Science of the Total Environment 506–507 (2015) 480–495

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Biogeochemical plant–soil interaction: Variable element composition in leaves of four plant species collected along a south–north transect at the southern tip of Norway

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HIGHLIGHTS

- Plant–soil element uptake and interactions were studied along a 200 km transect.
- 53 elements were analysed in leaves of 4 plants and 2 soil horizons.
- Element relations within and between the materials revealed unexpected behaviour.
- The mineral soil did not deliver a valid background for plants and soil O horizon.
- Plant–soil systems appeared individually actively regulated and highly non-linear.

ARTICLE INFO

Article history:
Received 11 August 2014
Received in revised form 21 October 2014
Accepted 22 October 2014
Available online 27 November 2014

Editor: James P. Bennett

Keywords:
Transect
Birch
Willow
Juniper
Heather
Critical zone

ABSTRACT

Leaves from four different plant species (birch, willow, juniper, and heather) together with samples of the soil O and C horizons were collected at 44–46 sites along a south-to-north transect extending inland for 200 km from the southern tip of Norway. The transect covers one of the steepest vegetation gradients on Earth, crossing six vegetation zones. Juniper and heather are evergreen, and preferably exclude potentially toxic elements to avoid their accumulation in assimilating tissues, birch and willow shed their leaves in autumn together with the load of potentially toxic elements, and thus can tolerate the uptake of such elements. The plant leaves show the highest concentrations for B, Ca, K, Mg, Mn, P, Rb and S. In the soil O-horizon Ag, Au, As, Bi, Cu, Ge, Hg, In, Pb, Sb, Se, Sn, Te and W are enriched with respect to the C-horizon, whilst Mn and Rb are depleted. Cadmium, Sr and Zn are enriched in willow and Cs, Na and Tl in heather. In terms of concentration gradients from the coast inland, two different patterns are detected: 1) short range with an almost exponential decrease of concentrations from the coast, which appears to be typical for seaspray-related element input, and 2) long range with an almost linear decrease of concentrations with distance from the coast. These patterns differ among the four species, even for one and the same element. Inter-element correlation is different from material to material. Along the transect each of the different plants at the same site individually adapts to the available element combination. High linear correlations in the plants occur between the lanthanides (La, Ce, Y), and interestingly, between P and Ti. The plant/soil system appears highly non-linear and self-regulated.

1. Introduction

Lithosphere, pedosphere, biosphere, hydrosphere and atmosphere all belong to a coupled and usually well regulated Earth surface system. Vernadsky (1926) and Goldschmidt (1937) were the first geochemists trying to describe the role of the biosphere in ecological terms (Mason, 1992; Müller, 2014). Goldschmidt recognized that in the pedosphere not only the soil B-horizon, with its element enrichment due to co-precipitation of many metals with Fe-oxides/hydroxides, but also the O-horizon is an important geochemical barrier. According to Goldschmidt (1937), a lot of elements tend to become enriched only in the O-horizon due to multiple steps of plant uptake, litterfall, and subsequent rotting in the soil O-horizon. The amount of enrichment in the O-horizon depends on the characteristics of the plants involved in this

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http://dx.doi.org/10.1016/j.scitotenv.2014.10.079

process, their bioproductivity, the turnover of the organic soil material and the binding characteristics and bioavailability of the relevant elements (e.g., Reimann et al., 2000, 2007b). The observation that vegetation and climate, in combination with geological settings, influence element concentrations as measured at the Earth's surface led to the development of landscape geochemistry (Perel'man, 1961, 1966; Fortescue, 1980, 1992). Today these concepts are studied under the term "critical zone research" at the forefront of geoscience (e.g., Amundson et al., 2007). The ability of plants to take up and enrich many trace elements has been used successfully by exploration geochemists in the search for mineral deposits (Kovalevsky, 1974, 1987, and more recently Dunn, 2007). Fig. 1 conceptualizes the interactions between different compartments of the ecosystem relevant for this study.

Geochemical gradients in surface soil and plant chemistry related to the input of marine aerosols (Na^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, Cl^-) have been described several times in the literature (Låg and Steinnes, 1976, 1978; Reimann et al., 2000; Derry and Chadwick, 2007). Låg and Steinnes (1978) were the first to report a seaspray effect on the Se concentrations in humus samples collected near the coast of Norway. The input of marine aerosols to plants and surface soil usually can be traced for a few tens of km, and sometimes up to more than 100 km, inland.

Terrestrial moss from the southern tip of Norway shows a strong geochemical gradient of declining Pb concentration with distance from the coast (Steinnes, 1980; Steinnes et al., 1992, 1994). Temporal variations in Pb of this gradient coincide with the use of leaded gasoline, indicating that, in moss, the cause is anthropogenic input of Pb. Steinnes et al. (1992, 1994, 2007) assign this changing Pb input to long-range transport (LRT) from British and central European anthropogenic sources (traffic, power plants, industry). Because they also observed a decreasing concentration of Pb in the organic surface soil from the southern tip of Noway with distance from the coast, Steinnes et al. (2007) suggested that essentially all Pb in the organic-rich surface horizon is of anthropogenic origin. In contrast, Reimann et al. (2009a) provided evidence that the natural conditions at the southern tip of Norway, which displays one of the steepest vegetation zone gradients on Earth (Moen, 1998), may be a more effective cause for the Pb concentration gradient in the soil O horizon than atmospheric input. They also demonstrated that other elements, such as Au, which can hardly be related to LRT, show similar or even steeper concentration gradients than Pb at this location. This claim was then intensely discussed in *Applied Geochemistry* (Steinnes, 2009; Reimann et al., 2009b).

Here we report concentrations and concentration gradients from the coast inland for 32 elements (53 when including elements where the majority of results were below the detection limit) in leaves (needles)

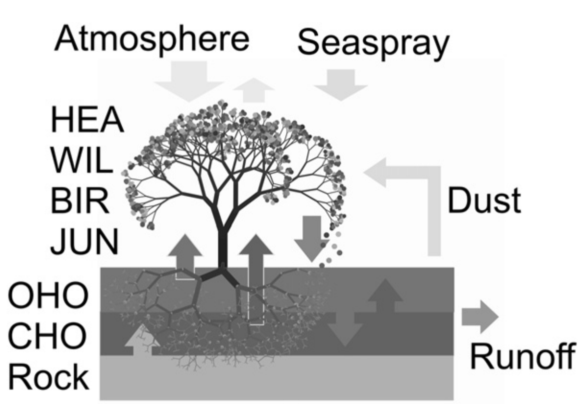

Fig. 1. Conceptual model of the intricate interplay between the different compartments of the ecosystem (Vegetation here represented by: HEA: heather, WIL: willow, BIR: birch, JUN: juniper; and soil represented by OHO, CHO: soil O and C horizons).

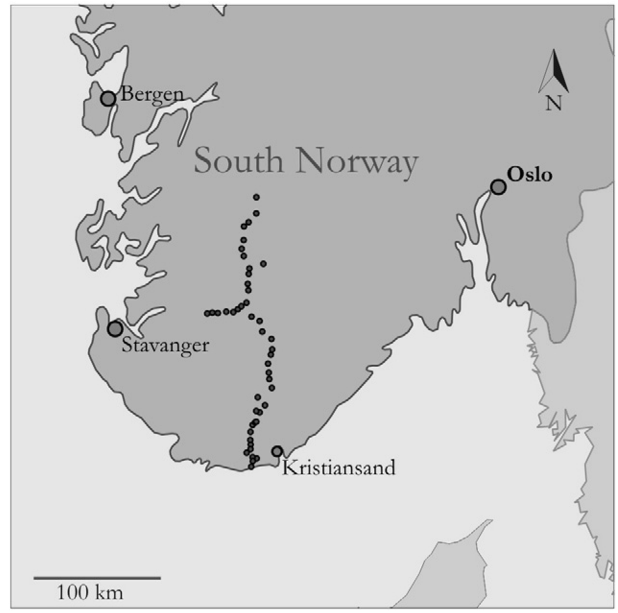

Fig. 2. Location of the transect at the S-tip of Norway. (For more detailed maps see Reimann et al., 2009a, 2009b).

of four different plant species (willow, birch, juniper and heather) which were collected together with soil samples from the tip of the southern coast in Norway to 200 km inland, as presented in Reimann et al. (2009a) (Fig. 2). While the paper of Reimann et al. (2009a) focussed on soils and on the question whether the observed gradients are of anthropogenic or geogenic origin, this study investigates the multielement geochemistry of the plant materials collected at the same time and similarities and differences between soils and plants. Whereas willow and birch shed their leaves every year and can thus use litterfall to dispose of elements exceeding physiological concentrations in the plant (tolerators — see Ernst, 2006), juniper and heather are evergreen species and are much more limited with regard to the uptake of certain elements in order to not exceed their toxicity limits (excluders — for a discussion see Baker, 1981). Here the element concentrations in plant leaves are studied in connection with the soil analyses to (a) discuss concentration differences between the two sampled soil horizons (soil C- and O-horizons) and the four plant species; (b) compare concentration gradients from the coast inland as observed for a variety of chemical elements for all or some of the plants; (c) study the correlation between element concentration in the plant materials and the two soil horizons; (d) investigate the correlation of certain elements in the different sample materials; and (e) conclude which origin of the elements in the plant materials the results suggest.

2. Materials and methods

Sample sites were selected at an approximate spacing of 5 km along the 200 km transect. The exact location of each sample site was determined in the field based on access, geology, and vegetation parameters (presence of heather, willow, birch and juniper). All samples were taken in forests at a minimum distance of 200 m from the nearest road.

2.1. Study area

2.1.1. Transect characteristics

In terms of land-use, the area is quite remote and, by European standards, hardly utilised. There is some tourism, mostly along the coast, along with farming, lumbering and sheep herding. There is a Ni-smelter in Kristiansand, at the coast, about 20 km to the east of the