Reply to comments from Katrin Fleischer

Veronika Kronnäs et al.

Author comment on manuscript "Effect of droughts on future weathering rates in Sweden" (Biogeosciences discussion bg-2022-78)

Introduction

We thank dr. Katrin Fleischer for her thorough reading, critical look and many thoughtful comments that will improve the quality and readability our manuscript. Especially the comments on how to structure the text, with many good ideas on how to present the scenarios and the results, which will improve the study. We are happy to apply revisions to improve our manuscript as formulated in the answers to the referee comments in this document. We will repeat the comments from dr. Katrin Fleischer in red, with our answers in black.

General remarks

The paper by Kronnäs et al. describes a timely issue of climate interactions with weathering rates under future climate change. Weathering is an important process for nutrient supply and limits plant growth in some ecosystems, and I read the manuscript with great interest. The authors present a model application for Swedish sites along an environmental gradient, which is a suitable study setup to better understand and model weathering dynamically. Current and future rates of weathering are reported for two future scenarios, considering seasonal variation of weathering rates. I appreciate the conclusion that we need dynamic modelling of weathering in space and time, however, I am not fully convinced that the presented study, in its current format, is advancing our understanding of the mechanistic drivers of weathering and how they are affected by climate change. I recommend the authors adopt a more ecosystem-level approach in the analysis and include interactions with plants, and fully explain, analyze, and discuss the underlying mechanisms that lead to the model outcome in terms of weathering.

The paper presents results on seasonal ambient weathering, and effects of a hypothetical drought in future scenarios. The presentation of results lacks important details and needs to be improved by providing clearer visualization items, and correct and clear presentation of quantitative results. E.g. statistics on mean weathering rates, in absolute terms, are not reported in the results section and are not adequately compared to other estimates. The underlying modelled processes in regards to weathering need to be fully explained in the paper, for the reader to interpret the model outcome and better follow the discussion. Also, the underlying soil texture and mineralogy effects are not well explained. Other small details such as units and explanations in captions and headers need to be carefully checked.

While the focus of the paper is clear, the scope of the results seems too narrow, given the presented scientific problem and the model tool ForSAFE. The paper does not present results in its main section on how weathering interacts with nutrient availability from other nutrient-mineralizing processes, nor how seasonal changes in weathering interact with the timing of plants' requirements for soil nutrients. All of which can be modelled by ForSAFE, and also the introduction leads the reader to believe that these interactions are subject of the study. The scope of the study should be clearly communicated in the introduction and abstract. The paper would improve its scientific depth if these aspects would be addressed within the analysis of the paper. In its current format, results on modelled plant-weathering interactions are reported in the discussion, without visual items or quantifications. Most parts of the discussion are actual material for the results section, and there is little scientific discussion of the model results.

I recommend the authors consider extending the scope of the paper and review the current structure and discussion of the manuscript.

Processes such as nutrient uptake in trees, weathering and decomposition, are interlinked in ForSAFE, which means that interactions with plants are included in the study. We realize that this is not clear from the ForSAFE descriptions in the Methods, and we will therefore add a section where we explain this. We will also add a section about the implications of the interactions on weathering rates in the Discussion.

We realize that the introduction can give the impression that the study will include results on how seasonal changes in weathering relate to the timing of plant nutrient uptake. However, the focus of this study is on weathering dynamics in a future climate, which is something that has not been extensively studied before. This paper is the first one that we are aware of, where weathering dynamics are studied with a daily time step, enabling improved hydrology modelling. We find it important to thoroughly analyse the effects of climate change on weathering rates, before we take the next step, where we plan to compare the weathering dynamics with the plant nutrition requirements in a future climate. We will change the introduction so that the scope of the paper becomes clearer.

In an earlier paper (Kronnäs et al., 2019), we studied the indirect effect of different forestry scenarios on weathering rates, but with a more severe climate scenario (which led to lowered future forest growth), a monthly time step and only two sites in southernmost Sweden. There was a clear effect on weathering of clear cuts, but with very little difference between stem only removal or whole tree harvest. The direct effects of climate change were larger than the indirect effects through feedbacks to plant uptake of base cations. This could be different in different sites and different scenarios, depending on base cation concentrations in the soil water, forest growth rate and other factors.

There are absolute average weathering numbers for each site reported in Table 4, but we could add a table with the averages from the same three time periods that are shown in Figure 3 as well.

We agree on the need to improve the structure of the paper, including the discussion, and we will do this, using the detailed suggestions you and anonymous referee 1 has given us.

Abstract

(page 1) L12 Unclear what a climate change base scenario is, and what a drought scenario is.

We will explain this better.

(page 1) L9 Why is the 2018 drought event singled out here? How is it relevant for the study?

It was a recent and unusual summer with very low precipitation for several months in a row, which had a large effect on forests, agriculture, and other sectors of society in Sweden and elsewhere in northern Europe and it is the basis for the drought scenario in this study.

(page 1) L17 Present weathering as absolute rates for better context. Also, in the sentences presenting results afterward.

We will do that, if it does not make the abstract too long.

(page 1) L25 Coarse soils respond quicker in which regard?

In the regard of how fast the weathering decrease during drought occurs, as well as how fast the soil rewets and resume normal weathering rates after the drought.

Introduction

(page 2) Methodology of weathering process in the model not well explained. General background knowledge on process-based weathering is not well explained. Too many unreferenced arguments and an unbalanced argument structure.

Agreed, we have not explained the weathering process in the model well enough and we will change this in the description of the model. We will provide references and look at the structure.

(page 2) L8-14 this paragraph is not well balanced in explaining the different drivers for nutrient scarcity in terrestrial ecosystems.

We will look at this text and try to improve it.

(page 2) L15-23 this paragraph is not well structured to follow a common argument. It is unclear what is currently known and where are the unknowns in e.g. how climate change will interact with weathering, and many statements lack an appropriate reference.

Thank you for pointing this out. We will structure the text, find references and be more clear on what is known and what is not.

(page 2) L28 if it is not possible to measure weathering in situ, how is the knowledge derived until now? Explain process knowledge on weathering.

We will explain more.

The processes are known from lab experiments, but it is impossible to let soil sit undisturbed in the lab for as long as it does in nature and therefor the weathering rates are much higher in lab than they are in nature under comparable climate, mineralogy and texture conditions. To assess weathering rates in nature, we need modelling or other indirect methods (like measurements of inflows and outflows to a catchment and calculation of weathering as the unknown to make the other flows add up, or methods that estimate how much of an element that is “missing” from the soil compared to the unweathered C-horizon, which gives average weathering rate since the soil was deposited at the end of the last glacial).

(page 2) L29 consider rewording here to express actual value of modelling, project into the future, derive hypotheses, etc.

We will develop this sentence to explain this.

Methods

(page 3) L3 why use 5 consecutive years, please justify

It was done to see the effect of a more severe drought, as these might get more common in a future warmer climate.

(page 3) Consider removing the small section 1.1 and move aims to introduction.

We will remove the subtitle and integrate the aims better in the rest of the introduction.

(page 3) Consider removing small text after methods and move it to 2.1 and 2.2

We will move it to the end of the introduction, to introduce the methods we use in this study.

(page 3) Section 2.1 Please explain in detail how ForSAFE models the process of weathering, and explain briefly how ForSAFE models other relevant processes that influence the rate of weathering, such as nutrient interactions and plant growth, in order to understand and interpret the modelling outcome.

Yes, we will explain the ForSAFE model better, especially the parts most relevant to the weathering.

(page 3) L18 please specify which research objectives (if you mention that) and which aspects are being improved. This helps understanding the strength and limitations of the model.

We will specify this.

One thing that has been developed is a shorter time step, which makes possible more detailed hydrology modelling, which is useful in this project. One version that can model a set of soil profiles in a row has been developed, which can be used to model the change in soil water chemistry from a hill to a stream.

(page 4) L1 How were the sites chosen, on which data requirement, environmental representation?

They were chosen among the currently or recently active SWETHRO spruce sites that has the required data, and one in each climate region. They are representative of managed spruce forests in their respective region.

(page 4) L2 what does “relatively low weathering rates” mean? Compared to other soils the same age? Can this be more specific?

We will explain better. Soils in Scandinavia are relatively young as they were formed at or after the last deglaciation, 16000-9000 years ago (depending on geographical region). Young soils generally have higher weathering rates than million years old soils. But most of Scandinavia have soils formed from granitic or gneissic bedrock (with exceptions at the large islands Öland and Gotland, parts of southernmost Sweden and part of the mountain region, where Ammarnäs is situated), and compared to areas with sedimentary bedrock, these soils have low weathering for their relatively young age.

(page 6) Why is the A1B scenario chosen? And which climate data is used for the 1990-2019 values? Units of climate variables missing, e.g. mean temperature, annual precipitation sum

The A1B scenario is chosen because it is a intermediate climate change scenario, approximately close to what society today is on track for if no further action is taken, so not unrealistically high, but also not in line with the Paris agreement. Data for 1990-2019 is from the CLEO program. We will be clearer about this.

(page 7) Please explain why the base cation content was not matched, or speculate. It is unclear what the implications of this fix are.

The base cation amount in the soil water, which has been studied by sampling three times per year since 1991, is too high compared to what only deposition and weathering from the measured mineralogy in the soil pit would be able to provide. The exchangeable calcium in the soil from the soil pit was also higher than what these two sources would be able to provide. The reason for this have to be that there are other sources of calcium for soil water and exchangeable calcium on soil particles. These other sources cannot be higher deposition, as too much deposition would be required, but since there are calcite rich soils in the area, inflow of water from calcite rich soils at the site or next to it would be a likely explanation. Therefore, we modelled this.

(page 7) L16 Do you investigate the effect of forest management on weathering rates? Or the effect of vegetation on the modelled weathering rates?

In Kronnäs et al. (2019) we investigated this in detail, but not in this study. These effects are included in this paper as well, since these processes are included in the model, but we do not quantify the effects of different forestry by modelling separate scenarios with different levels of forestry in this paper, as we did in Kronnäs et al. (2019).

(page 8) L1 It would be interesting to quantify the difference in dry deposition due to clear cutting. And also, what is the effect of base cation deposition on forest growth, and how does that interact with weathering in the model simulations?

We will explain the calculation of wet and dry deposition more. The sites are not base cation limited at all, so there is no effect of base cation deposition on forest growth as of now. There are effects on soil acidification or recovery from acidification, runoff chemistry, weathering rates and on base cation content of needles. Often, about half of the input of base cations are from deposition, but the dry deposition is often smaller than the wet deposition.

(page 8) L8 why use 5 consecutive years, please justify

It was done to see the effect of a more severe drought, as these might get more common in a future warmer climate.

(page 9) L2-6 Please show the seasonal variation of precip/T/PAR for the future scenarios.

Yes, good idea, we will include that!

(page 9) L7-9 Due to which factor have they transitioned into another climate zone?

The coldest winter month will be warmer than -3°C as an average, for all sites except the two northernmost, in the future scenario. The second most northern, Högbränna will go from 3 to 5 months with a warmer temperature than 10°C as an average. The northernmost site Ammarnäs will stay in the same climate zone in this future scenario.

(page 9) L11 please define "extreme drought" with quantitative measure, e.g. X reduction in mean precipitation during summer months. I also wonder how often such conditions were projected by the climate models?

Yes, we will give some kind of quantitative measure of the drought. Extreme events are usually not well represented in scenarios from climate models, as they are rare and also the uncertainty in whether they will become more common or not is large.

Figure 2 What is the absolute difference in precipitation between the scenarios? Please quantify the water deficit in meaningful ways, e.g. mean precipitation, monthly MCWD, etc. The difference in temperatures between scenarios is hardly visible on this plot and scale. Also, for precipitation, it would be nice to visualize the summer months, where the actual reduction took place.

We will quantify the water deficit during the drought summers in some way and find a better way to present the data.

Results

(page 11) L9 How is weathering dependent on the texture and mineralogy? Please explain before.

Yes, this should be explained in the introduction.

Weathering takes place on the surface of the mineral grains, and smaller grain sizes have a larger total surface relative to the mass, which means that smaller grains have more sites where weathering reactions takes place and thus more weathering. Different minerals have different weathering rates at the same conditions and their weathering reacts differently to changes in temperature, pH, CO2-concentrations, and other factors.

(page 12) Table 3. Instead or additionally, can the response of weathering to warming be plotted? So, the relative control of temperature on weathering can be seen across season, or across mineralogy, etc.?

Good idea, thank you.

(page 12) L15-17 Nice result, this could also be visualized and calculated per site, etc.

Thank you. If this refers to the results on lines 15-17 on page 11, the requested results are presented in table 3.

Figure 3 – why is weathering not increased more in some sites after 2030-59 ? or why is the effect larger or smaller per time frame? Please explain the underlying model drivers and processes.

We will explain the difference at different sites more.

Table 4 – this table is not easily comprehensible. What is the difference in base and drought scenario referring to in %? Is it soil moisture saturation? How long is summer now? It would be better to show % reduction of weathering, in my view. And why show yearly change in weathering, while the drought impacts summer weathering only? Is it possible to depict these results in an informative figure, and perhaps move the data table to the supplement? I am not sure for what kind of patterns I am supposed to look for in the table in its current format.

Thank you for the good ideas. We will change the table. But the weathering is not affected only in summer, since it takes time for the soil moisture to be restored, so for some sites weathering in the warmer beginning of autumn is also clearly affected.

Figure 4 – same as above, it is hard to see differences in weathering, perhaps use a different line size or time-smooth data a little to better visualize.

We will try these suggestions and find some way to improve the figure.

Results section lacks an evaluation of the model's performance in regards to weathering.

The model in itself has been evaluated many times in other projects. In this paper we compare the model results and the soil water chemistry, in the appendix, with the forest growth, and other measurements at the sites, which shows us that our results are as good as we expect them to be for this kind of model on this kind of data (soil water is only measured three times per year, for example, so the measurements themselves do not cover the whole variation in the chemistry). We cannot compare the weathering results with measured data, since there are no measured data on weathering in the field. Our weathering rates are the same order of magnitude that other weathering methods give for these kinds of sites, though (and the differences are partly due to different assumption, soil depths, time periods et c).

Results section lacks reporting of actual modeled weathering rates.

Modelled weathering rates are in figures 3 and 4 and in table 4.

Discussion

(page 17) L3-15 This discussion on plant-weathering interactions should be part of the results in my view. The discussion starts with a summary of climate and weathering interactions, and they are now represented more as general remarks and speculations in the discussion, however, since nutrient supply for forest growth can be modelled with ForSAFE, I wonder why the effect on plants was not further looked into in this study? I see in L. 26 that forest growth is changing dynamically. And in L. 26-29 effects on plant nutrition are actually reported. Please explain how forest growth is treated in ForSAFE in the methods, and consider quantifying nutrient requirements versus nutrient supply via weathering, across the scenarios, sites, etc. I wonder what effect does vegetation have on weathering in your model?

We will explain ForSAFE more thoroughly in the methods section than what we have done now, including the weathering modelling and feedbacks with vegetation. Vegetation has an indirect effect on weathering rates, via its effect on concentrations in the soil water.

Forest growth is modelled dynamically in ForSAFE. The results show that these sites are not growth limited by base cations, neither today or in the future scenario up to 2100, so differences in future growth and contemporary growth in the model results are not due to base cations. If there is an imbalance between needs of base cations for the forest and supple from weathering and deposition (as there is for several of the sites), this first affect soil water chemistry, soil base saturation and runoff acidification, before there are effects on forest growth. There can be other, earlier, effects of suboptimal levels of base cations than decreased growth, such as decreased ability to cope with pests and drought, and ForSAFE does not model these effects, which is why we mention them in the discussion without presenting results. The effect of different forestry on weathering was studied in Kronnäs et al. (2019), but we have not studied the effect on weathering of vegetation vs no vegetation at all. Generally, higher uptake of base cations to vegetation increase weathering.

We will add results, in the result section, showing that the sites are not limited by base cations, and compare the sizes of different fluxes of base cations, from weathering, uptake to vegetation, deposition and leaching.

(page 17) The importance of using dynamic modelling is highlighted only for climate and weathering impacts in this study. The link to plant nutrition is not directly made if I understand the study/model correctly.

In this study, the links to vegetation are in the model (as they always are), but the sites are not growth limited by base cations (as very few Swedish forests are), and early signs on low nutrition on the tree health are unfortunately not included in the model. A next step in another study could be to look at the exact seasonal dynamic of uptake of nutrients and how that compares to stores and weathering amounts during that time period. For this, more detailed measurements of the timing of uptake to trees might be needed and we did not have these for our sites in this study.

(page 17) L20-24 This is rather a result again, the difference in soil temperature and the underlying drivers.

Yes. We will move these results to the results section.

(page 17) L26 consider rewording, “faster … than today in this modelling”

Yes, that is better.

(page 18) L23-25 This is material for the results section. It is necessary to analyze the effect of soil texture on the model results.

We will move these results to the results section and we will show the effect of soil texture on the soil water dynamics and weathering rates during drought and rewetting.

(page 18) L26- 32, this is also material for the results section, not the discussion.

Yes. We will move these results to the results section.

(page 19) L7-9 Evaluation of model results need to be done in the results section, and actual measurements and observational-based estimates or model-based estimates need to be included here. A simple statement that they are comparable is not enough.

There are relatively few weathering modelling studies made, and weathering is not possible to measure in the field, so verification against measurements is not possible. Verification against verified observational-based estimates or model-based estimates are not possible, since other modelled weathering rates also are not verified against measurements. The original weathering equations in ForSAFE are verified against laboratory experiments, when the first versions of the model (PROFILE and SAFE) were made. In this study, we refer to other studies to show that our results (averaged over a year or longer periods) are of comparable size, but since these other studies themselves are not verified against measurements (and are modelled or calculated using the exact same assumptions and time periods), maybe this is unnecessary and should be removed.

Instead of evaluating the model based on the weathering rates, we compare soil water chemistry (in the appendix, referred to in the results section) to see if the model results overall are plausible. The ForSAFE model itself is tested in many studies. The modelling of six of these sites are also evaluated in Zanchi et al, which we will clarify in this paper.

(page 19) L15-17 So if weathering has been analyzed with a very comparable approach before, what is the added value of this study? How does this study take us further to what we have previously known?

We will clarify. Weathering was not analysed in that study, which had other objectives, but ForSAFE was used on the same sites except Ammarnäs (as it wasn't relevant for that study).

(page 20) L17-20 now this opens up many questions here, the immediate one is, can you test the effect of CO2 fertilization in your results, simply by keeping CO2 constant in a control scenario. Consider the effect of different CO2 scenarios. That would allow estimating the effect of eCO2 directly. At the very least, the mentioned processes need to be analyzed, e.g. how did soil moisture change or any other driver of weathering due to CO2?

Yes, that is possible and would be a very interesting study. Although it is not the objective of this study, we did model such a scenario as a test. A scenario where the climate changes according to one of the IPCC scenarios, but where the driver of the climate change is missing would be unrealistic, but of value to see what effect every driver has on vegetation on its own and in combination with other drivers. Scenarios with different levels of CO2 could be combined with scenarios with higher or lower nitrogen deposition, since nitrogen often is limiting for growth in Swedish forests in today's climate, and might very well be limiting the fertilising effect of higher CO2 concentrations also. It would be very interesting to see if ForSAFE how the fertilising effect would be affected by nutrient (mostly N and P in the Swedish context) status and other factors, such as water availability and light. Thank you for the suggestion!