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Spatial patterns of essential trace element concentrations in Swedish soils and crops

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ABSTRACT

Trace element (TE) concentrations in topsoil of Swedish arable soils and grain of winter wheat, spring barley and oats are regularly monitored. Data on Co, Cr, Cu, Mn, Mo, Ni and Zn were analysed in this study, in order to determine spatial patterns of geographical variation in concentrations and their correlations with soil parent material and bedrock geology, and to identify areas with possible TE deficiency or excess with regard to crop and livestock production and product quality. The results showed that pseudo-total (7 M HNO_3 extraction) concentrations of Co, Cr, Cu, Ni and Zn were elevated in heavy clay soils. Areas influenced by sedimentary rock containing alum shale clearly showed elevated concentrations of various TEs, but otherwise it was difficult to find a clear correlation between soil TE concentration and bedrock geology. This may be because in the recently glaciated Swedish landscape, the ice sheet itself and the melt water from the declining ice sheet have transported soil material over large distances and/or because of low sampling density in many parts of the country. Despite weak correlations for individual elements, there was a general correlation between concentration in soil and concentration in cereal grain for many of the elements studied. One exception was Mn, for which pH was much more important than the concentration in soil. However, there was large variation in TE concentrations within short distances, indicating that soils with high and low concentrations can exist side by side. Nevertheless, for most TE, the risk of low concentrations in crop plants appeared to be greatest on coarse-textured soils on felsic rock and on soils on sedimentary rock (other than alum shale) in southern Sweden. While soils in this region generally have lower concentrations of Co, Cr, Cu, Mn, Ni and Zn than soils in most of western and central Europe, it was difficult to find documented deficiency of elements other than Cu and Mn among those that are essential to plants. Comparing the data on cereal grain presented on this study with suggested critical values indicates possible Cu and Ni deficiency. For the cationic TEs, the generally lower pH in arable soils in Sweden may be one explanation for the modest deficiency problems observed despite rather low soil concentrations. No excessive TE concentrations in crops were recorded, but on clayey soils in eastern Sweden the concentrations were higher than the national average.

1. Introduction

The trace elements (TE) chlorine (Cl), iron (Fe), copper (Cu), manganese (Mn), molybdenum (Mo), nickel (Ni) and zinc (Zn) are essential for plants, animals and humans. Moreover, boron (B) is essential for plants, while fluorine (F), iodine (I), cobalt (Co), chromium (Cr) and selenium (Se) are essential for animals and humans. Cobalt also affects N-fixation by rhizobia in legumes (Alloway, 2008). In addition, some non-essential elements, e.g. B, can be beneficial for different organism groups (Linse et al., 2011) and, with advances in science and analytical methods, other elements may be discovered to have essential roles. However, the essential TEs can be toxic at elevated concentrations and for some elements the range between insufficient and toxic levels can be quite narrow, as is the case e.g. for B (Gupta et al., 1985) and Se (Fordyce, 2007). For some TEs, the supply from soil may be sufficient for the crop itself, but the resulting concentrations in feed and food may be suboptimal from the animal and/or human health perspective (Govasmark et al., 2005). Since the focus on TE supply in crop

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production is often on crop requirements, the demands of end users of the products may be more or less neglected. However, increasing awareness of food quality and associated health aspects among consumers has resulted in an increased focus in food marketing on the nutritional value of food products (Nehir El and Simsek, 2012). Another trend is for increased awareness among consumers of the environmental impact of food production, manifested e.g. in a preference for local products with low food miles among climate change-conscious consumers (Weatherell et al., 2003; Henseleit et al., 2007).

Due to increasing specialisation and geographical separation of crop and livestock production, there is a trend towards decreasing TE concentrations in soils on arable farms, while the opposite is true for livestock farms, where soil TE concentrations may approach excessive levels (Andersson, 1992; Knutson, 2011; Watson et al., 2012). However, on organic farms with animal production that largely rely on home-produced feed, a low supply of TEs to the livestock can still be an issue in areas with soils naturally poor in TEs, unless a mineral feed supplement is provided (Govasmark et al., 2005). The ongoing decrease in TE concentrations on arable farms may aggravate problems in regions where deficiency of one or more TE already occurs. If a TE deficiency is sufficiently severe to cause identifiable symptoms in crops, it is usually corrected by foliar application of the TE in question. However, 'hidden hunger' may be a problem, i.e. yield suppression due to sub-optimal nutrient supply without development of visible symptoms (Barker and Pilbeam, 2007). These trends highlight the need to understand how mineral concentrations of food and feed vary between different geographical areas.

Available information indicates that TE deficiency in crops most commonly involves B, Cu and Mn in north-west Europe (Knudsen, 2005; Sinclair et al., 2008; Swedish Board of Agriculture, 2015), but unfortunately aggregated information on the use of mineral fertilisers is lacking. Selenium is generally the most critical TE in animal and human nutrition (Lindberg and Jacobson, 1970; Bruce, 1986), but Co and Cu deficiency were probably more frequent in the past (Lundblad, 1956), with molybdenosis (secondary Cu deficiency) having been identified regionally in moose (Frank, 1998). Analyses of grass herbage indicate a risk of Co, Cu, Se and/or Zn deficiency in animals in regions across Sweden and the other Nordic countries (e.g. Stenberg et al., 1949; Frøslie and Norheim, 1983; Alfthan et al., 2011). Farm animals are therefore normally fed a mineral supplement today, although Co and Cu deficiency can still occur in ranch-type production systems (Schwan et al., 1987). Edwards et al. (2012) summarised data on TE concentrations in Scottish advisory service soil samples and found that the proportion of samples rated as potentially deficient according to the Scottish classification system was 18, 80, 25, 50 and 38% for B, Co, Cu, Mo and Zn, respectively. Deficiency in human nutrition most commonly involves Fe, Se and Zn and evidence of a direct quantitative relationship with deficiency in soils exists for I and Se, and possibly also for Zn (Alloway, 2008; Nubé and Voortman, 2011).

In the monitoring programme for Swedish arable soils, the TE concentrations in topsoil and subsoil are mapped. Paired soil-crop samples are also available from many sites, where the crop samples are grain of winter wheat, spring barley or oats. In the present study, these data were evaluated in order to:

– Describe spatial patterns of TE concentrations in arable soils in Sweden.
– Explore the relationship between TE concentrations and other soil properties.
– Investigate the correlation between geographical variation in TE concentrations in arable soils and soil parent material and bedrock geology.
– Assess how TE concentrations in cereal grain are affected by soil properties and geochemistry.
– Identify areas with possible deficiency or excess of TE with regard to crop and livestock production and product quality.

The essential TEs for which data are available within the Swedish monitoring programme are B, Co, Cr, Cu, Mn, Mo, Ni, Se and Zn. However, Se is not dealt with in this study, since data for that element have already been presented and discussed by Shand et al. (2012). Moreover, B is not included - mainly because the method for soil analysis was not comparable to that of the other TEs and because very few grain data are available.

2. Geology of Sweden and northern Europe

The natural concentration of TEs in mineral soils largely depends on the mineralogy of the parent material and ultimately on the geochemistry of the rock from which the parent material originates. However, the composition of soils may deviate from that of the bedrock due to processes taking place during and after accumulation of the soil material, e.g. sediments with a specific grain size may be depleted or enriched in certain minerals and elements. In addition, the TEs released from minerals by weathering can also be adsorbed to and enriched in the soil organic matter or secondary minerals such as Mn- and Fe oxides/hydroxides (Jenne, 1968; Singh and Gilkes, 1992; Kabata-Pendias, 2001). The bedrock in Sweden is dominated by the Fennoscandian shield, an ancient layer dominated by rock with a felsic composition (Stephens et al., 1997) (Fig. 1). In certain areas the shield is overlain by Phanerozoic sedimentary sandstone, shale and limestone. The western part of northern Sweden is dominated by bedrock belonging to the Caledonides, a mountainous area originally formed during the Silurian period. While the Fennnoscandian bedrock is dominantly felsic, there are areas with mafic composition throughout Sweden (SGU, 2012). In central and southern Europe the crystalline basement is covered by younger sedimentary rock, except in mountainous areas (Stephens et al., 1997). In Fennoscandia, the distribution of regolith is largely determined by processes taking place during and after the last ice age (Fredén, 1994). The dominant type of regolith is glacial till, mostly deposited during the last ice age. The till constitutes bedrock material transported from bedrock situated upstream in the ice direction. After the ice retreated, a large part of the present land area was covered by water and has thereafter undergone uplift. In these areas, fine-grained sediments once deposited in water frequently occur. These sediments were partly deposited by melt water from the receding ice and partly by redistribution of sediments during the postglacial land uplift. Large areas with such sediments, which are characterised by high clay content, occur in central and south Sweden (Fig. 2). The clays deposited in water constitute a mixture of material eroded from relatively large areas and can consequently emanate from many bedrock types. Agriculture is mainly confined to more fine-textured sediments deposited in water, since most of the tills have a sandy texture. However, tills derived from Phanerozoic sedimentary rock are frequently cultivated, since they are more clayey and often calcareous. Acid sulphate soils are frequent along the east coast to the Baltic Sea basin, especially in northern Sweden, in areas with uplifted postglacial sediments rich in organic material and sulphides.

3. Materials and methods

3.1. Sampling

Soil samples (n = 5170) collected in the Swedish monitoring programme for arable soils, covering approximately 2.6 million ha (Eriksson et al., 2010), were used in this study (see Fig. 3 for distribution of sampling points). The programme started in 1995, but samples from older surveys (principally taken for Cd monitoring) in 1988, 1992 and 1994 were re-analysed for more elements, together with new samples from 1995 (60% of the samples were taken in 1995). In 1988 and 1994 the sampling sites were spread across Sweden, but only sites where the standing crop was winter wheat (*Triticum aestivum* L.; both years), oats (*Avena sativa* L.; 1988) or spring barley (*Hordeum*