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Geosphere-biosphere circulation of chemical elements in soil and plant systems from a 100 km transect from southern central Norway

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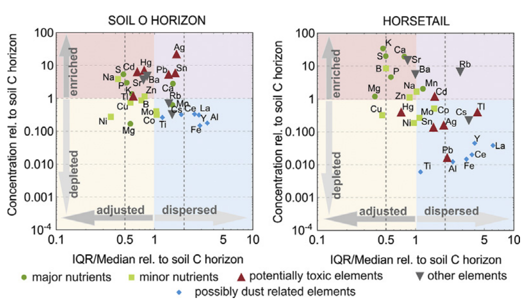
HIGHLIGHTS

- Biogeochemical soil-plant relations based on 14 sample media from 41 sites are studied.
- All plants studied show unique elemental preferences.
- The soil O horizon is a living system as expressed in its element composition.
- Plants adjust their elemental composition largely independent of the natural substrate variability.
- A large number of organisms in the critical zone individually modify its chemical composition.

GRAPHICAL ABSTRACT



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ABSTRACT

Geochemical element separation is studied in 14 different sample media collected at 41 sites along an approximately 100-km long transect north of Oslo. At each site, soil C and O horizons and 12 plant materials (birch/spruce/cowberry/blueberry leaves/needles and twigs, horsetail, braken fern, pine bark and terrestrial moss) were sampled. The observed concentrations of 29 elements (K, Ca, P, Mg, Mn, S, Fe, Zn, Na, B, Cu, Mo, Co, Al, Ba, Rb, Sr, Ti, Ni, Pb, Cs, Cd, Ce, Sn, La, Tl, Y, Hg, Ag) were used to investigate soil-plant relations, and to evaluate the element differentiation between different plants, or between foliage and twigs of the same plant. In relation to the soil C horizon, the O horizon is strongly enriched (O/C ratio > 5) in Ag, Hg, Cd, Sn, S and Pb. Other elements (B, K, Ca, P, S, Mn) show higher concentrations in the plants than in the substrate represented by the C horizon, and often even higher concentrations than in the soil O horizon. Elements like B, K, Ca, S, Mg, P, Ba, and Cu are well tuned to certain concentration levels in most of the plants. This is demonstrated by their lower interquartile variability in the plants than in the soil.

Cross-plots of element concentration, variance, and ratios, supported by linear discrimination analysis, establish that different plants are marked by their individual element composition, which is separable from, and largely independent of the natural substrate variability across the Gjøvik transect. Element allocation to foliage or twigs of the same plants can also be separated and thus dominantly depend on metabolism, physiology, and structure linked to biological functions, and only to a lesser degree on the substrate and environmental background. The results underline the importance of understanding the biological mechanisms of plant-soil interaction in order to correctly quantify anthropogenic impact on soil and plant geochemistry.

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1. Introduction

To understand element interactions in the critical zone, where rock meets life, a holistic approach to geochemistry is necessary, i.e. the combined study of several spheres of the ecosystem (Fortescue, 1980, 1992; Amundson et al., 2007; Brantley et al., 2007). Many potentially toxic elements (PTEs) such as Cd, Hg and Pb are enriched in soil and sediment horizons at the Earth surface (e.g., Reimann et al., 2007b, 2009, 2015b). In environmental sciences this observation is most often considered to indicate a massive global impact of anthropogenic activities on the critical zone (e.g., Steinnes and Lierhagen, 2018). While an anthropogenic impact undeniably exists, this interpretation neglects fundamental discoveries of Vernadsky, who highlighted the importance of the biosphere for geochemical processes at the Earth surface already in 1926 (Vernadsky, 1926), and Goldschmidt, who described such biogeochemical processes >80 years ago (Goldschmidt, 1937). This neglect is manifest in the current tendency in environmental sciences to oversimplify quantitative estimates of anthropogenic impact. For example, element concentrations in deep mineral soil (e.g., the soil C horizon) or even average values for the estimated element composition of the upper continental crust (e.g., Wedepohl, 1995 or Hu and Gao, 2008) are often indiscriminately used to present the "geochemical background" against which a supposed anthropogenic impact is assessed (e.g., Zhou et al., 2018).

The biosphere is deeply involved in the weathering process and strongly interacts with the developing soil and sediments (e.g., Gadd, 2007). Weathering involves a complete breakdown of the lithological mineral assemblage, and the precipitation or biogenic generation of new minerals (e.g., Graham et al., 2010). These processes will have an important impact on the bioavailability of many elements (e.g., Ugolini et al., 2001). Bacteria, plants and fungi all have specific needs or uses for chemical elements or may tolerate them and can enrich or deplete certain elements in different soil horizons (see Marschner, 2012). Because the biosphere applies its own strategies to dispose of or even use and enrich toxic elements, these elements are differently distributed in the critical zone compartments.

While element concentrations in different mineral soil horizons, e.g., the soil B and C horizon are most often correlated, this correlation is lost between mineral soil and organic topsoil, especially the organic forest soil O horizon. This change will affect all element ratios. The role of trace elements in plants and whether they are taken up on purpose or "accidentally" together with the nutrients is intensively discussed in the literature (e.g., Hall, 2002; Poschenrieder et al., 2006; Rascio and Navari-Izzo, 2011; Boyd, 2012; Viehweger, 2014). Different plants, growing on the same soil will have a specific elemental composition, stoichiometry and element allocation to its different parts (roots, stem, leaves, bark) depending of their particular metabolism, physiology and structure linked to their optimal functioning (their "biogeochemical profile" – see discussion of the "biogeochemical niche" in Sardans and Peñuelas, 2014). Vesteral and Rauland-Rasmussen (1998) have for example demonstrated that forest floor chemistry depends on the tree species growing in a stand. These authors even suggest that storage and immobilisation of elements may be managed by selection of the proper tree stands. Therefore, enrichment of PTEs at the Earth surface does not necessitate an external input, it can as well be due to natural, biogeochemical processes.

In order to decide whether an observed enrichment of certain elements at the Earth surface is due to anthropogenic activities, the whole functioning of the local ecosystem needs to be studied and understood.

To study plant soil interactions, and to delineate the active role plants take in the distribution of all chemical elements at the Earth surface, 14 different sample materials including the soil C and O horizon, were systematically collected at 41 sites along a 100 km long transect (subsequently referred to as the Gjøvik transect), cutting the Oslo Rift, one major and a minor Mo mineralisation and several Pb mineralisations (see Materials and Methods section).

The signal of the mineralisations encountered along the transect is covered in two separate papers, for the two soil horizons and terrestrial moss in Flem et al. (2018) and for the plants in Reimann et al. (2018b).

Here, the geochemical expression of the 12 plant materials in relation to the soil horizons collected at the same sites along the Gjøvik transect is investigated. For many elements these data establish the minimal detection limits required for future monitoring or mapping of the studied plant species. The chemistry of leaves and twigs is compared to the chemistry of soil C and O horizon samples collected at the same sites. The plants used for this study are among the most widespread species in the survey area. They are grubs for several herbivorous animals and initiate the food chain in this environment. The results provide fundamental insight into uptake of, and the relation between major nutrients, minor nutrients and other elements, including PTEs in the different plants/parts of plants.

2. Material and methods

2.1. Topography

The Gjøvik transect is a continuation towards the north of the Oslo transect (Reimann et al. 2006, 2007a,b,c, 2008b, c; Jensen et al. 2007; Fabian et al. 2011). The Oslo transect was designed to cover the geochemical footprint of a large city. The Gjøvik transect extends from the lake Hurdalssjøen in the southeast, runs through parts of Akershus and Oppland counties, South Norway, and ends in Aust-Torpa in the northwest about 100 km north of Oslo, on the west side of lake Mjøsa (Fig. 1). Due to its rather remote location, the Gjøvik transect complements the Oslo transect in that it is assumed that the local anthropogenic impact on element concentrations in moss, plant leaves and soil O horizon is lower.

2.2. Geology

The bedrock along the Gjøvik transect consists of four major rock units (Fig.1): Mesoproterozoic granitic gneisses, Permian Oslo Rift igneous rocks, Mesoproterozoic mica gneisses and schists and Neoproterozoic-Silurian sedimentary rocks. The south-eastern part of the transect (samples 3–15) belongs to the Oslo Rift, which here mainly comprises batholiths with alkali syenitic to alkali granitic composition (Larsen et al. 2008). In addition, monzonite intrusions and rhyolitic to trachytic ignimbrites occur in the area. The Oslo Rift is flanked by Mesoproterozoic granitic gneisses, belonging to the Iddefjorden lithotectonic unit (e.g., Bingen et al. 2008 - samples 1–2 and 16–18). The Mesoproterozoic mica gneisses and schists to the northwest of the Oslo Rift (samples 23–26) are here classified as a separate unit, although they share much of the same characteristics as the granitic gneisses further east (e.g. Bingen et al. 2005). The north-western part of the transect (samples 19–22 and 27–41) is dominated by sedimentary rocks of mainly Neoproterozoic-Silurian age belonging to the Oslofjord Supergroup and Hedmark Group (Henningsmoen 1960; Owen et al. 1990). They consist of tightly interbedded lithologies that are geochemically different. The groups are dominated by shale and limestone in the south (samples 19–22) and shale, sandstone, quartz arenite and limestone in the north (samples 27–41). This succession also comprises the characteristic black, graphitic and radiogenic shale formation known as the Alum shale formation. The Neoproterozoic-Silurian succession locally contains intervals of dolostone, marl and conglomerate (Lutro & Nordgulen 2008).

2.3. Mineralisations

The plutonic rocks of the Oslo Rift contain several mineral occurrences and deposits; among others a number of porphyry-type molybdenite deposits (Bjørlykke et al. 1989). One of them, the Nordli Mo-