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Dynamic modelling of weathering rates – Is there any benefit over steady-state modelling?

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Abstract. Weathering rates are of considerable importance in estimating the acidification sensitivity and recovery capacity of soil, and are thus important in the assessment of the sustainability of forestry in a time of changing climate and growing demands for forestry products. In this study, we modelled rates of weathering in mineral soil at two forested sites in southern Sweden included in the SWETHRO monitoring network using two models. The aims were to determine whether the dynamic model ForSAFE gives comparable weathering rates as the steady-state model PROFILE, and whether the ForSAFE model provided useful extra information on weathering behaviour.

The average weathering rates calculated with ForSAFE were very similar to those calculated with PROFILE for the two modelled sites. The differences between the models regarding the weathering of certain soil layers seemed to be due mainly to differences in calculated soil moisture. The weathering rates provided by ForSAFE vary seasonally with temperature and soil moisture, as well as on longer time scales, depending on environmental changes. Long-term variations due to environmental changes can be seen in the ForSAFE results, for example: the weathering of silicate minerals is suppressed under acidified conditions due to elevated aluminium concentration in the soil, whereas the weathering of apatite is accelerated by acidification. The weathering of both silicates and apatite is predicted to be enhanced by increasing temperature during the 21st century. In this part of southern Sweden, precipitation is assumed to be similar to today's level during the next forest rotation. However, in parts of Sweden with projected decreasing soil moisture, weathering might not increase despite increasing temperature.

These results show that the dynamic ForSAFE model can be used for weathering rate calculations and that it gives average results comparable to those from the PROFILE model. However, dynamic modelling provides extra information on the variation in weathering rates with time, and offers much better possibilities for scenario modelling.

1 Introduction

Most parts of Sweden are covered with glacial till, composed largely of slowly weathering minerals of granitic origin. This makes both soils and lakes sensitive to acidification. Two thirds of Sweden is covered by boreal and northern temperate forests, mostly consisting of Norway spruce and Scots pine, together with birch and a few other deciduous trees. Forests are

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one of Sweden's most important natural resources, and are used for timber (32 million $m^3 y^{-1}$ in 2013, Christiansen, 2014), pulp wood (31 million $m^3 y^{-1}$ in 2013) and biomass for energy production (6 million $m^3 y^{-1}$ in 2013). The last is especially important due to the need to replace fossil fuels with renewable sources of energy (Chu and Majumdar, 2012). Forests and their soil also determine the water quality of most lakes and streams, since the catchments of most lakes are forested and surface water is filtered through forest soils.

During the 1960s, lakes in Scandinavia became increasingly acidified (Odén, 1968). The cause of this was found to be air pollution in the form of atmospheric sulphur and nitrogen (Overrein, 1972), much of it from fossil fuel combustion. The regions most severely affected were those with high deposition of acidifying substances on shallow soils containing base cation poor minerals with low weathering rates and release of base cations (i.e. calcium, magnesium, potassium and sodium) (Galloway et al., 1983). In 1979, the Convention on Long-Range Transboundary Air Pollution (CLRTAP) was formulated by the United Nations Economic Commission for Europe (UNECE). CLRTAP was extended by the addition of several protocols for the mitigation of air pollutants, where participating countries were urged to submit data on emissions of pollutants and ecosystem sensitivity. A need thus emerged for ways of assessing ecosystem sensitivity, and different methods of estimating critical loads of acidity for sulphur and nitrogen for forest and lake ecosystems were developed (Sverdrup and Warfvinge, 1995). One of these was the PROFILE model, developed by researchers at Lund University during the 1990s (Sverdrup and Warfvinge, 1993; Sverdrup et al., 2005).

CLRTAP led to a considerable reduction in the emission of acidifying pollution, and lakes and soils in large parts of acidified areas in Europe slowly started to recover (Engardt et al., 2017; Garmo et al., 2014; Johnson et al., 2018). However, acidifying pollution is still a large and increasing problem in some parts of the world, for example, Southeast Asia (Cho et al., 2016). Forestry is also a potentially acidifying practice, as buffering base cations are removed during harvest (Farley and Werritty, 1989; Akselsson et al., 2016; Zetterberg et al., 2013). Furthermore, as the demand for forest products is growing, while both climate conditions and atmospheric deposition are changing, there is an increasing need to evaluate the sensitivity of forest soils and the weathering of base cations in greater detail, as an aid in forestry planning and regulation. The dynamic ecosystem model ForSAFE (Wallman et al., 2005; Belyazid et al., 2006), which consists of a dynamic development of the PROFILE model, together with models for tree growth and decomposition, has the potential to do this.

The aims of this study were:

- to investigate whether ForSAFE gives comparable weathering rates to those estimated with the PROFILE model, and to explain the results based on differences in the formulation of the models, and
- to investigate the weathering dynamics provided by ForSAFE by analysing the seasonal, inter-annual and decadal dynamics of ForSAFE modelled weathering rates with different driver parameter scenarios.

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2 Methods

The PROFILE and ForSAFE models were applied to two spruce forest sites in southernmost Sweden, Västra Torup and Hissmossa, included in the Swedish Throughfall Monitoring Network (SWETHRO) (Pihl Karlsson et al., 2011). Different scenarios for the input parameters were modelled with ForSAFE. ForSAFE-modelled weathering for the base scenario was averaged over the 21st century forest rotation and compared with PROFILE-modelled weathering. The weathering rates from the different scenarios from the ForSAFE model were examined in detail.

2.1 PROFILE

The PROFILE model is a steady-state mechanistic biogeochemistry model, developed at Lund University in the 1990s (Sverdrup and Warfvinge, 1993; Warfvinge and Sverdrup, 1995). It has been widely used for calculations of critical loads of acidification, weathering as an aid to improving the sustainability of forestry in Europe (including Iceland with its very different mineralogy), North America and East Asia, and has even been applied to agricultural land (Akselsson et al., 2016; Erlandsson et al., 2016; Phelan et al., 2014; Fumoto et al., 2001; Holmqvist et al., 2003; Stendahl et al., 2013). The ecosystem in PROFILE is represented by a soil profile divided into layers, each with its own chemical and physical properties, to which water, nutrients and pollutants are added via atmospheric deposition and litterfall from trees, and from which water, nutrients and pollutants are removed via uptake by trees and downward leaching. Chemical equilibrium reactions and weathering take place in the soil profile. Weathering is modelled using transition state theory, and the factors affecting it are soil temperature, soil moisture, mineralogy, soil texture, expressed as the exposed mineral surface area, soil density, and the concentrations of H^+, organic ligands and carbon dioxide, as well as the concentrations of inhibitors (reactants in the weathering reaction): base cations (Ca, Mg, K and Na), Al^{3+} and organic acids.

2.2 ForSAFE

The ForSAFE model consists of a dynamic development, SAFE, of the PROFILE model (Alveteg et al., 1995; Martinsson et al., 2005), together with the DECOMP model of the decomposition of soil organic matter (Wallman et al., 2006; Walse et al., 1998), the PnET model of tree growth (Aber and Federer, 1992) and the hydrological PULSE model (Lindström and Gardelin, 1992). It was developed to better model the process of recovery from acidification, and the effects on ecosystems of forestry and climate change, with dynamic feedbacks between soil chemistry and forest growth. Many parameters used as input data in the PROFILE model are modelled by the ForSAFE model. These include runoff, soil moisture, decomposition of litter and the uptake of nutrients by trees. The model is being continuously developed (Belyazid et al., 2011; Phelan et al., 2016; Zanchi et al., 2014; Yu et al., 2016; Rizzetto et al., 2016; Gaudio et al., 2015). In this study, a ForSAFE version with monthly time steps was used.

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2.3 Site descriptions

The characteristics of the two SWETHRO sites, at Västra Torup and Hissmossa, are presented in Table 1 and Table 2. Each site consists of a 30 m x 30 m square plot in a forest stand, where throughfall deposition is measured every month, and soil water chemistry parameters are measured with lysimeters at a depth of 50 cm three times per year; at Västra Torup since 1996, and at Hissmossa since 2010. Open field deposition is measured near the stands. Soil chemistry and properties as well as forest parameters have been measured previously (Tables 1 and 2).

Västra Torup has previously been modelled by Belyazid et al. (2006) with an earlier version of the ForSAFE model, using less detailed input data. Zanchi et al. (2014) have also modelled this site using the same version of ForSAFE as in the present study, as well as most of the input data, with the aim of describing changes in forest ecosystem services in a changing climate.

The forest at Västra Torup was clear cut in 2010, and the site at Hissmossa, 5 km to the north, was introduced into SWETHRO as a replacement site. Hissmossa has previously been modelled with ForSAFE, with the aim of explaining why this site shows continuously elevated concentrations of nitrate in soil water, while Västra Torup did not, prior to clear cutting (Olofsson et al., manuscript). Hissmossa has a courser, more sandy soil. Both sites are highly productive sites for Norway spruce.

The soil parameters used in the modelling are given in Table 3. Values of the field capacity and wilting point were calculated using the equations given by Balland et al. (2008). Mineral content was calculated from total soil chemistry data using A2M, a mathematical model that uses total chemistry of the soil samples to come up with possible mineral compositions (Posch and Kurz, 2007). The soil moisture input value for PROFILE is an estimated value based on observations at the sites: 0.2 $m^3_{soil\ water\ volume}m^{-3}_{soil\ volume}$ for all layers at both sites.

2.4 Scenarios and time series of driver parameters

ForSAFE uses time series of climate parameters, forest management and the deposition of atmospheric pollutants and base cations to the site. A set of these time series, from 1900 to 2100, is here called a scenario. The purpose of the different scenarios used in this study was to investigate how ForSAFE-modelled weathering rates responded to changes in the driving parameters. Thus, the scenarios used consist of the base scenario and scenarios in which one or more aspects of the environment are changed at a time.

The base scenario used represents the actual drivers at the sites from 1900 to today, followed by a reasonably realistic future to the year 2100 with regards to forestry management, climate and deposition. This base scenario has been used by Zanchi et al. (2014), and Olofsson et al. (manuscript). The future climate is based on a high-CO_2 emission scenario (SRESA2, modelled with ECHAM5: Nakićenović et al., 2000; Roeckner et al., 2006), with an approximately exponentially increasing temperature during the 21st century. Rainfall is almost unaffected by the climate change in this scenario for this part of Sweden. Future forest management of the sites in the base scenario is based on normal, but not intensively, managed forestry

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in Sweden today, with two thinnings and clear cutting after about 70 years, where only stem wood is removed. The deposition of pollutants and base cations is based on data from the EMEP programme (Simpson et al., 2012), and future deposition is assumed to be constant at today's levels.

Five scenarios were compared with the base scenario, where climate, deposition or forest management were changed (for the whole or part of the period 1900 - 2100), while the other input parameters were as in the base scenario. The scenarios were:

- Base scenario, described above.
- No forestry: no thinning or clear cutting between 1900 and 2100.
- Whole-tree harvest at clear cutting after 2000.
- No acidification: no increase in acidifying deposition after 1900.
- No climate change: no increase in temperature between 1900 and 2100.
- Background: no clear cutting or thinning, no increase in acidifying deposition and no climate change.

3 Results

3.1 Weathering rates from PROFILE and ForSAFE

The total weathering rates obtained with ForSAFE, averaged over a forest rotation, were similar to the weathering rates obtained with PROFILE (Figure 1). At Västra Torup, the total annual weathering rate of the base cations (Ca, Mg, K and Na) in the root zone (organic layer plus the 50 uppermost cm of the mineral soil) was 115 meq m^{-3} y^{-1} on average, according to ForSAFE (varying for different months between 51 meq m^{-3} y^{-1} and 260 meq m^{-3} y^{-1}), and 106 meq m^{-3} y^{-1} according to PROFILE. At Hissmossa, the total weathering rate of base cations in the root zone estimated with ForSAFE was 38 meq m^{-3} y^{-1} (varying from 16 meq m^{-3} y^{-1} to 86 meq m^{-3} y^{-1}) and 45 meq m^{-3} y^{-1} according to PROFILE.

The estimated weathering rate of base cations is lower at Hissmossa than that at Västra Torup according to both models. This is due to the coarser soil texture at Hissmossa, leading to a significantly lower exposed mineral surface area. Also, according to field measurements, Hissmossa has a more acid soil solution than Västra Torup, with twice the concentration of inorganic aluminium at Västra Torup. Dissolved inorganic aluminium, a product of the weathering of silicate minerals, inhibits the weathering of silicate minerals.

Differences in the weathering rates predicted by the two models are greater in soil layers where the differences between the values of soil moisture are higher in the two models. The input value for PROFILE was 0.2 $m^3_{\text{soil water volume}}$ $m^{-3}_{\text{soil volume}}$ for all layers at both these sites. The soil moisture is dynamically modelled in ForSAFE, with average values close to the defined field capacity for the respective layers (Table 3). The average soil moisture at Västra Torup, for the forest rotation 2011 - 2080, was 0.18 - 0.21 in the mineral layers and 0.29 in the thin organic upper layer. In the sandy soil at Hissmossa the average soil moisture in ForSAFE (for the forest rotation 2041 - 2100) was 0.13 - 0.18 in the mineral soil layers and 0.4 in the organic soil layer. The difference between the value of soil moisture used in PROFILE and that calculated by ForSAFE

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is thus greater at Hissmossa, and the differences in weathering rates between the two models are thus also greater at Hissmossa than at Västra Torup.

3.2 Seasonal, yearly and decadal variation in weathering rates from ForSAFE

The weathering rates obtained with ForSAFE vary seasonally with temperature and soil moisture, as well as on longer time scales, depending, for example, on forest stage, the acidification status of the soil and the climate (Figure 2). On the seasonal scale, weathering is lowest in winter and highest in the warmest period of summer, unless the soil is too dry. Weathering rates during the warmest month of the year are typically 3 to 4 times higher than during the coldest month, except for Ca and P, where weathering in the warmest month is 5 to 8 times higher than in the coldest month. On longer time scales, the yearly average weathering rates can vary by a factor of two during a forest rotation.

3.3 Effect of forestry on weathering

Thinning and clear cutting at Västra Torup increased the weathering of base cations by 9 % in the future forest rotation (2011 - 2080) in the base scenario, compared to the scenario with no clear cutting or thinning (Figure 3). Whole-tree harvesting increased the weathering by a further one percent. At Hissmossa the increase in weathering between the scenario with no clear cutting and the base scenario was 14 % for the forest rotation between 2041 and 2100, with a further increase of 2 % with whole-tree harvesting. The difference in weathering occurs during the first half of the forest rotation.

3.4 Effect of acidification on weathering

In ForSAFE, the weathering of silicate minerals is decreased by the acidified conditions in the soils during the second half of the 20th century, whereas the weathering of the only P-containing mineral, apatite, is enhanced (Figure 4). The effect of acidification on weathering is smaller than the effects of temperature and soil moisture. For the forest rotation 1941 - 2010 in Västra Torup, the weathering of base cations was 11 % lower in the base scenario than in the non-acidification scenario, while the P weathering was 11 % higher. At Hissmossa, for the forest rotation 1973 - 2040 (i.e., mostly after the most acidified period), the weathering of base cations was 6 % lower and the weathering of P 17 % higher in the base scenario than in the non-acidification scenario.

3.5 Effect of climate change on weathering

Temperature has a considerable effect on weathering rates. In the base scenario, the yearly average temperature increased from 7˚C in the 1990s to 11˚C in the 2090s. This leads to an increase in ForSAFE weathering rates of the base cations of 7 % per degree increase in temperature. The increase in temperature is greatest in winter (6˚C difference between 1900 - 1930 and 2080 - 2100) and smallest in summer (4˚C difference between 1900 - 1930 and 2080 - 2100). In Hissmossa, the weathering rates of Ca in L4 are 44 % to 49 % higher in 2080 - 2100 in the base scenario than in the no climate change scenario for all seasons (Figure 5).

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3.6 Overall effect of forestry, acidification and climate change

The overall effect of human practices on weathering rates, as in the base scenario: forestry, historical acidification and climate change, is positive. Climate changes and forestry have a positive effect on silicate weathering, while acidification has a negative effect, but not of such a magnitude that it cancels out the first two. For apatite weathering, the combined effect of climate change, forestry and decreasing acidification is an increase of the weathering in the future, especially for newly planted forest. The weathering-enhancing effect of forestry is also seen in the first part of a forest rotation for silicate weathering, whereas an aging forest has slightly decreasing weathering rates. Increasing temperatures combined with the forestry induced weathering dynamic with higher weathering in young forest, produces a step-like increase in weathering rates of silicates in the base scenario (Figure 6).

4 Discussion

The weathering calculations in PROFILE and ForSAFE are based on the same equations, but differ in that the ForSAFE model uses time series of input drivers and that several processes that are only given as input data into PROFILE are modelled dynamically with ForSAFE. We have shown that despite their differences, the two models produce comparable estimates of weathering rates.

The PROFILE model has often been used for critical load assessments and weathering estimates. This study shows that the more advanced model ForSAFE provides much more information on the variation in weathering rates due to forestry practices, climate changes and temperature change, which could increase our understanding of the dynamics of ecosystem sensitivity. General conclusions regarding acid sensitivity, critical loads and the sustainability of forestry would not change significantly, but our ability to make customised or more detailed forestry plans or to take acidification countermeasures would be improved.

Furthermore, the results of this study demonstrate the importance of soil moisture on weathering rates. In PROFILE the soil moisture is an input, often based on observation of the site and rough assumptions, whereas it is modelled in ForSAFE with soil texture, precipitation and temperature as inputs. For these two sites, soil moisture modelled by ForSAFE is similar to the rough estimates of moisture used as input for PROFILE. The average soil moisture modelled by ForSAFE is also close to the calculated field capacity. That average soil moisture is close to field capacity could partly be an effect of the monthly time step, which evens out precipitation and gives enough time for draining of excess water each time step. A daily time step, with a more realistic time distribution of precipitation, with rainfall events and dry periods in between, might shift the average soil moisture and thus the average weathering somewhat.

Another parameter that has a significant influence on weathering rates is the temperature. The climate is becoming warmer, and in some regions in Sweden, as elsewhere, it is possibly also becoming drier in the summer (Kjellström et al., 2018). Higher temperatures increase weathering, as shown in our simulations. However, drier conditions inhibit weathering, and dry

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periods in the summer, when weathering otherwise would be higher than in the rest of the year, might affect the yearly weathering considerably. Future studies, on regions that are believed to become drier in the future may help elucidate this.

Akselsson et al. (2016) calculated the increase in weathering rate due to climate change in the 21st century in Sweden, using the PROFILE model. They found that the increase in weathering rates due to temperature increase up to 2050 varied at different locations in Sweden. The median increase in base cation weathering rate was 20 % for the ECHAM projection and 33 % for the HADLEY projection, which are both equivalent to about 10 % $^{\circ}C^{-1}$. This is slightly higher than our result of a 7 % increase per degree increase in temperature. The difference is due to the fact that ForSAFE is a more complex model, with dynamic feedbacks between the uptake by trees, soil solution chemistry, soil moisture and weathering.

Forestry also affects weathering. After clear cutting, both soil moisture and soil temperature increase, leading to an increase in weathering rate. As uptake of nutrients to trees are halted and as the remaining litter starts to decompose, concentrations of base cations start to increase. Base cations in soil solution inhibit weathering of base cations (like inorganic aluminium inhibit weathering of aluminium), but the increase in base cations is not sufficient to reduce the rate of weathering, since the soil moisture is still high. With whole-tree harvesting, much of the litter is removed, and the concentrations of base cations do not increase as much as with stem only harvesting. This might be the reason for the very slight increase in weathering following whole-tree harvesting compared to stem only harvesting, found in this study. The fact that base cation concentrations do not increase as much after whole-tree harvesting as after stem only harvesting also leads to less leaching of base cations after whole-tree harvest. The slightly increased weathering rate and the decreased leaching may explain the diminishing difference in soil conditions with time between whole-tree harvesting and stem harvesting that has been seen in field experiments, despite the fact that a large quantity of base cations is removed from the ecosystem by whole-tree harvesting (Zetterberg et al., 2013).

According to ForSAFE, the weathering of silicate minerals is considerably suppressed by the atmospheric deposition of acidifying substances, whereas the weathering of apatite (P and some of the Ca) was enhanced. The reason for this is the combined effects of H^{+} as a driver of weathering and Al^{3+} as an inhibitor of silicate weathering, but not of apatite weathering.

Both the PROFILE model and the ForSAFE model are known to overestimate weathering in the lower soil layers (Stendahl et al., 2013; Zanchi, 2016). The soil horizon C consists of the less weathered parent material at the bottom of the soil profile, yet both PROFILE and ForSAFE currently calculate rather high weathering rates here, if these soil layers are included in the calculations. Most of the C-horizon is usually located below the root zone, usually defined as the uppermost 50 cm of mineral soil for spruce forests in Sweden, where more than 90 % of the spruce roots can be located (Rosengren and Stjernquist, 2004) and therefore not included in the modelling. The overestimation of weathering in the lower soil layers by these two models is likely to be, at least partly, due to the lack of calculation of the concentrations of dissolved silica in the soil water in both models. The dissolved silica, being a product of weathering of silicate minerals, acts as an inhibitor on the weathering of these minerals, i.e. all the minerals modelled in this study except apatite. The concentration of dissolved silica in the soil water is currently being included in the ForSAFE model.

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When the PROFILE and ForSAFE weathering profiles at Västra Torup and Hissmossa are compared to weathering rates at a nearby site, Skånes Värsjö, calculated with the depletion method (Stendahl et al., 2013), PROFILE and ForSAFE predict substantially higher weathering rates in the lower soil horizons, in line with the above discussion on overestimation in the lower layers. The weathering rates modelled in the upper horizons by PROFILE and ForSAFE are, on the other hand, lower than the rates obtained with the depletion method However, the depletion method does not calculate present-day weathering, but average weathering in the soil layer since deglaciation. The weathering rates have varied with time, were presumably higher in the young unweathered soil shortly after deglaciation and lower now – especially if silicate weathering is supressed by acidified conditions.

A monthly time step was used in the ForSAFE model in this study, but a new version with a daily time step is under development. A shorter time step may affect the calculations of soil moisture and might thus affect the predicted weathering rates; giving a greater variability in weathering between drier and wetter periods and potentially shifting the average. A shorter time step would potentially give more accurate results, given that soil moisture is an important parameter for weathering and soil moisture is variable on a shorter time scale than monthly.

5 Conclusions

We have shown that despite the differences between PROFILE and ForSAFE, the two models give comparable estimates of annual weathering rates.

The PROFILE model has often been used for critical load assessments and weathering estimates. This study shows that the more advanced model, ForSAFE, provides much more information on the variation in weathering rates in response to forestry and climate change.

The results from ForSAFE presented in this paper demonstrate that weathering rates vary considerably; between seasons, between years and on longer time scales. This dynamic behaviour can be of importance in nutrient leaching and nutrient availability to the trees: during seasons with high nutrient demand there might be risk of nutrient deficiency, even though there might be higher availability of nutrients than demand and nutrient losses through leaching during other seasons.

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References

Aber, J.D. and Federer, C.A.: A Generalized, Lumped-Parameter Model of Photosynthesis, Evapotranspiration and Net Primary Production in Temperate and Boreal Forest Ecosystems. OecoIogia 92: 463 – 474, 1992.

Akselsson, C., Olsson, J., Belyazid, S., Capell, R.: Can increased weathering rates due to future warming compensate for base cation losses following whole-tree harvesting in spruce forests? Biogeochemistry 128(1 - 2): 89 – 105, 2016.

Alveteg, M., Sverdrup, H. and Warfvinge, P.: Regional assessment of the temporal trends in soil acidification in southern Sweden, using the SAFE model. Water, Air, Soil Pollut. 85, 2509 – 2514, 1995.

Balland, V., Pollacco, J.A.P., Arp, P.A.: Modeling soil hydraulic properties for a wide range of soil conditions. Ecological modelling 219, 300–316, 2008.

Belyazid, S., Westling, O., Sverdrup, H.: Modelling changes in forest soil chemistry at 16 Swedish coniferous forest sites following deposition reduction. Environmental Pollution 144, 596 – 609, 2006.

Belyazid, S., Sverdrup, H., Kurz, D., Braun, S.: Exploring Ground Vegetation Change for Different Deposition Scenarios and Methods for Estimating Critical Loads for Biodiversity Using the ForSAFE-VEG Model in Switzerland and Sweden. Water, Air and Soil Pollution 216:289–317, 2011.

Christiansen, L. (red.): Swedish Statistical Yearbook of Forestry 2014. Swedish Forestry Agency. ISBN 978-91-87535-05-5, 2014.

Cho, Y., Kang, H., Jeon, E.-C.: The Effects of Reactive Nitrogen (Nr) Compounds on the Acidification in Soil and Water Environment Ecosystems and the Mitigation Strategy. KJEE 49(1): 1 - 10 (in Korean), 2016.

Chu, S., Majumdar, A.: Opportunities and challenges for a sustainable energy future. Nature. 8/16/2012, Vol. 488 Issue 7411, p 294 – 303, 2012.

Engardt, M., Simpson, D., Schwikowski, M., Granat, L.: Deposition of sulphur and nitrogen in Europe 1900–2050. Model calculations and comparison to historical observations. Tellus B: Chemical and Physical Meteorology, 69:1, 1328945, DOI: 10.1080/16000889.2017.1328945, 2017.

Erlandsson, M., Oelkers, E.H., Bishop, K., Sverdrup, H., Belyazid, S., Ledesma, J.L.J., Köhler, S.J.: Spatial and temporal variations of base cation release from chemical weathering on a hillslope scale. Chemical Geology 441: 1 – 13, 2016.

Farley, D.A., Werritty, A.: Hydrochemical budgets for the Loch Dee experimental catchments, southwest Scotland (1981 - 1985). Journal of Hydrology, 109, 351 – 368, 1989.

Fumoto, T., Shindo, J., Oura, N., Sverdrup, H.: Adapting the PROFILE model to calculate the critical loads for east Asian soils by including volcanic glass weathering and alternative aluminium solubility system. Water, Air and Soil Pollution 130: 1247–1252, 2001.

Galloway, J.N., Norton, S.A., Robbins Church, M.: Freshwater acidification from atmospheric deposition of sulfuric acid: A conceptual model. Environ. Sci. Technol., Vol. 17, No. 11, 1983.

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Garmo, Ø. A., Skjelkvåle, B.L., de Wit, H.A., Colombo, L., Curtis, C., Fölster, J., Hoffmann, A., Hruška, J., Høgåsen, T., Jeffries, D.S., Keller, W.B., Krám, P., Majer, V., Monteith, D.T., Paterson, A.M., Rogora, M., Rzychon, D., Steingruber, S., Stoddard, J.L., Vuorenmaa, J., Worsztynowicz, A.: Trends in Surface Water Chemistry in Acidified Areas in Europe and North America from 1990 to 2008. Water, Air, & Soil Pollution, March 2014, 225:1880, 2014.

Gaudio, N., Belyazid, S., Gendre, X., Mansat, A., Nicolas, M., Rizzetto, S., Sverdrup, H., Probst, A.: Combined effect of atmospheric nitrogen deposition and climate change on temperate forest soil biogeochemistry: A modeling approach. Ecological Modelling 306: 24 – 34, 2015.

Hellsten, S., Stadmark, J., Pihl Karlsson, G., Karlsson, P.-E., Akselsson, C.: Increased concentrations of nitrate in forest soil water after windthrow in southern Sweden. Forest Ecology and Management 356, 234–242, 2015.

Holmqvist, J., Øgaard, A.F., Öborn, I., Edwards, A.C., Mattsson, L., Sverdrup, H.: Application of the PROFILE model to estimate potassium release from mineral weathering in Northern European agricultural soils. European Journal of Agronomy 20 149 – 163, 2003.

Johnson, J., Graf Pannatier, E., Carnicelli, S., Cecchini, G., Clarke, N., Cools, N., Hansen, K., Meesenburg, H., Nieminen, T.M., Pihl-Karlsson, G., Titeux, H., Vanguelova, E., Verstraeten, A., Vesterdal, L.,Waldner, P., Jonard, M.: The response of soil solution chemistry in European forests to decreasing acid deposition. Global Change Biology. England, Mar. 31. ISSN: 1365 - 2486. 2018.

Kjellström, E., Nikulin, G., Strandberg, G., Bøssing Christensen, O., Jacob, D., Keuler, K., Lenderink, G., van Meijgaard E., Schär, C., Somot, S., Lund Sørland, S., Teichmann, C., Vautard, R.: European climate change at global mean temperature increases of 1.5 and 2 ◦C above pre-industrial conditions as simulated by the EURO-CORDEX regional climate models. Earth Syst. Dynam., 9, 459–478, 2018.

Lindström, G. and Gardelin, M.: Modelling groundwater response to acidification, Report from the Swedish integrated groundwater acidification project. 1992.

Martinsson, L., Alveteg, M., Kronnäs, V., Sverdrup, H., Westling, O., Warfvinge, P.: A regional perspective on present and future soil chemistry at 16 Swedish forest sites. Water, Air, and Soil Pollution 162: 89–105, 2005.

Nakićenović, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Grubler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H.M., Price, L., Riahi, K., Roehrl, A., Rogner, H.-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S.J., Swart, R., van Rooijen, S., Victor, N., Dadi, Z. (eds.): IPCC Special Report on Emissions Scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. 2000.

Odén, S.: Nederbördens och luftens försurning: dess orsaker, förlopp och verkan i olika miljöer. Ecology Committee Bulletin No.1. Swedish National Science Research Council, Stockholm ISSN: 0375-2208 (in Swedish with English summary). 1968.

Olofsson, J., Akselsson, C., Zanchi, G., Belyazid, S. Identifying soil parameters decisive for nitrogen leaching in forests through a combined empirical and modelling approach. Manuscript.

© Author(s) 2018. CC BY 4.0 License.

Overrein, L.N.: Sulphur Pollution Patterns Observed; Leaching of Calcium in Forest Soil Determined Ambio, Vol. 1, No. 4 (Sep., 1972), pp. 145 – 147, 1972.

Phelan, J., Belyazid, S., Kurz, D., Guthrie, S., Cajka, J., Sverdrup, H., Waite, R.: Estimation of soil base cation weathering rates with the PROFILE model to determine critical loads of acidity for forested ecosystems in Pennsylvania, USA: Pilot Application of a Potential National Methodology. Water Air and Soil Pollution 225(9), 2014.

Phelan, J., Belyazid, S., Jones, P., Cajka, J., Buckley, J., Clark, C.: Assessing the Effects of Climate Change and Air Pollution on Soil Properties and Plant Diversity in Northeastern U.S. hardwood forests: Model simulations from 1900 - 2100. Water, Air and Soil Pollution, 227:84, 2016.

Pihl Karlsson, G., Akselsson, C., Hellsten, S., Karlsson, P.-E.: Reduced European emissions of S and N - Effects on air concentrations, deposition and soil water chemistry in Swedish forests. Environmental Pollution 159, 3571 – 3582, 2011.

Posch, M., Kurz, D.: A2M - A program to compute all possible mineral modes from geochemical analyses. Computers & Geosciences 33, 563–572, 2007.

Rizzetto, S., Belyazid, S., Gegout, J.C., Nicolas, M., Alard, D., Corcket, E., Gaudio, N., Sverdrup, H., Probst, A.: Modelling the impact of climate change and atmospheric N deposition on French forests biodiversity. Environmental Pollution 213: 1016 – 1027, 2016.

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., Schulzweida, U.: Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. Journal of Climate 19, 3771 – 3791, 2006.

Rosengren, U. and Stjernquist, I.: Gå på djupet! Om rotdjup och rotproduktion i olika skogstyper. Alnarp : SUFOR, ISBN 91-576-6617-2. 2004.

Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., and Wind, P.: The EMEP MSC-W chemical transport model – technical description, Atmos. Chem. Phys., 12, 7825 – 7865, 2012.

Stendahl, J., Akselsson, C., Melkerud, P.A., Belyazid, S.: Pedon-scale silicate weathering: comparison of the PROFILE model and the depletion method at 16 forest sites in Sweden. Geoderma 211: 65 – 74, 2013.

Sverdrup, H. and Warfvinge, P.: Calculating field weathering rates using a mechanistic geochemical model PROFILE. Applied Geochemistry 8: 273 – 283, 1993.

Sverdrup, H. and Warfvinge, P.: Critical loads of acidity for Swedish forest ecosystems. - Ecol. Bull. (Copenhagen) 44: 75 – 89, 1995.

Sverdrup, H., Martinson, L., Alveteg, M., Moldan, F., Kronnäs, V., Munthe, J.: Modeling Recovery of Swedish Ecosystems from Acidification. Ambio, Vol. 34, No. 1, pp. 25 – 31, 2005.

Wallman, P., Svensson, M.G.E., Sverdrup, H., Belyazid, S.: ForSAFE—an integrated process-oriented forest model for long-term sustainability assessments. Forest Ecology and Management 207, 19 – 36, 2005.

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Wallman, P., Belyazid, S., Svensson, M.G.E., Sverdrup, H.: DECOMP – a semi-mechanistic model of litter decomposition. Environmental Modelling & Software 21, 33–44, 2006.

Walse, C., Berg, B., Sverdrup, H.: Review and synthesis of experimental data on organic matter decomposition with respect to the effects of temperature, moisture and acidity. Environmental Review 6, 25 – 40, 1998.

Warfvinge, P., Sverdrup, H.: Critical loads of acidity to Swedish forest soils. Methods, data and results. Reports in ecology and environmental engineering 1995:5, Lund University. 1995.

Yu L., Belyazid S., Akselsson C., van der Heijden G., Zanchi G.: Storm disturbances in a Swedish forest-A case study comparing monitoring and modelling. Ecological Modelling 320: 102 – 113, 2016.

Zanchi, G.: Modelling nutrient transport from forest ecosystems to surface waters: The model ForSAFE2D. Lund, Sweden: Lund University, Faculty of Science, Department of Physical Geography and Ecosystem Science. ISBN: 9789185793686. 2016.

Zanchi, G., Belyazid, S., Akselsson, C., Yu, L.: Modelling the effects of management intensification on multiple forest services: a Swedish case study. Ecological Modelling 284: 48 – 59, 2014.

Zetterberg, T., Olsson, B.A., Löfgren, S., von Brömssen, C., Brandtberg, P.-O.: The effect of harvest intensity on long-term calcium dynamics in soil and soil solution at three coniferous sites in Sweden. Forest Ecology and Management 302, 280–294, 2013.

SOIL Discuss., https://doi.org/10.5194/soil-2018-25
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Table 1. Characteristics of the two sites.

	Västra Torup	Hissmossa
Coordinates	56.135, 13.510	56.181, 13.515
Active years	1988 - 2010	2010 -
Year of planting	1941	1973
Year of clear cutting	2010	-
Standing stem biomass (g m^{-2}) (year in parenthesis)	18841 (2010)	10559 (2011)
Measured throughfall		
Precipitation (mm)	430 - 780	460 - 730
S deposition (kg ha^{-1} y^{-1})	4.5 - 27 *	3.6 - 6.9
N deposition (kg ha^{-1} y^{-1})	6.2 - 12	6.8 - 11
Cl deposition (kg ha^{-1} y^{-1})	21 - 50	33 - 87
Ca+Mg+Na+K deposition (kg ha^{-1} y^{-1})	31 - 57	39 - 80
Measured soil water chemistry		
pH	4.4 - 4.9	4.2 - 4.5
SO_4-S (mg l^{-1})	0.8 - 7.3	2.1 - 4.4
Cl (mg l^{-1})	3.2 - 20	17 - 51
NO_3-N (mg l^{-1})	0 - 0.1	0.5 - 3.3
NH_4-N (mg l^{-1})	0 - 0.2	0 - 0.1
Ca (mg l^{-1})	0.2 - 1.0	0.2 - 1.7
Mg (mg l^{-1})	0.2 - 1.0	0.6 - 1.9
Na (mg l^{-1})	2.8 - 8.4	12 - 23
K (mg l^{-1})	0.1 - 1.1	0.2 - 1.0
Inorganic Al (mg l^{-1})	0.2 - 3.4	0.6 - 5.3
Organic Al (mg l^{-1})	0 - 0.4	0.6 - 1.1
Al-tot (mg l^{-1})	0.4 - 3.7	1.5 - 6.2
TOC (mg l^{-1})	3.5 - 15	8.2 - 21

* Decreasing steeply with time

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Table 2. Measured soil parameters for the five soil layers (O, A, AB, B and C) at the two sites. Above: thickness of layer, bulk density, percentage organic matter, estimated percentage stones, measured size fractions, pH, exchangeable ions, cation exchange capacity, base saturation, fraction of carbon and nitrogen. Below: total chemistry of all dry soil matter.

Horizon	Thickness	Bulk density	OM	Stoniness	Clay	Silt	Sand	pH H_2O	Exchangable ions (µeq g^{-1})						CEC	BS	Tot-C	Tot-N
	(m)	(kg m^{-3})	(% of DW)	(%)	(% of mineral soil)				Al	H	Na	K	Mg	Ca	(µeq g^{-1})	(%)	(g (kg DW)$^{-1}$)	
Västra Torup																		
O	0.05	181	87	0				4.0	29	84.5	<0.1	13.0	27.9	50.1	205	43.0	543	20.9
A	0.06	959	6	20	5	27	68	4.1	31	16.5	<0.1	1.0	0.7	0.8	50	4.9	34	2.0
AB	0.20	1062	5	20	5	31	64	4.6	27	6.1	<0.1	0.6	0.4	1.2	36	6.4	25	1.7
B	0.20	1279	4	20	3	21	76	4.8	16	1.3	<0.1	0.4	0.1	0.6	18	6.5	18	1.3
C	0.04	1446	2	20	0	17	83	4.9	13	4.8	<0.1	0.4	0.1	0.5	19	5.0	8	0.6
Hissmossa																		
O	0.05	394	65	0				3.5	45	63.5	3.7	8.1	21.4	26.4	164	36.8	391	19.8
A	0.13	909	8	10	0	5	91	3.8	36	15.3	0.6	1.4	3.8	2.9	60	17.6	46	3.0
AB	0.10	1075	8	10	1	8	89	4.6	27	4.6	0.4	0.8	2.5	2.3	37	17.8	38	3.0
B	0.28	1276	3	10	0	9	88	4.5	12	0.3	0.4	0.7	2.3	2.3	17	34.2	17	2.2
C	0.04	1316	3	10	0	8	88	4.7	11	0.7	0.4	0.7	2.4	2.3	17	36.1	14	2.0

Horizon	Total chemistry of mineral and organic matter (mg (kg DW)$^{-1}$)									
	Si	Al	Ca	Fe	K	Mg	Mn	Na	P	Ti
Västra Torup										
O	33100	5060	1760	2540	2540	623	167	1440	789	337
A	349000	50000	7110	20000	26300	1540	386	15900	253	4280
AB	335000	56400	8190	28600	26600	2610	469	16300	401	4510
B	341000	58600	8920	22600	27700	2950	436	17100	540	3700
C	348000	59500	9820	24400	28700	3240	493	17800	602	4240
Hissmossa										
O	77300	13500	1970	4370	5710	580	103	3540	787	844
A	322000	51500	5040	19200	28400	822	277	14600	166	3540
AB	322000	65700	7030	29100	29600	2070	459	16900	217	3340
B	340000	66000	7490	27600	30700	2140	419	18900	231	3290
C	329000	70500	8840	28800	33600	2670	822	19000	451	3030

Table 3. Soil input data to the models, standard values (partial pressure of CO_2 and gibbsite constant) or calculated from measured soil parameters at the two sites (mineral area, field capacity, wilting point, field saturation and percentage of minerals). The modelled layers L1 - L5 correspond to soil layers O, A, AB, B and C in the two soils. Hissmossa L5 is below the modelled root zone of 50 cm.

Layer	Mineral area	pCO_2	Kgibb	FC	WP	FS	Quartz	K-feldspar	Albite	Anorthite	Muscovite	Epidote	Hornblende	Apatite	Illite	Vermiculite1	Vermiculite2	Chlorite1	Chlorite2
	(10^6 m^2 m^{-3})			(m^3 m^{-3})			SiO_2	$KAlSi_3O_8$	$NaAlSi_3O_8$	$CaAl_2Si_2O_8$	a	b	c	d	e	f	g	h	i
Västra Torup																			
L1	214161	10	6.5	0.31	0.11	0.87	50	17	19	2.2	2.4	2.0	0.4	0.2	1.3	0.6	0.2	0.4	0.2
L2	1131959	20	7.6	0.21	0.06	0.68	50	17	19	2.2	2.4	2.0	0.4	0.2	1.3	0.6	0.2	0.4	0.2
L3	1334007	20	8.6	0.24	0.06	0.64	46	16	19	2.4	4.4	2.1	0.7	0.2	2.3	1.0	0.4	0.6	0.4
L4	1167398	20	9.2	0.22	0.06	0.54	45	16	20	2.5	4.1	2.2	0.8	0.3	2.2	1.1	0.5	0.7	0.5
L5	909226	20	9.2	0.18	0.03	0.47	44	17	20	2.6	3.3	2.3	0.9	0.3	1.9	1.3	0.5	0.8	0.5
Hissmossa																			
L1	143372	10	6.5	0.42	0.17	0.80	42	18	17	1.5	1.2	1.4	0.2	0.1	2.9	0.3	0.1	0.2	0.1
L2	330775	20	7.6	0.18	0.05	0.65	42	18	17	1.5	1.2	1.4	0.2	0.1	2.9	0.3	0.1	0.2	0.1
L3	491284	20	8.6	0.20	0.06	0.58	39	17	19	2.1	2.9	1.8	0.6	0.1	5.2	0.7	0.3	0.4	0.3
L4	534872	20	9.2	0.14	0.03	0.51	41	17	21	2.5	4.8	1.7	0.5	0.1	3.5	0.7	0.3	0.4	0.3
L5	538935	20	9.2	0.15	0.03	0.50	37	18	21	2.7	5.5	2.0	0.7	0.2	3.7	0.9	0.4	0.5	0.4

a $K_{44}Na_2Mg_8Fe_{12}Ti_2Al_{96}Si_{120}O_{390}(OH)_{94}$
b $Ca_{80}Fe_{30}Al_{96}Si_{124}O_{495}(OH)_{44}$
c $K_{18}Na_{54}Ca_{166}Mg_{210}Fe_{180}Ti_{11}Al_{216}Si_{606}O_{2146}(OH)_{188}$
d $Ca_{10}(PO_4)_6(OH)_2$
e $K_{0.6}Al_2(Al_{0.6}Si_{3.4}O_{10})(OH)_2$
f $Ca_{20}Mg_{103}Fe_{182}Al_{162}Si_{293}O_{832}(OH)_{804}$
g $Ca_{10}Mg_{103}Fe_{22}Al_{68}Si_{123}O_{249}(OH)_{490}$
h $Na_2Ca_3Mg_{107}Fe_{124}TiAl_{124}Si_{138}O_{540}(OH)_{442}$
i $Mg_{103}Fe_{58}TiAl_{100}Si_{87}O_{365}(OH)_{302}$

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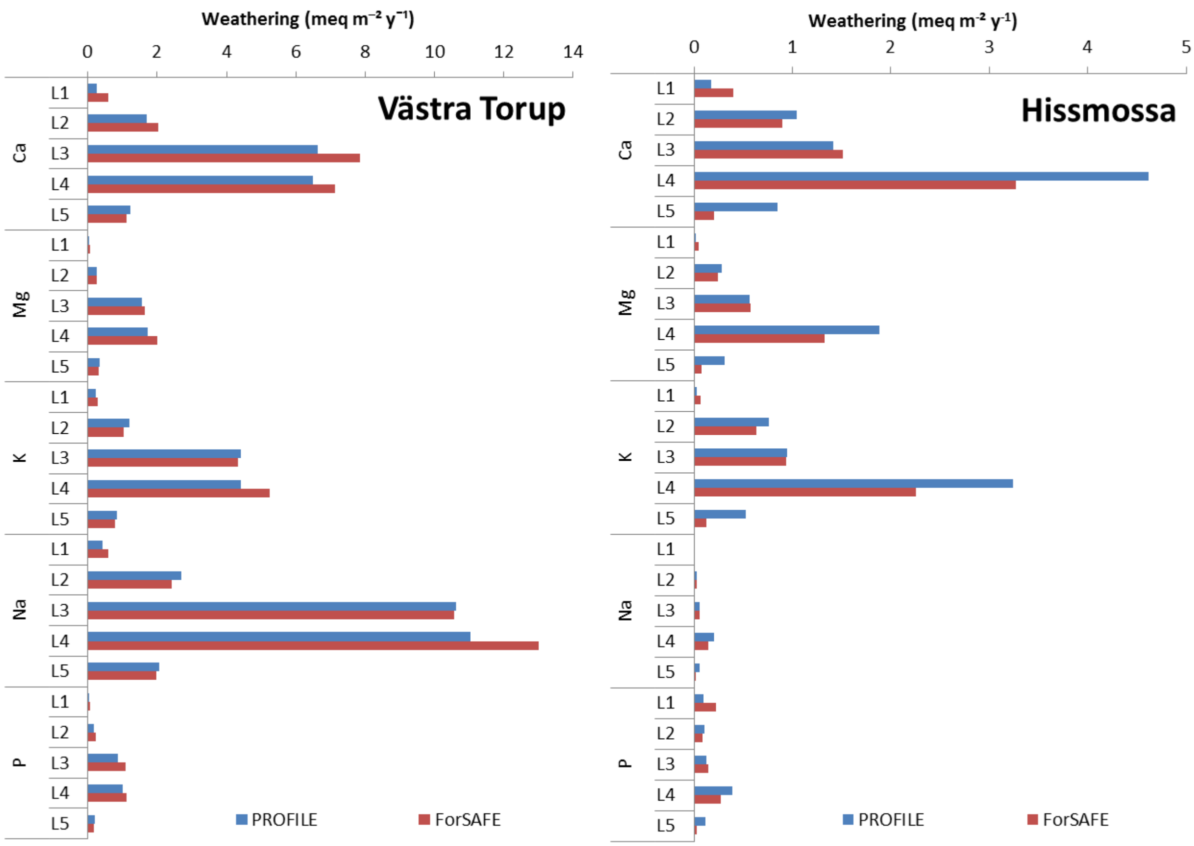

Figure 1. Weathering rates (meq m^{-2} y^{-1}) calculated with the PROFILE model and the ForSAFE model (averages over a forest rotation), for the sites at Västra Torup and Hissmossa, for soil layers L1 (top layer) to L5 (bottom layer at ~50 cm depth).

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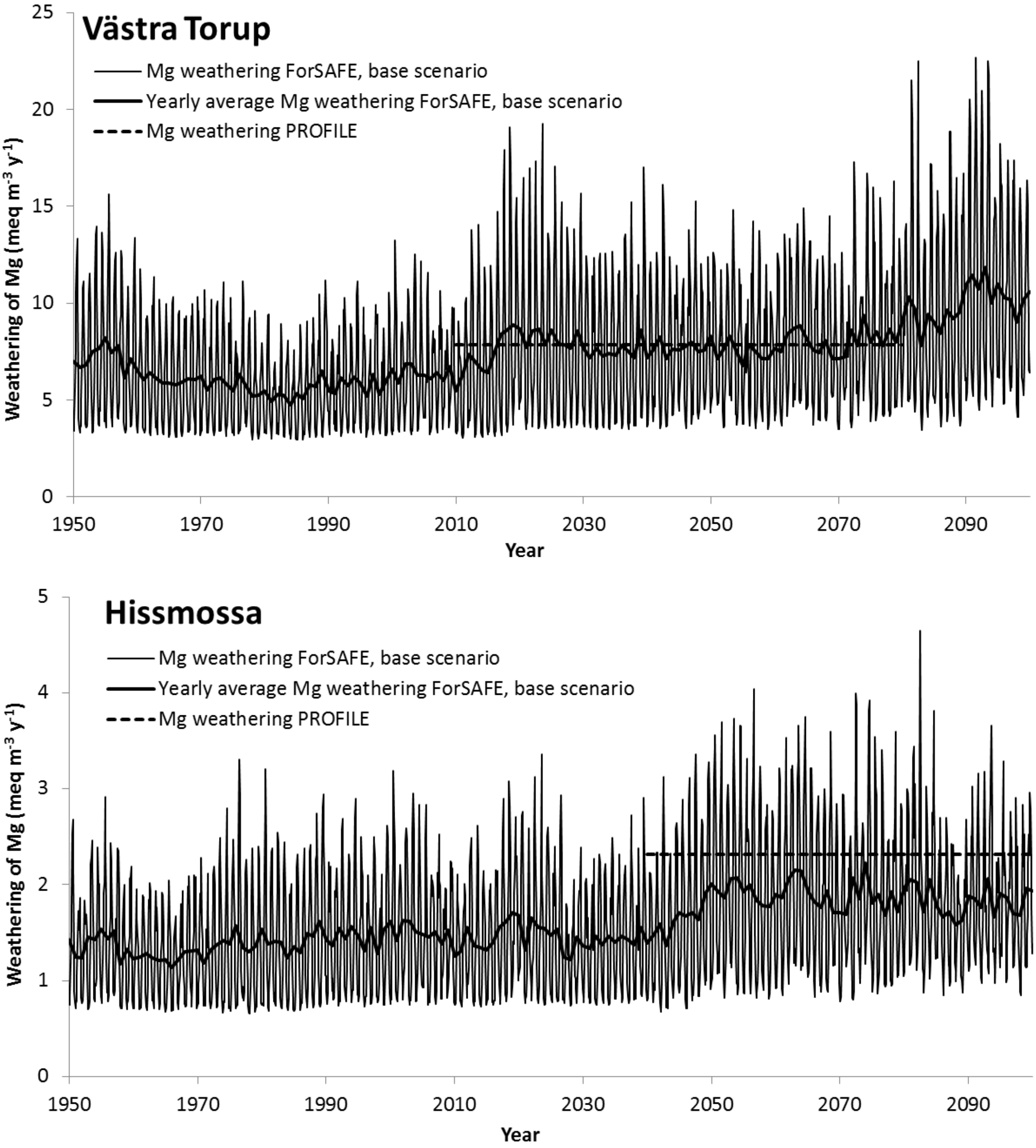

Figure 2. Modelled Mg weathering in Västra Torup (above) and Hissmossa (below) from 1950 to 2100 (note the difference in scale for the two sites). PROFILE calculates the average weathering rates for the time period represented by the input values, while monthly weathering values were calculated with ForSAFE.

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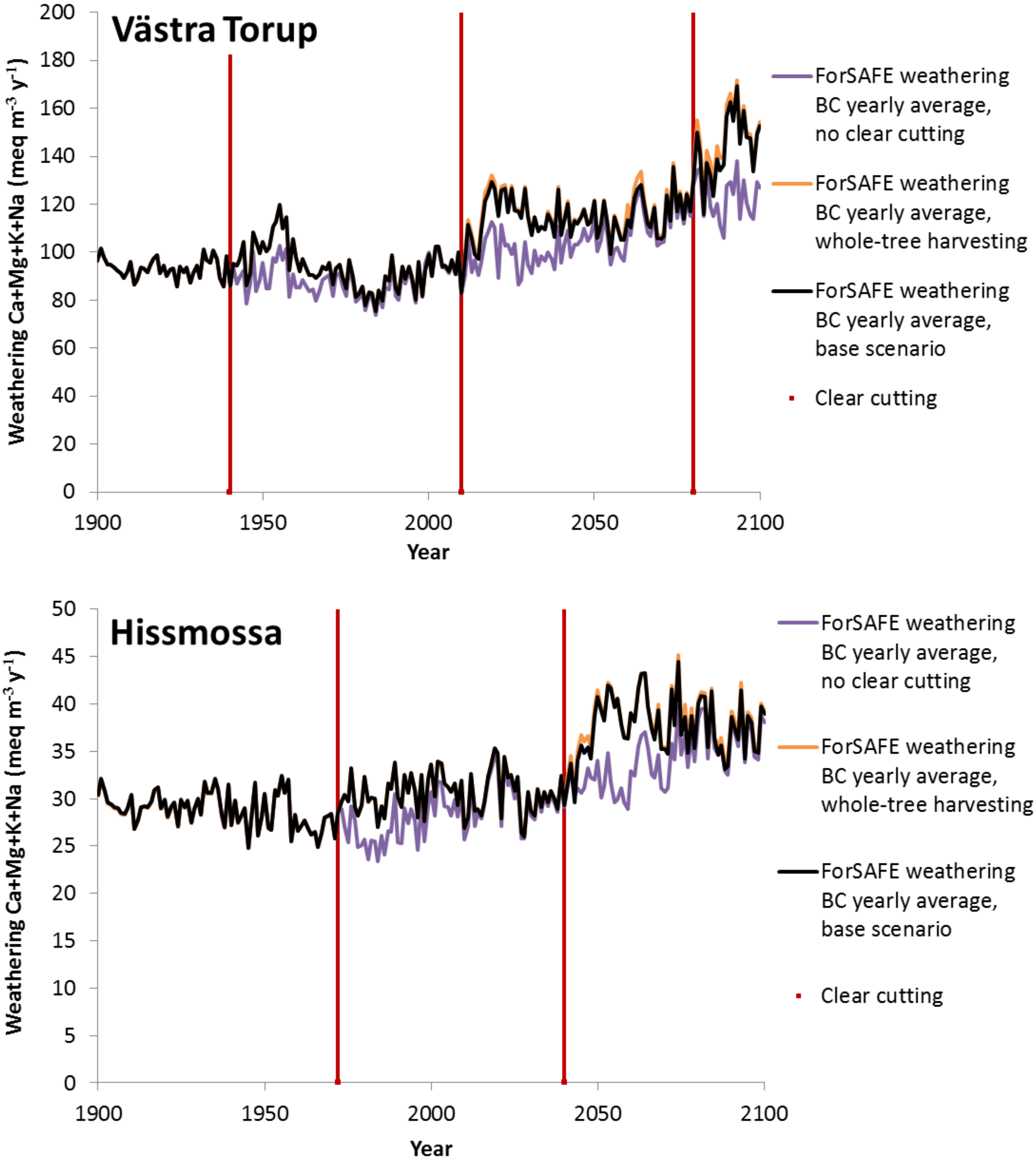

Figure 3. Yearly average weathering of base cations in the whole soil profile, for the base scenario, the whole-tree harvest scenario, and the scenario without any clear cutting or thinning.

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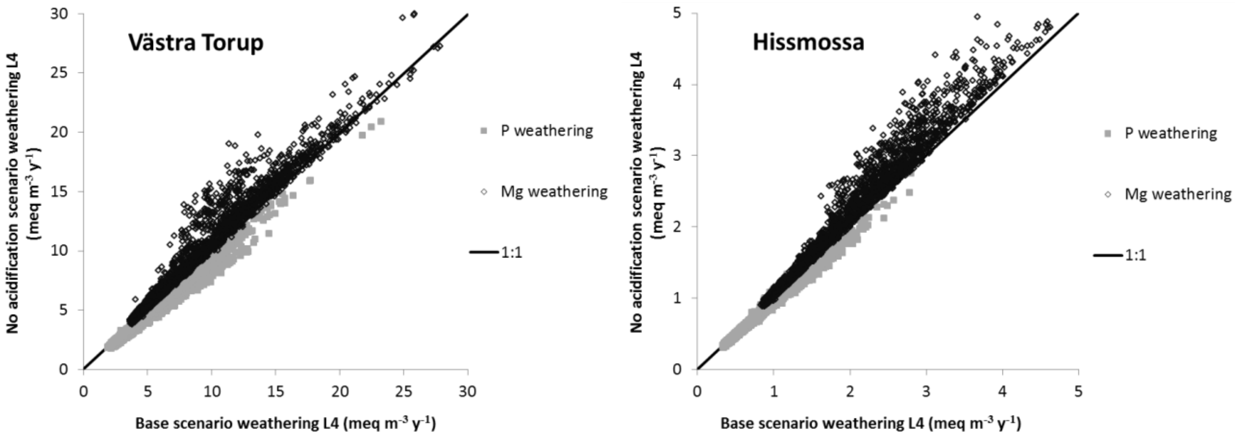

Figure 4. Comparison of weathering rates of Mg and P in soil layer L4 in the non-acidification scenario and the base scenario (meq m^{-3} y^{-1}).

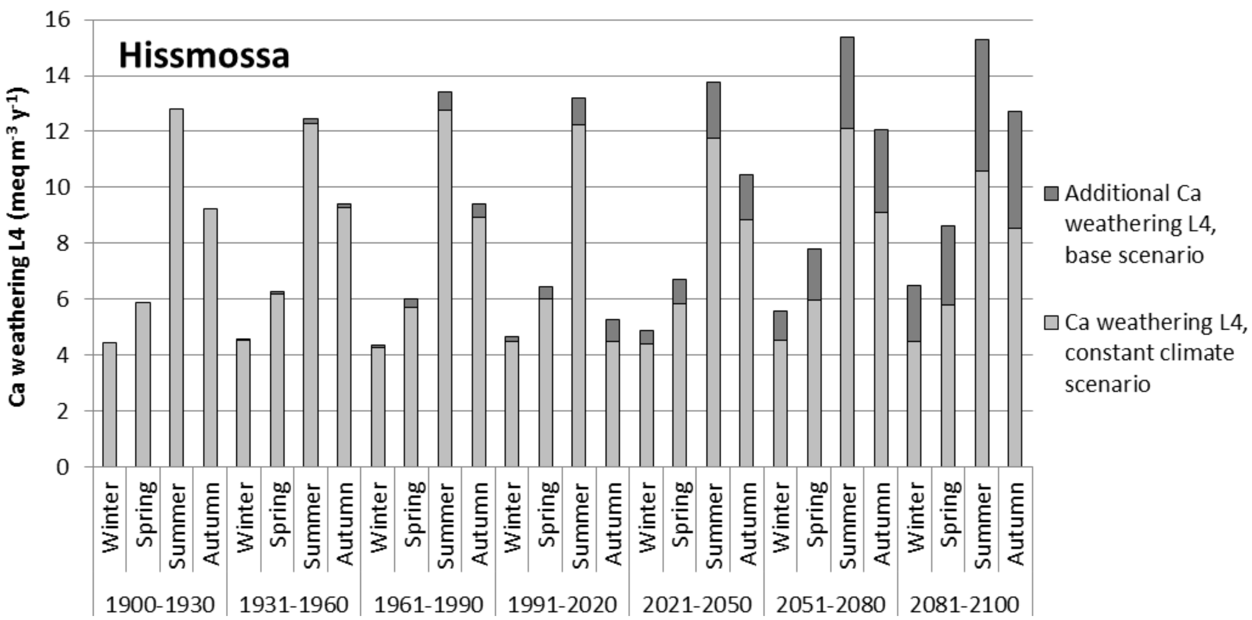

Figure 5. Effect of increased temperature on Ca weathering in L4 at Hissmossa, shown as averages for seasons over periods of 30 years. Winter = December, January and February, spring = March, April and May, summer = June, July and August and autumn = September, October and November.

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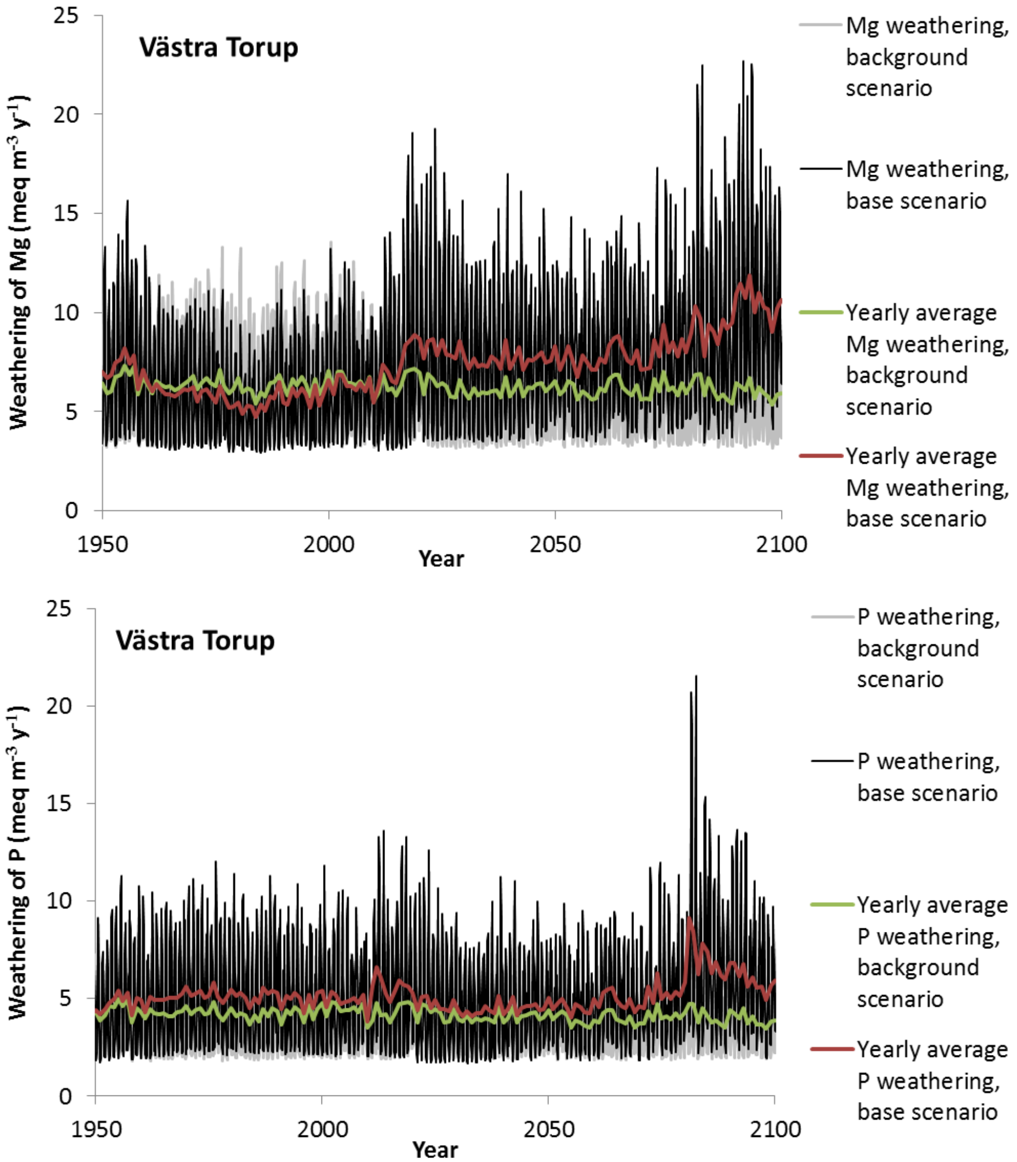

Figure 6. Weathering of Mg (from silicates) and P (from apatite) at Västra Torup, under the base scenario and the background scenario.