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Pedon-scale silicate weathering: comparison of the PROFILE model and the depletion method at 16 forest sites in Sweden

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ABSTRACT

Weathering of soil minerals is important for the recovery from acidification and for the sustainability of forestry. However, there is still substantial uncertainty about its absolute rate. This study presents a harmonized comparison of field weathering rates estimated with the mechanistic model PROFILE and the depletion method for 16 intensively sampled soil profiles across Sweden representing different site conditions. In general, a correspondence in total weathering rates was found between the two methods except in rare cases where either method yielded deviating results. The weathering rate was higher according to the depletion method than according to PROFILE for Mg, while PROFILE produced higher weathering rates for the other base cations. The Spearman rank correlation (ρ) between the two methods indicated significant correlation for Ca ($\rho = 0.44$, $p = 0.04$) and non-significant correlation for Mg ($\rho = 0.51$, $p = 0.09$), Na ($\rho = 0.25$, $p = 0.34$), K ($\rho = 0.07$, $p = 0.80$), and the sum of the base cations ($\rho = 0.11$, $p = 0.67$). The variation in weathering rates with depth showed opposite gradients in the upper 50 cm, which reflects the conceptual differences between the methods. This study shows the potential of using multiple methods to identify a probable weathering rate, if harmonized input data are used. Furthermore, it highlights the importance of making comparisons for individual elements in order to interpret differences between methods. Regardless of the method used, weathering rates were below or at the same level as the losses caused by whole-tree harvesting, particularly in southern Sweden, indicating a risk of negative effects on soils and waters.

1. Introduction

Chemical weathering is important for the nutrient sustainability of forests, the neutralization of acidifying compounds and the quality of water transported from upland soils to surface water systems downstream. The historical deposition of acid compounds, which culminated around 1980 (Schöpp et al., 2003), caused substantial leaching of base cations from soils to waters, leading to base cation depletion and acidification of soils. A reduction of acid deposition to levels below the total of base cation weathering and base cation deposition is a prerequisite for the recovery of soils from acidification. However, recovery will also depend on the export of nutrients from the forest ecosystem through harvesting, which has increased recently owing to the increased focus on using harvest residues for bioenergy, e.g. whole-tree harvesting. While active measures, such as ash recycling, are recommended in e.g. Sweden (Swedish Forest Agency, 2008) a basis for such activities is an assessment of the mass balance of input and output of mineral nutrients in the ecosystem. Thus, there is a demand for robust estimates of the release rate of mineral nutrients by weathering for predictions of future recovery from acidification and for optimizing forest management policies.

Proposed methods for determining weathering rates include the mass balance approach using experimental data (Bain et al., 1994), the mass balance approach using catchment modeling (Cosby et al., 2001), the depletion method using an immobile element as an internal standard (Brimhall and Dietrich, 1987; Olsson and Melkerud, 1989), and the process oriented model PROFILE where weathering rates are estimated for soil pedons (Sverdrup and Warfvinge, 1993). The various methods are conceptually different and are intended for different spatial scales: from the soil pedon at site level to the entire soil deposit at the catchment level. Furthermore, the estimates consider different time perspectives: from long-term historical averages to present day weathering and steady state weathering.

Several attempts have been made to quantify weathering rate uncertainties through an ensemble approach (Futter et al., 2012; Klaminder et al., 2011; Kolka et al., 1996; Koseva et al., 2010; Starr et al., 1998; Sverdrup et al., 1998; Whitfield et al., 2006). Sverdrup et al. (1998)

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compared rates from six different approaches in two catchments in Gårdsjön, Sweden. The variation in base cation weathering rates (Ca, Mg, Na and K) was 30–39 and 47–81 meq m^{-2} yr^{-1} in the two catchments respectively, indicating relatively low uncertainties. On the other hand, Klaminder et al. (2011) demonstrated a wide span for Ca and K weathering rates, 7–150 meq m^{-2} yr^{-1} and 2–32 meq m^{-2} yr^{-1} respectively, at a site in northern Sweden where ten studies were compared, and concluded that estimated weathering rates were too uncertain to be used in assessments of sustainable harvesting. They revised their conclusions slightly in Futter et al. (2012), where they pointed out that much of the variation was related to input data and known conceptual differences between the methods, for example that different estimations were valid for different soil depths. They concluded that at least three independent estimates should be used when making management decisions. This is in line with the conclusions by Whitfield et al. (2006) who compared weathering estimates from five approaches in five catchments in Canada. The three soil profile-based approaches gave similar results, with low weathering rates ranging from 3 to 13 meq m^{-2} yr^{-1}. However, the two catchment-based methods gave one order of magnitude higher rates. Koseva et al. (2010) compared PROFILE weathering estimated with catchment mass balance calculations for 19 sites. The PROFILE weathering rates were in most cases within the range of the catchment mass balance weathering rates, but PROFILE weathering rates were generally lower, as expected when comparing soil pedon weathering rates with catchment weathering rates. Although they did not present any direct uncertainty measures based on this, they used it to demonstrate the reliability of PROFILE. A critical aspect when comparing weathering estimates is the quality of the input data, boundary conditions and assumptions made, e.g. the maximum soil depth considered and corrections for coarse fragments and organic matter. The stone and boulder content may amount to $>50\%_{vol}$ in many forest soils (Stendahl et al., 2009) and the way it is treated will have a strong influence on estimated pedon-scale weathering rates. It is crucial that comparisons of weathering estimation methods are harmonized with regard to assumptions and input data, and they should be carefully evaluated when published results from different studies are synthesized.

In this study we estimated the base cation weathering at the pedon-scale by the depletion method and PROFILE for 16 intensively sampled soil profiles representing a wide range of soil conditions in Sweden. Both methods have been frequently used to estimate weathering rates on local, regional and national scale for assessments of sustainable harvesting (Akselsson et al., 2007a,b; Olsson et al., 1993; Sverdrup and Rosén, 1998). The depletion method quantifies the loss of mobile elements since the parent material was deposited, whereas PROFILE estimates the release of elements due to the dissolution of soil minerals at steady state. Hence, the two methods consider very different time perspectives. Despite the different time perspectives of the methods the comparison was justified by the relatively young age of the profiles (10 000–16 000 years). The methods were applied in a harmonized way using input data from the same forest sites and the same pits, as well as using the same assumptions. Furthermore, the estimated weathering rates were compared with estimated base cation losses at whole-tree harvesting on a selection of the sites, in the same way as in e.g. Olsson et al. (1993) and Klaminder et al. (2011). This simplified mass balance calculation puts the difference in weathering rates between the two methods in a sustainability perspective. The objectives of this study were to: (i) compare how the two methods ranked the sites with regards to Ca, Mg, K, and Na weathering, (ii) compare how weathering intensity vary with depth in the uppermost soil profile for the two methods, (iii) investigate the causes for deviating results between the two methods, and (iv) put the results in a sustainability perspective by comparing the estimated weathering rates with base cation losses associated with whole-tree harvesting.

The comparison can shed light on how the total weathering rate and weathering intensity within the soil profile evolve over time and can be seen as a robustness test of the two methods.

2. Materials and methods

2.1. Sites and soil profile data

The 16 sites, which are part of the NORDSOIL database (Raulund-Rasmussen and Callesen, 1999), are located at latitudes 56–68 °N across Sweden on podzolised glacial till without stratigraphic layering (Fig. 1, Table 1). All sites are located above the highest Quaternary shoreline and it was assumed that no redistribution of soil material has occurred since deglaciation. The parent material is of granitic composition with varying mineralogical composition. Among the sites 12 were used previously in weathering studies by Olsson and Melkerud (1989, 1991, 2000) and Olsson et al. (1993). For each site, a profile was used that had complete soil chemical and physical data necessary to apply the two methods. Sampling was made at 10 cm depth intervals from the top of the mineral soil to the maximum mineral soil depth (42–263 cm, Table 1). Volumetric samples were taken by a core sampler for each 10 cm layer in the A, B and uppermost C horizon and bulk density was determined after drying and weighing. Grain size distribution data were determined for 10 cm layers, although it was missing for the A

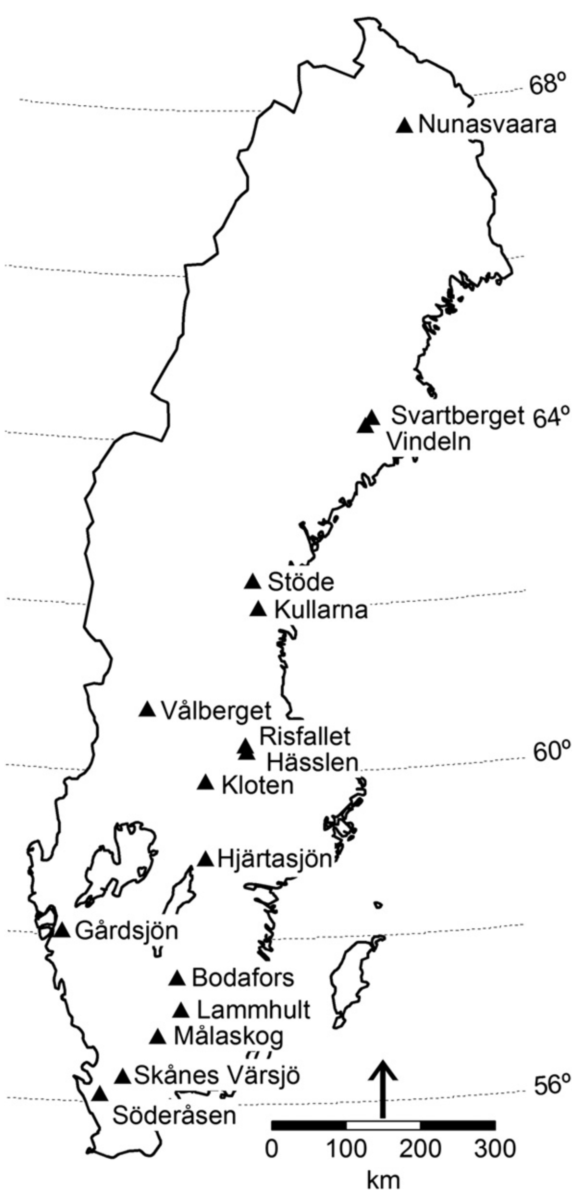

Fig. 1. Location of the 16 sampling sites.