8	8.8	4.5	11.0	171.0	12.4
		Bw	4.8	8.4	30.9	7.2	9.2	9.2	119.0	10.6
Z4680	4680	AC	5.8	10.0	28.8	9.5	5.0	11.0	293.0	10.8
Z4880	4880	AC	4.5	9.8	20.0	6.3	4.0	8.3	183.0	9.9
Z4940a	4940	A	8.5	14.8	31.3	17.3	6.5	16.8	260.5	17.9
Z4940b	4940	A	10.3	12.5	42.5	18.3	11.3	17.8	275.5	20.0
Z4940c	4940	A	13.3	14.6	45.0	43.3	14.0	24.3	250.0	29.4
Z4950	4950	A	10.0	9.3	37.5	24.1	10.1	12.0	306.3	24.5
Z4955	4955	A	10.5	10.3	42.5	37.3	11.9	14.3	266.0	20.6
		C	4.8	7.3	27.5	6.8	6.5	8.3	79.0	8.9
Z4960	4960	A	6.5	6.6	26.3	22.3	2.1	13.0	173.8	15.1
Z4965	4965	A	10.3	16.1	33.8	22.8	7.5	20.3	344.3	21.6

Z5050	5050	A	11.0	9.9	40.0	25.3	10.0	18.0	248.8	18.1
Z5100	5100	A	9.3	9.6	41.3	23.0	8.9	14.0	242.5	24.0
Z5170	5170	A	8.3	8.8	38.8	20.8	9.0	14.3	266.8	18.4
Z5245	5245	A	11.0	10.6	36.3	30.8	7.9	19.0	273.8	24.5
Z5250	5250	A	11.3	9.3	35.0	25.0	10.1	15.8	283.8	25.9
Z5260	5260	A	11.3	12.6	37.3	36.3	9.0	20.0	271.3	21.3
Z5265	5265	A	8.5	9.9	35.0	24.0	8.0	15.3	221.3	17.0
Z5280	5280	A1	10.8	11.6	41.3	29.3	9.8	18.5	288.0	14.3
		A2	10.5	11.9	37.5	26.5	10.3	19.0	270.0	27.5
		AB	11.3	10.7	59.3	19.0	18.6	20.6	365.0	16.6
Z5300	5300	A	6.0	8.0	36.3	7.5	7.3	8.8	221.0	11.8
		AB	6.7	9.4	48.6	11.2	11.6	12.2	199.1	24.1
		Bw	7.9	8.0	49.4	12.2	13.6	12.7	227.0	11.7
Z5320	5320	A	9.8	12.3	23.8	34.1	1.9	18.3	217.5	18.1
Village	3570	A	9.5	14.9	37.5	20.3	20.3	20.8	273.0	28.5
		AC	10.1	13.9	51.7	19.6	20.8	22.8	270.0	32.0
Waste disposal	3700	A	18.5	428.5	1360.0	90.0	241.5	45.0	868.0	34.5
Agricultural soil	4405	A	2.5	19.5	12.5	4.0	2.5	15.5	56.2	6.2

Table 2. Topsoil and soil profile trace element contents along the altitudinal gradient.

	Biplot scores		
	PC1	PC2	PC3
Eigenvalue	6.697	2.409	0.893
Cumulative variance explained	0.558	0.759	0.833
Altitude	0.998	0.453	0.160
TOC	-0.565	-0.829	-0.376
C/N	-0.441	-0.906	0.164
pH	0.180	0.843	-0.163
Co	1.152	-0.157	-0.058
Cu	0.737	-0.331	-0.790
Zn	1.068	-0.117	0.288
Cr	1.060	-0.055	0.064
Pb	0.609	-0.819	0.439
Ni	1.058	-0.169	-0.326
Mn	1.038	0.056	-0.061
Fe	1.014	-0.242	0.043

Table 3. PCA eigenvalues, variance explained, and biplot scores of the main soil properties and trace elements in topsoil samples (KMO measure of sampling adequacy = 0.7). Village, waste disposal and agricultural soil sites were excluded from the analysis.

Sample	Altitude m a.s.l.	Classification IUSS 2015	Horizon	Depth cm	Stones % vol	Color	TOC %	C/N	pH	Fed g kg^{-1}	Feo g kg^{-1}	Feo/Fed %	Fed/Fet %	Alo g kg^{-1}	Clay %	Fine silt %	Coarse silt %	Fine sand %	Coarse sand %
Concave (C)	5055	Dystric Cambisol (Loamic, Raptic)	A	0-9	0	10 YR 4/3	4.9	13.2	5.2	4.3	2.5	57.9	22.1	1.4	3.1	8.9	18.1	58.7	11.2
			AB	9-18	0	10 YR 4/4	2.1	12.1	5.4	7.4	3.9	53.0	32.1	1.8	2.9	11.3	20.3	57.6	8.0
			Bw1	18-35	0	10 YR 4/3	1.9	12.3	5.5	6.4	4.8	75.5	29.9	2.8	2.9	8.2	15.0	62.8	11.1
			Bw2	35-40	0	10 YR 4/3	1.5	14.2	5.6	4.2	2.5	59.3	22.6	3.2	2.1	5.6	7.6	58.2	26.5
			2BC	40-45+	20	10 YR 4/3	1.3	13.9	5.7	3.2	1.9	60.4	17.1	2.8	2.3	5.4	5.9	52.9	33.4
Slope (S)	5065	Brunic Dystric Arenosol (Aeolic, Raptic)	A1	0-3	0	10 YR 3/3	6.1	16.8	5.3	4.3	2.0	47.2	22.4	1.2	1.5	5.0	14.1	49.5	29.9
			A2	3-9	0	10 YR 4/3	4.7	15.8	5.3	5.4	2.2	41.4	25.4	1.3	1.6	7.7	14.1	56.0	20.6
			A3	9-19	0	10 YR 3/4	3.4	15.0	5.6	5.6	2.8	50.1	26.8	1.8	1.8	9.1	16.1	61.3	11.7
			A4	19-30	0	10 YR 3/3	3.4	15.9	5.8	7.0	2.6	37.2	34.3	1.8	2.8	10.8	20.6	58.1	7.8
			AB1	30-50	0	10 YR 3/4	2.4	13.8	5.9	6.5	3.3	51.7	30.4	2.3	2.3	10.9	14.3	62.9	9.5
			AB2	50-60	0	10 YR 4/3	2.3	17.5	5.9	6.3	4.0	64.4	33.2	3.1	1.7	8.6	11.0	65.7	13.0
			BC	60-80	0	10 YR 4/3	1.2	12.4	5.8	3.3	1.8	52.8	14.5	2.3	1.5	6.7	6.4	56.9	28.5
			2C	80-85+	50	10 YR 5/3	0.7	11.0	6.0	1.1	0.8	65.9	10.9	1.5	2.4	12.6	7.0	34.0	44.0
Ridge (R)	5070	Dystric Cambisol (Loamic, Raptic)	A1	0-5	0	10 YR 3/3	3.2	10.7	5.4	5.2	1.3	24.3	21.8	1.6	3.3	12.4	20.6	51.3	12.4
			A2	5-12	0	10 YR 4/3	2.6	10.6	5.7	4.0	1.8	44.5	17.1	2.2	4.1	12.4	16.8	57.5	9.3
			AB	12-21	0	10 YR 4/4	2.3	11.2	5.8	3.9	2.3	57.9	18.0	2.4	3.9	11.0	15.0	56.4	13.8
			2Bw	21-30+	40	10 YR 5/4	0.8	10.1	6.0	1.0	0.6	56.7	9.3	2.1	2.0	13.2	4.6	31.2	48.9

Table 4. Soil characteristics in the high-elevation toposequence. Stone content (% stones) was estimated qualitatively in the field.

Sample	Altitude	Horizon	Co	Cu	Zn	Cr	Pb	Ni	Mn	Fe
	m a.s.l.					mg kg^{-1}				g kg^{-1}
Concave (C)	5055	A	8.8	7.9	58.8	11.3	13.8	16.3	241.0	19.6
		AB	12.5	7.3	63.5	12.0	16.8	13.0	524.0	23.0
		Bw1	12.3	9.8	54.8	10.0	16.3	12.3	464.1	21.3
		Bw2	11.0	9.8	56.0	15.3	12.3	16.8	268.0	18.8
		BC	9.3	9.0	44.8	13.5	10.0	15.3	243.0	18.9
Slope (S)	5065	A1	9.3	9.4	60.0	14.0	11.3	16.0	280.0	19.3
		A2	9.0	8.9	68.8	15.5	11.0	16.0	256.4	21.3
		A3	8.8	8.1	61.3	12.5	11.0	14.0	229.0	21.0
		A4	8.5	8.1	43.8	13.3	13.5	14.3	243.0	20.4
		AB1	8.0	9.0	51.0	11.5	14.3	12.0	249.2	21.3
		AB2	7.3	7.5	38.5	9.0	12.0	13.3	190.1	18.9
		BC	10	9.8	36.0	20.5	11.3	19.3	240.0	23.0
		C	3.8	4.8	21.0	8.5	6.8	11.3	94.0	10.5
Ridge (R)	5070	A1	12.2	10.4	62.5	15.0	14.8	22.5	311.0	23.9
		A2	12.3	9.6	57.5	12.8	13.5	20.5	303.0	23.1
		AB	11.0	10.3	51.0	11.3	16.5	14.5	259.3	21.6
		Bw	4.5	5.3	16.0	4.3	8.5	10.3	96.1	10.4

Table 5. Soil trace elements in the high-elevation toposequence.