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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.

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 re-deposited, 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

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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 glacio-fluvial 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 > 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