

Interactive comment on “Dynamic modelling of weathering rates – Is there any benefit over steady-state modelling?” by Veronika Kronnäs et al.

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We would like to thank the reviewer for your comments. They were very helpful and we think that we now have made the manuscript more clear and understandable. Below we give our answers to the questions the reviewer had. GENERAL COMMENTS Comment: “A neat and generally well written and structured paper, the subject of which (weathering) falls within the scope of SOIL and is of broad international interest. However, several related and somewhat similar applications of the models have already been published, as indicated by the strong Sweden related references.” Answer: Thank you! It is true that other outputs from ForSAFE (such as soil water chemistry) have

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been analyzed and evaluated in a number of recent papers, but the actual weathering rates themselves have not been compared with any other methods. This study shows that the weathering calculations in ForSAFE give weathering rates of the same size as the much more tested and evaluated model PROFILE. Comment: “And - as stated by the authors - as both models are based on the same weathering equations, it is hardly surprising that the results (long-term) from both models are similar and suggests little benefit is gained in using the more complex model when looking at long-term climate change and forest management impacts.” Answer: Both models are based on the same weathering equations, but in ForSAFE the equations are dynamic, while they are not in PROFILE. There are processes in ForSAFE, which are important for the weathering and which are not modelled at all in PROFILE – soil hydrology for example. Also, the timing of different processes relative to each other can be important for the weathering and affect the weathering rates; also the long term average rates. This cannot be captured in PROFILE. For example the timing of the relatively high uptake to vegetation in the beginning of the vegetation period vs the timing of the high weathering during warmer months, and high leaching during wetter months – these processes affect soil water chemistry which in its turn affect weathering in the next time step. Also, PROFILE assumes steady state and cannot take into consideration how the system got there, if the changes were slow and gradual or abrupt. Reality is never in steady state, and climate in the future is less in steady state now than in a long time, which makes a dynamic model more important than in earlier calculations of what loads of acidity the ecosystem in climatic steady state could tolerate. We tried to describe this in the discussion. See also our answer to the second reviewer’s second question. Comment: “Furthermore, the dynamic ForSAFE model, by definition is bound to provide more detailed and seasonal results and information, making the answers to the question posed by the title and to the hypotheses somewhat self-evident.” Answer: We have changed the title to “Dynamic modelling of weathering rates – the benefit over steady-state modelling”, as suggested by the second reviewer. We have also added a bit to the second objective: “...scenarios, representing important ecological issues:

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acidification, climate change and nutrient removal through land use. The potential impacts of these issues are investigated.", since large part of the paper describes the weathering response to environmental drivers (i.e. describes in detail some benefits that can be gained by dynamic modelling). By doing those changes, the title and the second objective fits better to what we actually do in the paper –describing the benefits and the dynamics in weathering. For example, we show that even though ForSAFE weathering rates vary a lot, averages over the same period represented in the PROFILE modelling, fall so close to PROFILE values, which gives credit to the ForSAFE weathering. This we didn't know before we performed the study. Comment: "I think the paper could be substantially improved if there were more focus on and calibration of the ForSAFE model with empirical data; for example, with measured soil temperature, soil moisture, forest growth (base cation uptake) and leaching data." Answer: ForSAFE is not calibrated with empirical field data except base saturation and soil carbon and nitrogen. Other data can be used for comparisons with model results. Unfortunately we don't have measurements of soil moisture or soil temperature for these sites. Since soil moisture and temperature are very important parameters, a very good next step would be to compare ForSAFE modelled soil moisture and soil temperature to measured data, but that is outside the scope of this paper, as that would have to be on other sites. We include this suggestion in the discussion as a suggested future study. There are measured forest growth and soil water concentrations for these sites, but there are already papers comparing ForSAFE modelled values with these kinds of measurements (Yu et al in the reference list and others).

SPECIFIC COMMENTS Comment: "p. 1, l. 20 (and p. 4, l. 31). Annual precipitation may remain similar but what about the seasonal distribution? How will temperature change affect snowfall and snowmelt, surely a very important feature of climate change in such latitudes, the water cycle and weathering?" Answer: In this part of Sweden, there is already very little snow. Otherwise it would probably be an important feature. The seasonal distribution of precipitation does change in this scenario, with less precipitation in summer in the second half of the century. The last decades the yearly

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precipitation increases somewhat too, about 8%. We corrected the text in the abstract with regards to seasonal distribution of precipitation and did the same in the chapter about scenarios (2.4) and in the discussion. Comment: "p. 3, l. 19 (and p. 8, l.11). Why/how are base cations, Al³⁺ and organic acids inhibitors of weathering? Do you mean that if the concentrations of weathering products in the soil solution increase, the weathering reaction slows down as equilibrium concentrations are reached? But then aren't the weathering products being continually taken away through uptake, leaching or adsorption by the soil allowing weathering to proceed?" Answer: Yes, exactly, ions in the soil solution slow the weathering down, they don't stop it altogether, since the weathering products are leached, adsorbed or taken up by trees. Nonetheless, in acidified conditions the concentration of Al in the soil increases substantially compared to non-acidified conditions, and slows weathering of silicates down. Also, in the C-horizon, where water flows are slower and uptake to trees are lower, concentrations of weathering products increase and should slow weathering down to a minimum – that is probably why the C-horizon consists of less weathered parent material even though there is so much weatherable material. We corrected the text; the inhibitors base cations and aluminium are products of the weathering. Comment: "p. 4, l.16. There is little description of the soil type at the two sites. From the horizon abbreviations listed in Table 2, it would appear the soils are not Podzols?" Answer: The two soils are assessed in the SWETHRO database as transition types (developing towards podzols). O is the thin uppermost layer consisting of mostly organic material, A is greyish, but not deemed a true E zone, AB is a light brown, B is a reddish brown and C is the parent material, which is till. We added information about the soil type in chapter 2.3. Comment: "p. 5, l.16. Furthermore, thickness of the mineral soil horizons at Hissmossa is 55 cm (and not 50 cm; Table 2) and how/why is the organic layer included where surely it is a question of organic matter decomposition rather than mineral weathering? It is not stated how stoniness was derived and if the hydraulic parameter values (Table 3) have been corrected for stone content. Given the concluded importance of soil moisture, the J_Ax value used in PROFILE and same value for all layers (0.2) seems rather crude.

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The iñAeld capacity values in Table 3 also seem somewhat low – is this because of stone content correction? How have any time related changes in organic layer thickness (and therefore soil moisture content) been taken into account?” Answer: The modelled soil horizon at Hissmossa is 55 cm+organic layer, but the root zone is still 50 cm+organic layer. We included the C-horizon in the modelling, even though it lies below the root zone, but we did not include it in calculations representing the weathering in the root zone. We clarified this in the text to figure 1. The organic layers do contain some mineral soil and the modelled weathering in those layers is from the minerals, not from the organic matter. They are included in the modelling since they are important for the modelled ecosystem and thus for the soil water chemistry for the rest of the layers – for example much of the nutrient uptake takes place here, especially of nitrogen. Stoniness is estimated at the soil sampling. We added this in chapter 2.3. PROFILE, being a steady state model, can only handle fixed (in time) values. The same soil moisture value for all horizons may be crude, but without measurements over long time periods in all soil layers, there is not much of an alternative –and in Västra Torup’s case it is not wrong (see new figure 2). The field capacity values are calculated according to Balland (2008). Dynamic changes in layer thicknesses are not modelled by any of the models. Comment: “P. 4, l. 31: by “rainfall” you mean annual precipitation?” Answer: Yes, thanks. I have changed the text. Comment: “p. 5, l. 6-11. The description of the scenarios is unclear, at least to me. For example, does the base scenario mean there are two thinnings and a clear cut every 70 years (and starting from the year of planting – Table 1), deposition loads constant from “todays” (which year?) levels into the future plus climate change temperature (but no change in precipitation)? What is the whole tree harvesting treatment: stems + branches or stems + branches + stumps? Is it carried out every 70 years during the 1900-2100 period? It would be useful to number or letter the scenarios and refer to them in the text and, tables and iñAgures.” Answer: We have given the scenarios three letter abbreviations and use those in the text and figures. We have clarified the scenario descriptions, both the description of the base scenario (BSC) and how the others differ from the BSC scenario. Yes, the

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BSC has forestry with a clear cut approximately every 70 years (Västra Torup: 1940, 2010, 2080. Hissmossa: 1972, 2040, 2100) and thinnings at about 25 and 45 years of plant age (more “on time” with the thinnings in the future scenario than in actual history of the sites). Deposition of SOx peaks in 1970 and decrease sharply afterwards and is in the future scenarios kept constant at 13% of the peak deposition after 2020. Deposition of N peaks in 1985 and decrease more slowly. It is kept constant at 50% of the peak deposition after 2020. Climate: Both temperature and precipitation changes in the BSC scenario, according to the SRESA2 scenario) – the temperature increase almost exponentially from 1900-1910 to 2090-2100 with about 5.9°C in winter and 3.7° in summer. Yearly precipitation changes less and without trend, but summer precipitation is lower in 2050-2100 than before and winter and spring precipitation is higher. Whole tree harvest is in this study stems and 60% of branches, treetops and needles, but stumps are not removed. Whole tree harvest in the WTH scenario is carried out in thinning and clear cutting from the clear cutting in 2010 (Västra Torup) or 2040 (Hissmossa) and forward. Comment: “Which scenario is used for Figure 1?” Answer: Base scenario (BSC). We gave the scenarios abbreviations and clarified in the running text and in the figure texts which scenario was used. Comment: “Doesn’t the 70 year rotation period cover a different set of years between the two sites (2011-2080 vs. 2041-2100), when the climate change has changed the climate. Doesn’t this explain the differences in weathering between the two sites rather than differences in soil texture (p. 5, l. 21), which anyway would also affect the soil hydraulic properties besides surface area?” Answer: Yes, the rotation periods are different for the two sites. As can be seen in figure 2 (in the previous version of the manuscript, now figure 3, since we added a new figure number 2, showing soil moisture), this does not explain the difference in weathering rates between the sites, as the increase in weathering because of climate change in 20 to 30 years is a lot smaller than the difference in weathering rates between the sites. Also, if the increase in temperature in the time between the clear cuts of the two sites would have been the reason for the difference in weathering between the sites, then Hissmossa would have had the higher weathering rates and

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not the lower. Comment: "Why is only Mg weathering presented in Figure 2 and in Figure 4 to represent silicate mineral weathering? Wouldn't the sum of base cations be a more appropriate measure of overall silicate weathering?" Answer: One of the base cations, Ca, comes in about equal amounts from weathering of apatite and of silicates. The weathering of Ca is also relatively large. Thus, to examine the release of base cations from only silicate weathering in our models, we chose to show one of the base cations that are not released from apatite, Mg. We clarify this somewhat in the figure caption for figure 4 (now figure 5). Figure 2 (now figure 3) could as well have shown the sum of base cations, since the focus of the figure isn't difference between silicates and apatite, so we changed figure 2 (now figure 3) to sum of base cations instead. Comment: "As weathering largely takes place by acid (proton) attack, why is silicate weathering decreased by acidified conditions (p. 6, l. 17) and why would apatite weathering be increased?" Answer: Apatite weathering is increased by more acid conditions because there are more protons in solution, and not at the same time high concentrations of something that inhibits weathering. Silicate weathering was not increased by the more acid conditions on those two sites, according to ForSAFE. Those two sites had high concentration of Al in soil solution during the acidified conditions, as Al is more soluble in acid conditions, and Al inhibits weathering of silicates in ForSAFE, but not of apatite since there is no Al in apatite. We added a little text in the discussion to clarify this. Comment: "Doesn't the base scenario include harvesting effects besides climate change effects (p. 6, l. 29)? See also p. 8, l. 21-24." Answer: Yes, but so does the NCC scenario. Forestry and acidification are equal in the NCC and the BSC scenario. Only climate differs. We clarified the scenario descriptions a bit. Comment: "p. 7, l. 19: by "more detailed forestry plans" do you mean timing of thinning and timing and intensity of harvesting?" Answer: yes. And with additional soil data, at least on soil texture, differences within a stand or a couple of nearby stands could also be modelled, so that more sensitive areas within the stand could get a less intensive forestry. Comment: "p. 8, l. 13- Isn't a matter of litter decomposition and not weathering? And I think you need to give a reference that supports the statement about harvesting in-

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tensity effects of soil solution base cation concentrations. Concentrations and leaching loads may increase with whole-tree harvesting as a result of increased drainage (percolation) and disturbance of the site." Answer: We didn't explain this clearly enough, thank you for the question. With standard clear cutting where branches and treetops and litter are left on the site, litter decomposing after harvest lead to increases in base cation concentration, especially of K. This can be seen in data from SWETHRO sites (krondroppsnatet.ivl.se) and in Piirainen et al. (2004). After whole tree harvesting, where branches and treetops, with most of the needles, are removed, there will be less decomposable litter on the site, which should mean that concentrations in soil water do not increase as much after WTH as after stem only harvest (as discussed in Ågren et al., 2010). The concentrations in the soil water in its turn affect the weathering rates. Comment: "p. 8, l. 25-. The contribution of your C-horizon is small (Table 2). And if the material is less weathered, then there would be more weatherable minerals and therefore potential or weathering? Is the explanation for taking silica concentrations into account the same as mentioned above, i.e. equilibrium concentrations reached?" Answer: The contribution of the C-horizon is small because we only model a small portion of it. But the rates of weathering per volume in the C-horizon are equivalent to the rates in the horizons above. The material in the C-horizon is less weathered since the weathering in the C-horizon is smaller than in the B-horizon, even though there is more weatherable material. The environment in the C-horizon inhibits weathering (or the C horizon would already be weathered and not a C horizon), probably because of slow water movements, so that some reactants are depleted and some products of the weathering build up and inhibit further weathering. And Si is one of the products that are building up, one that we do not model with ForSAFE and PROFILE yet. We added a little text in the discussion to clarify this. Comment: "p. 9, l. 6. A paper by Starr & Lindroos (Geoderma (2006) 133: 269–280) shows this." Answer: Thank you! We included it in the text. Comment: "Conclusions: I appreciate the recognition of the importance of soil moisture to weathering (and decomposition) and for the reasons stated (time step). However, wouldn't a model with a daily time step be more suited to forest

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stand nutrient/biogeochemical cycling studies rather than modelling long-term climate change effects. ” Answer: A daily time step is more suited for modelling of hydrology, which in its turn affects all other processes both on short term and possibly also their long term averages. The effects on long term averages might be large, if average soil moisture is affected significantly or if the dynamic shows that the timing of different processes produce for example lack of soil moisture at high temperatures or lack of nutrients when vegetation needs them. In any case, studying if the daily time step that has been implemented in another version of ForSAFE has an impact seems like a reasonable next step. We clarified the text on model development (4.3) somewhat. Comment: “Units: Wouldn’t it be more correct to present weathering in units of moles charge rather than equivalents? And why sometimes meq m⁻² yr⁻¹ and sometimes meq m⁻³ y⁻¹ (Fig. 2, 3, 4, 5). Is it somehow because the latter refer to a specific layer (of differing thicknesses) rather than to the topsoil organic layer + 50 cm layer or simply a typo? ” Answer: To our understanding, moles of charge and equivalents are equivalent in this case. We used weathering per area in figure 1 to make it easy to sum up the weathering from the different layers, even though they have different thicknesses and to show how much each layer contributes to the total weathering. But since the layers have different thicknesses, the total weathering per forest floor area for a layer is not as easily comparable to other soils in other studies as weathering per soil volume, and therefore we converted the weathering rates into meq m⁻³ y⁻¹ for the text and the rest of the figures. We clarified the use of different unit in figure 1 in the caption to figure 1. Comment: “Table 1. Coordinates are decimal degree latitude (N) and longitude (E). Answer: Yes, thank you. We added unit in the table. Comment: “Figure 1. Title: Using which scenario and for which period of time? Answer: BSC scenario and the “future forest rotation”: 2011-2080 in Västra Torup and 2041-2100 in Hissmossa. We added this in the figure caption. Comment: “Figures 2 & 6. Is it necessary to include the ForSAFE monthly values? See Fig.3. Answer: Since one of the objectives of the paper is to describe the dynamics of the weathering in ForSAFE it seems necessary to show the dynamics of the weathering and not only averages over time periods of

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different length at least in figure 2 (now figure 3) where ForSAFE weathering (=the monthly weathering values) is compared to PROFILE weathering. We removed the monthly values from figure 6 (now figure 7). Comment: “Fig. 3. Use a circle around the years of clear cutting on the whole tree harvesting scenario and base scenario lines rather than the vertical line that intersects all scenarios. Are the years 1941, 2010 and 2080 for Västra Torup and 1973 and 2043 for Hissmossa? Answer: A circle would still seem to indicate all scenarios, since the average weathering is the same before the clear cut for all three scenarios. We think that the vertical lines are more clearly visible and divides the time into the different rotation periods, but we have clarified the figure caption somewhat. The years of clear cut are 1940, 2010 and 2080 in Västra Torup and 1972, 2040 and 2101 in Hissmossa. Comment: “Fig. 4. Is each dot is a year of the 70 year rotation period? Why only layer 4 (B-horizon)? Answer: Each dot represents a month. L4 is the largest layer (in Hissmossa) and one of the two largest layers (in Västra Torup) of the root zone and it is at the depth of the soil water chemistry measurements, so it is the best layer for comparing modelled and measured soil water chemistry and thus the layer we look most at. Figure 4 (now figure 5) is intended to show the modelled different reaction to acidification between silicate weathering and apatite weathering and for this any layer could be used, but we chose to use L4. Comment: “Fig. 5. The base scenario includes the climate change temperature scenario and does the “constant climate change scenario” refer to the last one in the list on p. 5? ” Answer: We have now given the scenarios names and refer to them in the text and in the figures with these. The base scenario (BSC) include climate change, yes, and the other scenario used in figure 5 (now figure 6), the NCC, is the same as BSC with regards to forestry and acidifying deposition – but it has no climate change. The last scenario of the list (the BGR) has no forestry, no acidification and no climate change and is used in figure 6 (now figure 7).