This document contains the referee comments (indented and with blue font) and our responses, regarding the submission of bg-2019-395: "*Uncertainty sources in simulated ecosystem indicators of the 21st century climate change*". We have also included the marked up differences (latexdiff) made to the manuscript.

Referee 1 comments

Mäkelä et al. disentangle different sources of uncertainty regarding the projected changes in a set of carbon and water cycle indicators during the 21st century. They apply the land ecosystem model JSBACH and the forest growth model PREBAS, which allows them to study not only the effects of prescribed climates and representative concentration pathways (RCPs), but also of parameter uncertainties and forest management practices.

This comprehensive analysis sheds light into the impact of uncertainties in projected climate, RCPs, model parameters and, which I find most interesting and novel, harvesting practices on a selection of important ecosystem indicators at two boreal forest sites in Finland. Although the authors have already put huge efforts into this work, I can see a few issues regarding the applied methods and presentation of results that should be addressed before this work can be published in Biogeosciences. I recommend the authors to address especially the major comments below.

Major comments

A. What are the conclusion and implications of this work? This should be highlighted also at the end of the abstract.

We have now added a concluding sentence to the end of the abstract to highlight the importance of management actions. We also note in the abstract that parameter uncertainty is usually not included in these types of simulations. We have also slightly modified the Conclusions section to better reflect this comment and added a new concluding paragraph.

B. Please describe the parameter selection and sampling in more detail in the methods and/or Appendix A, even if this has been presented in earlier studies. This would make it easier for the reader to understand your work. I am not sure what it means to use 100 parameter vectors (Line 105)? Only 100 combinations in total (this seems insufficient to cover the uncertainty in ca. 20 parameters)? Or do you mean 100 values sampled for each parameter? It is also not clear to me why largely different sets of parameters have been selected for the 2 models (Appendix A)?

The parameter selection was based on previous calibration experiments, referenced in the manuscript. These were run prior to the uncertainty simulations (and independently of those). The calibrations were later deemed reasonable for the uncertainty simulations (no new parameters were added as their interdependencies would not be known). The calibration simulations were done independently, so naturally the sets differ (as the focus of the calibrations was different). This explanation also touches on Major comment D and we have made a note of the explanation to the end of the Introduction.

The parameter values were systematically drawn from the calibration processes, so they are not random samples from the predictive distribution. Each sample has been evaluated at some part of the calibration process. For PREBAS, a standard approach was used and values from the MCMC chains were drawn at fixed intervals – this results in an approximation of the posterior distributions, with parameter interdependencies intact. For JSBACH the situation is a bit different as the calibration was done with adaptive population importance sampler (APIS). APIS produces a posterior estimate at each iteration. The estimate at 20-iterations was used as basis and complemented with later draws from 40, 60, 80 and 100 iterations. This was done to ensure robustness of the posterior estimate.

The parameter vector just means a vector in the parameter space, so it has a value for each parameter. This results in 100 values for each parameter, but they are given in combinations with regards to one another (so the interdependencies are not lost and these are not random samples). We have modified the corresponding text paragraphs (mainly in the Appendix A) to better reflect the referees requests.

C. Since canonical correlation analysis allows identifying linear relationships between two sets of variables, I wonder if this is the most appropriate approach here, given the non-linearities in the processes determining the investigated indicators? I see that this point is mentioned in the discussion section, but wonder if there is no other, better suited approach that could be applied?

The problem here is multiple-in-multiple-out variable dependencies and there are two “commonly” used ways to determine the relationships between two multivariate sets of random variables. These are CCA and analysis of variance (ANOVA) methods, but both of these should yield similar results. CCA has the advantage of exploring multiple outputs together and to better summarise the results (as we have done). CCA should be viewed as a method to (somewhat indefinitely) assess the factors and not a exact measure of the sensitivity of the output.

D. It is unclear to me why some of the indicators are calculated for both models and others either for JSBACH or PREBAS (Table 1)? I understand that some indicators may not be simulated by both models, but for instance biomass and soil carbon should also be available from JSBACH simulations.

The choice of which indicators to calculate was made based on the pre-existing calibration simulations. The parameter calibration etc. was already previously done and the indicators were chosen to represent the most prevalent processes etc. related to the calibrations. With regarding JSBACH, the non-essential variables were removed from the model I/O to reduce runtime. Thus we did not output and save all normally produced variables. Additionally, we did not utilise any “disturbances” for JSBACH, so GPP is a sufficient proxy for biomass. We have added a note of this to the end of the Introduction.

E. The potential impact of uncertainty arising from different process implementations (or missing processes) in the models could be at least discussed.

We have now added a short note of the missing processes in “Validity of estimates” section: “Model calibration and the parameter distributions also compensate for missing and imperfectly modelled processes” as well as touching on the subject in materials and methods section and conclusions. The missing processes are partially accounted for by the different model parameterisations and we believe that the suggested topic would not benefit the manuscript in a meaningful way. Another approach would be to examine model ensembles, which we have only two.

Minor comments

1. I am not sure if the term “ecosystem indicators of climate change” is very descriptive for the selected indicators. These are a collection of carbon fluxes / stocks and vegetation and water cycle properties and maybe you could find a more suitable name.

The term “ecosystem indicators” was coined as an overall “umbrella” term to encompass all of the presented indicators. It is clear that the term itself covers also many other indicators, not just the ones discussed in the manuscript. Unfortunately, we have not been able to come up with an alternative that would be concise and precise.

2. Title: You should mention that this study focuses on boreal forest sites (in Finland)

This information has been added to the title.

3. Line 41: The impact of what?

The impact of management practices. This has been added to the manuscript.

4. Line 42: Do you mean future forest productivity in Finland or in general?

In Finland, this has now been specified in the manuscript.

5. Lines 61-73: It would be interesting to get to know the distribution in tree diameter at both sites. This would make it easier to understand the differences in the effect of the forest management scenarios at both sites.

Unfortunately this information has been lost. When we submitted the manuscript, we informed the editor that PREBAS simulation outputs were lost (only the examined periodic indicator values were recovered) - this is also the reason why we only include more detailed JSBACH images.

6. Line 83: Maybe describe the harmonized FMI meteorological data in a bit more detail.

The original word order has been a bit misleading. What was meant is that the reference is FMI meteorological data set, harmonised by Kriging (with external drift). This has now been stated explicitly in the manuscript.

7. Line 100: Which version of JSBACH do you use? Not sure if Kaminski et al. 2013 is the most appropriate reference for the JSBACH land surface model.

The JSBACH version (branch: cosmos-landveg-tk-topmodel-peat, revision: 7384) was modified to e.g. include multiple stomatal conductance formulations and delayed effect of temperature to photosynthetic activity in spring. The modifications and the calibrations are described in Mäkelä et. al (2019). The modified model modules (fortran code) is available from github (after agreeing to the MPI license agreement). We agree that the Kaminski reference is not really appropriate, but there are not very good alternatives. We have substituted the reference with two others (Raddatz 2007 and Reick 2013). The model version information has been added to "Code and data availability" section.

8. Line 102: Please state here that the parameter distributions are shown in the Appendix.

Added.

9. Line 102: How would the results be affected by coupled model runs?

This is a very broad (albeit interesting) question and unfortunately way out of scope of this manuscript, hence we will only give some comments on the topic. Firstly, we are using a model version that was calibrated offline (uncoupled), so the simulations are "in-line" with the calibration. Secondly, coupled model (MPI-ESM) would use a largely different driving data and the setup would be more akin to different MPI-ESM (CMIP) scenarios, not different "climates" *per se*.

10. Line 104: You mean only 1 PFT is present in the study regions?

No. In the study regions there are other PFTs, such as birch and understory, but the sites are extensively dominated by evergreen trees. In the simulations (and in the previous calibrations), the non-evergreen vegetation has been set to occupy a zero fraction of the grid-cell, so there is no other vegetation besides evergreen trees. This has now been stated in the manuscript.

11. Line 108: Wouldn't the "model uncertainty" also comprise uncertainty due to model structure (i.e. implementation of processes, missing processes)

This is absolutely true and we have amended the description accordingly.

12. Line 123: Do you mean mortality due to competition for resources?

Mortality is based on the Reineke self-thinning model (Reineke 1933). Reineke, L., 1933. Perfecting a stand-density index for even-aged forests. Retrieved from. J. Agric. Res., Washington.

13. Line 136: These are not only biophysical, but also biogeochemical indicators.

Added.

14. Line 138: Please list in detail how many scenarios have been investigated for each uncertainty component. Maybe a table would help to present this.

We have now added a new Table 1 indicating the number of uncertainty components. The models are run with each combination of these components.

15. Table 1: Why is "gross growth" grouped into the "Biomass" group and how does it differ from GPP?

The naming here has been a bit unfortunate, but follows that used in forest sciences. In this instance gross growth refers to increment in tree volume that also considers living, dead and harvested trees. The units in Table 1 for this variable were wrong and have also been corrected.

16. Lines 158-164: Please state the values of the redundancy index for the different scenarios (at least in the bar plot in Figure 1) and explain what these values actually mean (what is a typical value range of Rd?)! What does it mean if Rd values for all factors are low (cf. Fig. 2)?

The value of the redundancy index is between 0 and 1. There are no generally accepted guidelines for the interpretation of these values, hence our interpretation is based on the relative uncertainties between the factors. This is also one of the reasons we did not present the exact Rd values. As an alternative to adding the values in the bar plots, we would suggest presenting them in a Table format as a supplement.

We updated the descriptions in the manuscript accordingly and also added more details in the CCA Appendix so that it may be easier to follow what is actually calculated. If the Rd values for all factors are low, then likely there is low correlation and small variance.

17. Figure 1: I suppose the colour scheme for the JSBACH simulations is not correct (management scenarios are displayed, although they have not been implemented in JSBACH).

Yes, this was my error as I forgot to link the updated file to the pdf. This has now been corrected.

18. Figure 2: Please use the same colour scheme as in Fig. 1.

Again, as above and has been corrected.

19. Line 179: Please always state if you refer to ecosystem, autotrophic or heterotrophic respiration.

In almost every case this is the ecosystem respiration. The CCA analysis for PREBAS was done using autotrophic respiration as indicated in Table 2.

20. Lines 187-188: Isn't this statement in conflict with your previous finding that the impact of parameter uncertainty on overall uncertainty would be small?

This is a question about interpretation. The variation of the parameter values (the actual "spread" of the value distributions) is not in itself parameter "uncertainty". The parametrisations represent different realisations of the model (same as e.g. different RCP's). Parameter uncertainty should be examined as the difference between the "initial spread" and the "end spread". Furthermore, the effect of climate models and RCP scenarios should also be removed. When these are taken into account, the "initial spread" and "end spread" are relatively alike. This is a bit simplified explanation, but should suffice here.

So the uncertainty is not directly the spread of the values, but rather how (and if) the distribution changes over time (since our interest is on the relative changes arising from the different factors). This shorter explanation has been amended and added to the manuscript.

21. Line 197: Which processes are (not) considered in the models that could lead to an impact of management on the seasonality indicators?

Firstly, management affects e.g. the amount of trees and therefore LAI, transpiration, albedo, soil water content, soil carbon content etc. The question about which missing processes could impact management is a bit more difficult. Ingrowth (i.e., the volume of young trees that enter to the measurable size classes) is not implemented in PREBAS. Also understory is not modelled. However, in managed forests, these processes are minimal and the lack of them in the modelling framework should not affect the analysis.

22. Line 222-223: Why are the model parameterisations responsible for the differences in soil moisture distributions and not rather the climate models?

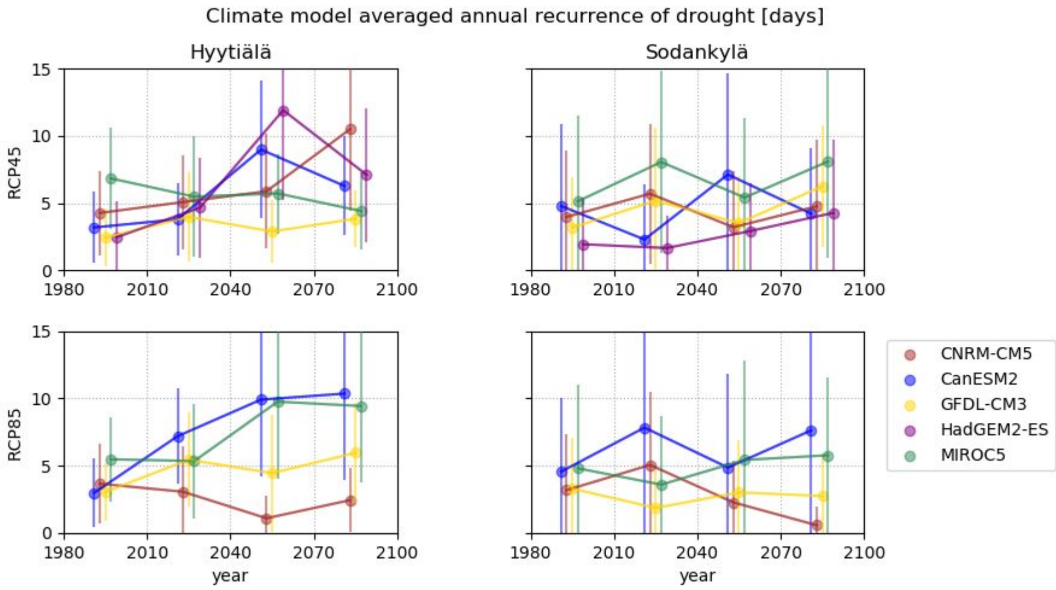
The text has been poorly worded. It was meant as an observation that the soil moisture value distributions are similar for all climate models during the reference period, but the same distributions differ for the last 30-years. The value spread is produced by 100 simulations for each climate model, where only the parameters vary. The observed differences are due to both climate models and parameters (and we can also see differences due to RCP scenarios). We have amended the text accordingly.

23. Figures 7 and 8: A legend could explain which colour refers to which climate model.

Yes, the legend was originally left out as we did not want the discussion to devolve into a comparison of individual climate models. This does not seem to be an issue in the manuscripts current shape, so we will add the legends to the figures.

24. Figure 8: Why are cumulative drought days displayed and not the trend in drought days over time? This might make it easier to spot changes in drought days.

There is a lot of year-to-year variation in the annual number of drought days (from 0 to 89 days, with 30-year deviation typically ranging from 6 to 16 days), which makes the "trend plot" visually extremely challenging. This also means that the correlations in such plots are negligible (some positive, few negative but mostly no trends according to Mann-Kendall - we have added this information to the manuscript). Below is periodically and over climate-model specific simulations averaged plot of drought recurrence. For these individual models we can fit trendlines, but the Mann-Kendall test does not yield a trend for all simulations (in any of the four cases below).



25. Line 254: I suggest using a more informative heading than "Impact to ecosystems".

Changed to "Ecosystem indicator sensitivity".

26. Line 341: I cannot find the supplementary material?!

We will make the supplements available at the next opportunity.

Referee 2 comments

The article by Makela et al. applies two ecosystem models to two boreal pine sites in Finland using 3 RCP scenarios from 5 CMIP5 climate models to determine uncertain-ties in carbon and water variables due to parameters, climate models, RCP scenarios, and management options (which are only covered in one of the ecosystem models).This is an interesting uncertainty analysis, though the breadth of the work is limited as it only covers two sites within a single biome, rather than more broadly defining uncertainty based on a wider-range of sites or biomes or through extrapolation. While the authors have made clear why their choice of particular climate models, it is not clear how these two ecosystem models fit into the broader range of such models. The significance of this study is also not great without further justification. Are these sites representative of other boreal forested site? Do results for pines also apply to spruce or larch forests? Are the same climatic trends also occurring at most other boreal forested sites? Does one set of model results for two sites really make the case that management is more important than the other factors? The paper can be improved if this approach and results can be put into the broader context.

It appears that the referee has got a hold of a previous version of the manuscript (bg-2019-395-manuscript-version1.pdf) and not the preprint version available at the discussion page. We have tried to answer these comments while reflecting both manuscript versions.

1. Line 104 (Section 2.3): Please provide more description of the "100 vectors". I count around 20 parameters from Table 1 in the 2019 paper – are these the parameters that are being varied? There needs to be a more thorough discussion of how the parameter uncertainty is determined.

This comment is in line with major comment B of referee 1. We have added information regarding the parameter sampling etc. to the manuscript text and appendix A.

2. Section 3.1 – define DEL (delayed management scenario)

The delayed ecosystem logging (DEL) is now defined in Section 2.4 while introducing the PREBAS model, but as a reminder we have also added these definitions in Section 3.1.

3. Line 162: Should be Figure 3, not 2

We gathered all the CCA images to one figure and this reference has been corrected.

4. Figure 4: I assume the respiration is ecosystem respiration, and not heterotrophic or autotrophic, so please specify.

Yes, this has now been stated (at other parts of the manuscript as well).

5. Figure 5: How are the Cfluxes determined – are these the mean or net difference (NEE) of the GPP and ecosystem respiration? Similarly, in Figure 9, how are the Wfluxes determined?

These variables are defined in Table 1 and the uncertainty is extracted from all variables simultaneously. These include GPP, NPP, NEE and respiration as well as soil carbon for PREBAS.

6. Figure 8: Need y axis labels and title and x axis title

This information was previously in the image title, but has now been relocated as axis labels.

7. Lines 201-203 (Section 3.4): What is meant by different model parameterizations here – this should not be confused with parameters as used throughout the paper, as isn't the meaning here different functional relationships in the different models?

This section has been amended in the new version. What was meant here is that the parameterisations, together with the drivers (climate models), yield initially similar value distributions but the situation is different when we examine the last 30 years.

8. Figure 10: There is a reference to drought frequency from this figure, so a better (or additional) figure would be one that showed the frequency distribution of droughts between the different models.

The problem with drought frequency is that it varies considerably throughout the years. Hence, we cannot plot any trendlines etc. for this kind of plot. We circumvented the issue by examining the accumulated drought days. Please also see our answer to question 24 by referee 1.

9. Line 204: What is A1?

This was a reference to Appendix A1 and it has now been explicitly specified.

10. Figure 13: This figure is really just comparing the two models (JSBACH and PREBAS). There are references in the discussion to this figure about pathways (lines 259-260) and high variation (lines 260-261), but I don't see that from this figure. Also how is linearly lengthening of VAP shown in Figure 6?

The pathways in this context refer to the development NEE through time with different management actions. The BAU scenario follows a convex "path" and DEL a concave one and these "paths" are separate in Fig. 10. Moreover the time development is "continuous" from left to right along the path. In Fig. 6 VAP is the difference between SOS (yellow) and EOS (red) - the development of both of these is linear and therefore it is linear for VAP as well.

11. Lines 251-252: How do you know how much CO2 has contributed to GPP? That would have to come from modeling or a FACE experiment.

This was a result from Grönholm et. al (2018), but since the reference only directs to an abstract and they have not yet submitted/published the results (that were presented in EGU2018), we have also added a global article reference to reaffirm the credibility of the claim.

12. Lines 304-306 don't make much sense to me, as the amount of drought days is increasing in Figure 10.

Figure 10 shows the amount of cumulative drought days from the beginning of 1980. Therefore the recurrence of drought remains the same if the cumulative drought days are linearly increasing. WE have modified the image heading to highlight that the drought days are accumulated from the beginning of 1980. Please also see our answer to question 24 by referee 1 - this explains why we are not using annual drought days (the variation if too large for the image to make sense).

13. Conclusions: I like general points that management is most important to carbon, that effects of RCP are more important with time, and that NEE is complex due to offsetting effects of GPP and respiration. But the last paragraph is a weak ending – can use a better closing paragraph to highlight the importance of the study, how it informs the broader modeling community, and where to go from here.

We have now added a new concluding paragraph.

Referee 3 comments

Mäkelä et al. quantify the contribution of different uncertainty sources (climate, RCP, management, model parameters) on uncertainty in predictions of various ecosystem indicators made by two ecosystem models throughout the 21st century. The topic of the study is timely, and relevant for the field. It also fits well to Biogeosciences. I believe that the study is overall sound. More effort, however, could be spent on discussing the implications of the results for vegetation modeling and climate change research. I also had some questions regarding the quantification of input uncertainties and some other aspects of the methodology (see details below), which should be considered by the authors.

General comments

A. The abstract does a fine job at describing the methods and results, but the motivation and the implications could be better worked out. The same point could also be made about the main part of the paper - relevance / insight could be better worked out in introduction / conclusion.

Hopefully the changes made in the manuscript are sufficient.

B. The way input uncertainties were quantified should be more systematically described and justified. Taking the example of management: you consider two management scenarios, which you effectively consider equally likely. On which basis were those chosen? I assume that there are more options for management. Regarding the RCPs – your analysis seems to put equal weights on all 3 RCPs, so you consider them equally likely? It's OK if your uncertainty ranges are chosen "ad hoc", but it should be clear if you interpret those as a probabilistic, or just as a range of options. It seemed to me that in several parts of the discussion, you interpreted the results more like a sensitivity analysis (as in: through management, we can change a lot) than an uncertainty analysis.

This comment is much appreciated as much of our interpretation is more akin to sensitivity analysis. We have now updated the manuscript title and give a more overall view of the experiment design (and reasons for the choices made) at the beginning of the "materials and methods" section. Even though much of the discussion is in the style of sensitivity analysis, we have sticked to our original uncertainty terminology and give the justification as per Swart et. al (2009) [Swart, R., Bernstein, L., Ha-Duong, M., and Petersen, A.: Agreeing to disagree: uncertainty management in assessing climate change, impacts and responses by the IPCC, Climatic Change, 92, 1–29, 10.1007/s10584-008-9444-7].

C. Maybe I missed it, but you never explained the reason for using 2 models – I'm also asking because the model (structure) could of course also be seen as a source of uncertainty, but it seems you don't view it that way?

We have now included this information in the overview at the beginning of "materials and methods" section. The model structure is, of course, a source of uncertainty but it is (at least partially) compensated by model calibration and the use of an ensemble of parameter values (instead of single point estimate). This topic is slightly outside the design of our experiment and although we could speculate how the model deficiencies affect the relative uncertainty estimates, there is not much that can be said with any (reliable) amount of certainty.

D. I appreciate that there is no ideal method to attribute back the output uncertainty to the inputs, but the CCA certainly has some limitations due to its linearity assumptions.

In https://www.sciencedirect.com/science/article/abs/pii/S0378112717304371, we use a random forest for the same problem. There are some caveats for this approach as well, in particular if there is collinearity between input variables, but it might be a more robust alternative if nonlinearity is an issue.

We appreciate the suggestion but at this point we are not changing the methods. As remarked earlier, some of our interpretation is more in the line of sensitivity analysis and we have not quantified the uncertainties exactly. Even though CCA has not captured the variation in the outputs, we have shown that all inputs have an impact on the ecosystem indicators (namely Water cycle variables) and considering the nature of the manuscript, we believe that this is enough. However, we have added the suggested method as a reference in the conclusions so that others who might consider using CCA have another option as well.

Specific comments

1. L1 THE forest -> consider deleting "the"

Considered and deleted.

2. L2 ongoing -> redundant?

Yes. We have now removed the offending word.

3. L4 The logical connection between the increase of CO_2 and the necessity to do this study was not clear to me. Aren't the changes you are analyzing here mostly driven by climate change (which is of course created by CO_2 increase)?

Absolutely correct. We have amended the first sentence in the abstract to better highlight CO_2 as a driver of climate change.

4. L8 Stages – you mean points in time?

Yes. We have amended the sentence.

5. L9 indicators of climate change -> I wouldn't say that these are climate change indicators, maybe just "ecosystem indicators"?

Modified all "ecosystem indicators of climate change" to -> "ecosystem indicators".

6. L11 This sounds weird – do you mean: the uncertainty induced by the climate model…

Yes, amended.

7. L14 One would usually expect some kind of conclusion / summary at this point

We have now added here a more impactful statement about the management.

8. L16 delete "and"

Sentence was modified.

9. L16 I think this paragraph would be easier to understand if you would start with the topic, which is that there is agreement that climate is changing, but uncertainty about the magnitude

We have included the magnitude uncertainty as the second sentence.

10. L24 Again, motivation not quite clear to me.

Hopefully the previous addition and other changes in the paragraph clarify the motivation.

11. L87 How can they have good performance and at the same time represent well the variation of models? This seems to be a contradiction

The models have good performance in terms of simulating current climate whereas the statement on variation refers to their performance in predicting the future and serves as an introduction on the more elaborated description on the performance that follows. The latter sentence has been deleted and the following sentence slightly reworded in order to bridge from current day considerations to the future.

12. L98 Overall, the explanation about the selection of the climate models didn't sound particularly convincing to me. Why would it be scientifically beneficial to have climate models from different continents? The only concern is that the selection you make is not representative of the distribution of climate models as a whole. If you would shortly state that this is not the case, that would fine for me

We deleted the sentence about the geographic versatility of the origins of the models. The different aspects regarding the representativeness of the selected models in terms of seasonal temperature and precipitation changes have been discussed in the text with quite some detail already. We believe that by removing the admittedly misleading notion about good representation of the variation (see previous comment) we direct reader's attention better to the description of their performances among the 24 CMIP5 models used in the analysis of Ruosteenoja et al (2016).

13. L101 I would recommend active voice: we used the model...for these parts

Changed.

14. L105 You mean the "parameter uncertainty"? Because model uncertainty includes more

Yes, we have now amended the manuscript and systematically refer to this as parameter uncertainty.

15. L105 The parameter description is hard to understand. Also, I assume what you did is to have these 100 parameter combinations, and then you cross them with the other options in a full factorial design? This could be better explained, and also why you choose to do this, as opposed to drawing parameter values from the posterior for all model runs.

Yes, we have now included an amended parameter description at the beginning of the "materials and methods" section, where we give an overview of the simulation design.

16. L106 Parameter uncertainties?

This has been amended (see answer above).

17. L109 I think it should have been called like this all the time, because model uncertainty could be read as structural uncertainty

This has been amended, see answer to 14.

18. L135 One could think about introducing a subsection explaining and comparing the 4 sources of uncertainty here

We have added this description to the start of “materials and methods” section.

19. L138 Why 2000 vs. 6000? Maybe explain how the numbers come about.

We have added a new Table 1 to the manuscript that explains this.

20. L159 Well, the uncertainty has to be caused by something, right?

Agreed.

21. L160 I think it would be good to shortly explain the interpretation of the RD index here or before. The reader should be able to interpret the figures without referring to the appendix

We have added a description of Rd values etc. in the manuscript, at the end of “materials and methods” section.

22. L166 Maybe some introductory sentence here that explains why we next look at this? Fig. 3 Although I understand the reason why you present it like this, it is slightly confusing to have the site on the y axis, and the variable as title of the figure

We added a sentence at the end of the preceding paragraph. We have also modified (rotated) the images so that Hyytiälä and Sodankylä are presented column wise and the variables on y-axis.

23. L179 Not sure if bifurcation is really the best word for it. Just because it is used so often in a slightly different context in maths

Agreed, the sentence was slightly modified and the “bifurcation” changed to “divergence”.

24. L195 I was struggling to see the motivation for this section, in the context of uncertainty– isn’t this all more about describing climatic trends?

Partially yes, as explained in answer to general question B, we also consider indicator sensitivity and in such cases the climatic trends are interesting.

25. L202 well, given that the model is (I think deterministic), it must be explained by the input uncertainties. It seems to be rather that there is no linear correlation that could be picked up by the CCA?

Absolutely correct, this was meant to be taken in the context of our analysis method. We have amended the sentence.

26. Fig. 9 the site labels are very hard to spot

We have now redrawn the images with bigger labels etc.

27. L249 Similar, really? The two models look quite different to me in Fig. 1. Also, Fig. 9 looks to me as if there are quite some differences between the models

We have clarified the meaning that the uncertainty estimates are mostly similar, especially when we take into account the management effects.

28. L264 It seems to me that you interpret the results here more like a sensitivity analysis than an uncertainty analysis. In an UA, we wouldn’t have the choice to change management, it’s uncertain.

Yes, this was addressed in general comment B.

29. L272 I'm a bit surprised – are these models suitable to understand changes in snow melting periods? If so, by what mechanism would that occur, increased LAI?

The snow melting was included only for the JSBACH, where the model tracks the accumulated amount of snow and its density, which affects e.g. soil temperature. The mechanisms are quite straightforward and snow melting is due to temperature changes. The changes in snow melting period should therefore be mostly affected by climatic drivers.

30. L281 Again, this would seem to me an interpretation of a SA, not UA

Yes, this was addressed in general comment B.

31. L291 next 4 lines: I didn't understand what you mean here

We have clarified the meaning.

32. L295 I don't understand how you can deduce this from Fig. 4 / 7 – isn't the KDE showing the combined other uncertainties, not just the parametric?

The text was a bit misleading and has been amended (not parameter distributions but value distributions induced by the parameterisations). In Fig 4 the KDE is indeed containing other sources, but it is explained in the text that the distributions are similar for all climate models and RCPs. In Fig. 7 the value distributions are shown for the different RCPs and for each climate model separately.

33. L317 when they are correlated, they could also be both wrong in the same way

Yes, the sentence was modified to indicate that the effect is captured by CCA (not that it would be automatically reliable).

~~Uncertainty sources in simulated ecosystem indicators~~ Sensitivity of ~~the~~ 21st century simulated ecosystem indicators to model parameters, prescribed climate ~~change~~drivers, RCP scenarios and forest management actions on two Finnish boreal forest sites

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Abstract. ~~The forest~~ Forest ecosystems are already responding to ~~increased~~ changing environmental conditions that are driven by increased atmospheric CO_2 concentrations~~and changing environmental conditions. These ongoing~~ . These developments affect how societies can utilise and benefit from the woodland areas in the future, be it e.g. climate change mitigation as carbon sinks, lumber for wood industry or preserved for nature tourism and recreational activities. We assess the effect and the relative magnitude of different uncertainty sources in ecosystem model simulations from the year 1980 to 2100 for two Finnish boreal forest sites. The models used in this study are the land ecosystem model JSBACH and the forest growth model PREBAS. The considered uncertainty sources for both models are model parameters ~~,~~ and four prescribed climates ~~and~~ with two RCP (Representative Concentration Pathway) scenarios. Usually, model parameter uncertainty is not included in these types of uncertainty studies. PREBAS simulations also include ~~an additional RCP scenario and~~ two forest management ~~actions~~scenarios. We assess the effect of these sources of variation at four different ~~stages of the simulations~~ points in time on several ecosystem indicators~~of climate change~~, e.g. gross primary production (GPP), ecosystem respiration, soil moisture, recurrence of drought, length of the vegetation active period (VAP), length of the snow melting period and the stand volume. The ~~climate model uncertainty~~ uncertainty induced by the climate models remains roughly the same throughout the simulations and is overtaken by the RCP scenario impact halfway through the experiment. The management actions are the most dominant uncertainty factors for Hyytiälä and as important as RCP scenarios at the end of the simulations, but contribute only half as much for Sodankylä. The parameter uncertainty is the least influential of the examined uncertainty sources, but it is also the most elusive to estimate due to non-linear and adverse effects on the simulated ecosystem indicators. Our analysis underlines the importance to carefully consider the implementation of forest use when simulating future ecosystem conditions, as human impact is evident and even increasing in boreal forested regions.

1 Introduction

The global atmospheric greenhouse gas concentrations are rising~~and inducing~~ , which induces changes in land ecosystem carbon balances, water cycles and their seasonality. However, there is uncertainty in the magnitude of these changes. The rate of the expected concentration rise depends on human actions and the corresponding emission pathways chosen. The pathways presented in IPCC AR5 report (**?**) lead to a radiative forcing of 2.6 W/m^2 to 8.5 W/m^2 in the year 2100. In addition to climate pathways connected to human actions, the variability in the IPCC climate projections is due to model differences and to internal variability in the climate system. Climate sensitivity has proven to be extremely difficult to constrain (**?**). The multi-model spread in e.g. temperature and precipitation has not been narrowing during the last few years despite substantial model development (**?**). However, narrowing the uncertainties should not be the only aim and sign of progress in climate modelling. Models improve as more processes are described in detail, which may also introduce new unknown uncertainties. Thus it is important to study what are the contributions of different factors to the total uncertainty of examined variables, and how does the uncertainty evolve in the future.

The climate models provide drivers for the land ecosystem models. The predictions by land ecosystem models are affected by the driver uncertainties and by uncertainties related to the land surface model itself. Usually, only variability between different models is examined (see e.g. **??**), and the uncertainty related to model parameters is not taken into account (**?**). The unaccounted model processes can lead to significant underestimation of the overall uncertainty (**?**). Furthermore, the spread in the uncertainty of the model outcome depends on the variable and region investigated. High latitude ecosystems are predicted to experience significant changes due to climate warming (**?**). The change in seasonality of the ecosystems is predicted to manifest itself via decrease in snow cover duration, earlier soil thaw and later soil freeze and longer growing season (**???**). The longer growing season and warmer temperatures are predicted to increase both ecosystem carbon uptake and respiration (**?**), while harmful extremes connected to heat, soil drought and soil excess water are also predicted to become more severe (**?**). The evolution of net ecosystem exchange (NEE), defined as the difference between net ecosystem primary production (NPP) and heterotrophic respiration (R_h), is rather uncertain in future due to opposing drivers and may follow a trend towards net emissions or net uptake.

Forest management in Finland is a strong modifier of ecosystem carbon budgets and usually an unaccounted source of uncertainty in future predictions. The harvesting intensity defines the impact of the management practices to the ecosystem carbon exchange (**?**). According to **?**, the future forest productivity in Finland was predicted to increase towards the end of the century. The climate model ensemble predictions were the dominant source of uncertainty for forest productivity, but closer to the end of century the role of emission pathways became more important. Estimation of future development of ecosystem carbon budgets together with impact factors such as management, seasonality and water conditions adds information to the whole ecosystem functioning. Assessment of uncertainties related to carbon budgets and growing season length together with water and snow conditions is important in estimating the forests ability to provide ecosystem services related to e.g. carbon sequestration, wood harvesting, maintaining habitats and promoting nature tourism (**??**).

Here we estimate how biomass, carbon, growing season, water and snow -related ecosystem indicators ~~of climate change~~ and their uncertainties progress in the future. We engage two ecosystem models at southern and northern boreal forest sites – JSBACH is developed to study land surface processes with closely coupled carbon balances and hydrology, while PREBAS is aimed to study carbon budgets with implementation of forest management. Both models have been previously calibrated for boreal ecosystems (**??**) – these calibrations were independent of one another and therefore the calibrated parameter sets are different. This also gives rise to a different set of examined ecosystem indicators. We estimate the contribution of model parameter uncertainty, climate model variability, RCP pathway and management actions to the total uncertainty of these indicators. We apply canonical correlation analysis (CCA) to cross-correlate the uncertainty sources with the chosen ecosystem indicators. Finally, we aim to combine the model estimates to determine which are the dominant sources of uncertainty in future ecosystem projections.

2 Materials and methods

~~We will first briefly introduce~~ In this paper we examine the impact of several uncertainty sources on model outputs in a full factorial design, depicted in Table 1. The models were run separately for both sites with all possible combinations of the uncertainty factors. The experiment design resembles that of the CMIP5 simulations (fifth phase of the Coupled Model Intercomparison Pro . Hence, in the same spirit (**?**) we present this work as uncertainty analysis, although parts of the results and discussion will be more akin to sensitivity analysis. We will next give a brief overview of the experiment design, followed by an introduction of the sites and their characteristics, ~~followed by the~~ RCP scenarios and climate models ~~used in this study~~ as well as the models used to run the simulations ~~. Next we describe~~ in this study. Finally we will define our ecosystem indicators ~~of climate change and define the methods used to analyse the simulations.~~ and the analysis methods.

Table 1. Composition of JSBACH and PREBAS model simulations: number of parameter combinations (Par), climate models (Clim), RCP scenarios (RCP), management actions (Manag) and sites as well as the total number of 120-year long simulations.

Model	Par	Clim	RCP	Manag	Sites	Total
JSBACH	100	5 (4)	2	-	2	1800
PREBAS	100	5	3	2	2	6000

The JSBACH and PREBAS models were selected for this study because we had recently calibrated them for boreal ecosystems (**??**). Thus, we were able to preserve the parameter interdependence by extracting a set of 100 parameter combinations from the calibration chains – instead of merely sampling the parameter values from their marginal distributions. The extraction methods, parameter definitions as well as sample mean and deviation are given in Appendix A. It should be noted that model calibration (partially) compensates for inaccurate or missing model processes and other model deficiencies, which is why we do not focus on this subject.

In addition to model parameterisations that reflect the parameter posterior distributions, we use a sub-set of climate models and representative concentration pathways (RCPs) from the CMIP5 ensemble (smaller set for JSBACH is due to missing bias corrected variables). We do not assign any particular probabilities (weights) to the different climate models and RCPs, so these scenarios are considered to be equally likely. Additionally, two management actions were used in PREBAS simulations. They were chose as to represent the current management practises and a modification that aims for near term carbon sink increase. These two practises are relatively alike, but more intrusive management actions were not included in this experiment as to focus the study.

2.1 Sites

The sites used in this study are called Hyytiälä (FI-Hyy; 61~~º~~°51′N, 24~~º~~°17′E, 180 m a.s.l.) and Sodankylä (FI-Sod; 67~~º~~°22′N, 26~~º~~°38′E, 179 m a.s.l.); they are respectively located in southern and northern Finland and represent the southern and northern boreal pine forests. These sites can be characterised as Boreal evergreen needleleaf forests, where the dominant species is the Scots pine (*Pinus sylvestris*).

The Hyytiälä site (**?**) was planted in 1962, after burning and mechanical soil preparation. The soil type is Haplic Podzol on glacial till. The site has an understory of Norway spruce (*Picea abies*) and few deciduous trees. The maximum measured all-sided leaf area index (LAI) for the Scots pine is 6.5 m^2/m^2, the average measured annual precipitation is 709 mm and temperature 2.9 ~~º~~°C.

The Sodankylä site (**?**) has been naturally regenerated after forest fires and hosts trees ranging from approximately 50 to 100 years of age. The soil type is fluvial sandy Podzol. The ground vegetation consists of lichens, mosses and ericaceous shrubs. The maximum measured LAI for the Scots pine is 3.6 m^2/m^2, as determined from forest inventories, the annual precipitation is 527 mm and temperature -0.4 ~~º~~°C.

2.2 RCP scenarios and climate models

We selected model runs ~~of the fifth phase of the Coupled Model Intercomparison Project (CMIP5; **??**)~~ from the CMIP5 project (**??**) following three representative concentration ~~pathway~~ pathways (RCPs), that reach radiative forcing levels of 2.6, 4.5 and 8.5 W/m^2 by the end of the century (**??**). Throughout the historical period that ends in 2005 the land cover data and the greenhouse gas concentrations corresponding different RCPs follow common trajectories (**?**).

Climate data for years 1980-2100 was obtained from five global climate models (GCMs; CanESM2, CNRM-CM5, GFDL-CM3, HadGEM2-ES and MIROC5). The climate variables were bias corrected and further down-scaled to a 0.2~~º~~°×0.1~~º~~° longitude-latitude grid, similarly to **??**. The bias correction methods are described in **??**. The ~~harmonised FMI meteorological data by **?**~~ FMI meteorological observation data, harmonised by Kriging with external drift (**?**), was used as ~~reference~~a reference climate for the period 1980-2010 (**?**).

The sub-set of five climate models was selected because of their good performance in reproducing current climate in Northern Europe and because they provided complete data sets for running impact models (**?**). The ~~five chosen models represent well the variation from current climate conditions (1981-2010) to the end of the ongoing century (2070-2099). The~~ future winter-time ~~(i.e. December, January and February) precipitation~~ precipitation changes in Finland for the five models in RCP4.5, covers the range of variability depicted by 24 out of 28 CMIP5 models investigated by **?**. In summer the precipitation change range is generally narrower than in winter and the selected models cover the range of roughly half of the 28 CMIP5 models. Winter temperature change shows intermediate values among the 28 models and the range captures the ranges of change shown by 11 models. In summer the five model selection represents the range of change depicted by the upper half of the 28 models analysed by **?**. ~~Furthermore, the five climate models represent host institutes from different countries and from three continents: Asia, Europe and North-America.~~ CO_2 concentrations from the RCPs 2.6, 4.5 and 8.5 increased monotonously through the calendar years reaching respective global means of 421, 538 and 936 ppm by the end of the century. PREBAS was run with results from all five climate models and three RCP scenarios, whereas JSBACH simulations included only RCP4.5 and RCP8.5 due to missing bias corrected climate variables. Moreover and for the same reason, JSBACH was not run with the HadGEM2-ES climate model for RCP8.5.

2.3 The JSBACH model

The JSBACH ecosystem model ~~(**?**)~~ (**??**) is the land-surface component of the Earth system model of the Max Planck Institute for Meteorology (MPI-ESM). ~~In these simulations, the model setup and parameter distributions are derived from **?**. JSBACH is used~~ We modified the underlying JSBACH model version (specified in "Code and data availability" section) as in **?**, where the model is calibrated and validated with site level measurements from 10 different evergreen needleleaf forests throughout the boreal zone (including Hyytiälä and Sodankylä). The calibration was done simultaneously on multiple sites to reduce parameter dependency to any single site – the aim of the calibration was to produce a parameter set suitable for the whole boreal zone. We run JSBACH uncoupled from the atmosphere, ~~applying~~ apply five layers within a multilayer soil hydrological scheme (**?**) and ~~utilising~~ utilise the BETHY model for canopy/stomatal conductance control (**?**). Additionally, ~~the model effectively uses~~ we set the model to effectively use only one plant functional type (PFT), coniferous evergreen trees~~.~~

~~The JSBACH model uncertainty is represented by a set of 100 parameter vectors, defined and described in more detail in Appendix A. The parameter distributions were derived from the simulations described in **?**, where the model is calibrated and validated with site level measurements from 10 different evergreen needleleaf forests throughout the boreal zone (including Hyytiälä and Sodankylä). In order to avoid confusion with the climate models, the model uncertainty will be henceforth referred to as parameter uncertainty~~, which is the dominant vegetation type on the study sites.

The JSBACH model initial state was derived from the end state of several thousand year long regional simulations that equilibrate the soil carbon storages. In addition, the simulations included a simulation specific spin-up period of 20 years to ensure adequate site level LAI and soil water storages. The spin-up was achieved by running the model through the first 20 years of simulation data, saving the state of the model variables and using them as the initial state for the 120-year long simulations. This type of spin-up introduces a discontinuity between the initial state and the driving climate but differences in the examined climate indicators should be negligible.

2.4 The PREBAS model and management actions

PREBAS (**???**) is a simplified forest carbon and water balance model, which also considers forest growth and management. It calculates photosynthesis (GPP) using a light-use-efficiency (LUE) approach and ambient CO_2 concentration (**??**). Daily

GPP is influenced by soil moisture, radiation, temperature, vapour pressure deficit and precipitation. The model also calculates evapotranspiration (ET) and updates the water balance daily. Mean tree growth is calculated from GPP and respiration at an annual time step, and growth is allocated to different tree organs under assumptions on tree structure (**?**). The model includes tree mortality due to crowding. The growth module annually updates the canopy leaf area index (LAI) for the GPP and ET estimation. In order to estimate soil carbon, the annual litter fall is calculated by the growth allocation module, and fed to Yasso07 soil carbon model (**??**). NEE is calculated annually.

In addition to weather data, PREBAS requires information about the initial state of the simulated forest, defined as soil fertility class, stand basal area, mean height and mean diameter, at an appropriate spatial resolution. This information was extracted from the multisource forest inventory data maps (**??**). The forest resource maps have a 16 m resolution and report the forest data for the year 2015. The model was initialised with forest data extracted for an area of 8×8 km square centered at the eddy covariance towers of Hyytiälä and Sodankylä.

~~In this study, two management scenarios~~ Two management actions were used in PREBAS simulations. The business as usual (BAU) scenario follows present forest management recommendations in Finland (**?**), where trees have to be at least 24–30 cm diameter at breast height (dbh; 130 cm) and of age from 60–100 years before harvesting. The delayed ecosystem logging (DEL) scenario aims for the near term carbon sink increase by increasing the minimum harvesting diameter to 36 cm dbh.

2.5 Ecosystem indicators ~~of climate changes~~and result analysis

We study the uncertainty sources related to key biophysical and biogeochemical indicators and their future development. ~~Thus we ran the JSBACH and PREBAS models with different combinations of climate, RCP and management (only for PREBAS) scenarios with each realisation of the model parameterisations, resulting in approximately 2 000 site specific simulations for JSBACH and 6 000 for PREBAS. These simulations~~ All simulations, depicted in Table 1, produced daily variables that were used to calculate ~~the ecosystem indicators of climate change,~~ ecosystem indicators that are presented in Table 2. We have included details on how we calculated the derived variables (number of dry days, start and end days of growing season and snow melting period) in Appendix B.

~~Ecosystem indicators derived from the recorded values of the JSBACH and PREBAS simulations, separated into groups for the canonical correlation analysis. The group names relate to biomass distribution, ecosystem carbon exchange, length of the growing season, water cycle and snow melting period.~~

2.6 ~~Analysis of results~~

We analyse the results by producing means, standard deviations and correlations of the model variables. This analysis is based on the annual values or averages over certain months (e.g. summer soil water) – one value per year. We utilise the ~~Mann-kendall~~ Mann-Kendall test (**??**) to verify the existence of trend lines and kernel density estimation (KDE) to visualise the distribution of values (this approach can be viewed as a smoothed histogram).

We also carried out canonical correlation analysis (CCA) to quantify the impact of the different factors on the ecosystem indicators. The factors in this analysis are parametric uncertainty (par), climate models (clim) and RCP scenarios (rcp) for

Table 2. Ecosystem indicators derived from the recorded values of the JSBACH and PREBAS simulations, separated into groups for the canonical correlation analysis. The group names relate to biomass distribution, ecosystem carbon exchange, length of the growing season, water cycle and snow melting period.

Indicator	Abb.	Units	JSB	PRE	Group
basal area	BA	m^2 / ha		x	Biomass
stand volume	V	m^3 / ha		x	Biomass
harvested volume	Vharv	m^3 / ha		x	Biomass
volume of dead trees	Vmort	m^3 / ha		x	Biomass
tree biomass	Biom	kg(C)		x	Biomass
tree litterfall	Lit	kg(C)		x	Biomass
leaf area index	LAI	m^2 / m^2		x	Biomass
gross growth	Growth	m^3 / ha		x	Biomass
gross primary production	GPP	g(C) / m^2 day	x	x	Carbon
net primary production	NPP	g(C) / m^2 day	x	x	Carbon
net ecosystem exchange	NEE	g(C) / m^2 day	x	x	Carbon
respiration (autotrophic)	R_{at}	g(C) / m^2 day		x	Carbon
respiration (ecosystem)	R_{eco}	g(C) / m^2 day	x		Carbon
soil carbon	Csoil	kg(C)		x	Carbon
start of growing season	SOS	DOY	x	x	Growth
end of growing season	EOS	DOY	x	x	Growth
length of growing season	VAP	days	x	x	Growth
evapotranspiration	ET	mm / day	x	x	Water
annual soil water	aSW	mm		x	Water
summer soil water	sSW	mm	x	x	Water
number of dry days	Ddry	days	x		Water
albedo	alb		x		Snow
snow amount	snow	m	x		Snow
start of snow melt	melt	DOY	x		Snow
snow clear date	clear	DOY	x		Snow
length of snow melt	SM	days	x		Snow

JSBACH and additionally management scenarios (man) for PREBAS. The indicators were averaged and divided into four consecutive 30-year long periods for both models: 1980-2009 (p1, reference), 2010-2039 (p2, interim), 2040-2069 (p3, mid-century) and 2070-2099 (p4, future). This produced single indicator values for each period and simulation (single instance of each factor) that were calculated for both sites separately.

CCA is a multivariate extension of correlation analysis that allows identifying linear relationships between two sets of variables (**?**). We summarise the CCA results with the use of the redundancy index (Rd) that expresses the amount of variance ~~of~~ in a set of variables ~~explained by another set of variables~~ (ecosystem indicators) by CCA uncertainty factors) (**???**). In essence, the redundancy index takes into account both correlation and variance between uncertainty factors and ecosystem indicators. The value $R_d \in [0,1]$, where a higher value indicates that the factor explains more of the uncertainty related to a given indicator (group). There are no general guidelines for the interpretation of the R_d values. Therefore, we examine the resulting indices in relation to one another to reveal relative uncertainties. The details of the CCA and the redundancy index are given in ~~appendix~~ Appendix C.

3 Results

Forest management was the most dominant factor of uncertainty for Hyytiälä (Fig. 1) throughout the simulation. There was a clear difference for Sodankylä, where management gains only half as much influence. Disregarding management, the climate models and RCP scenarios represent major sources of both JSBACH and PREBAS predictive uncertainty. The impact of climate models was dominant during the reference and interim periods and remained roughly constant over time. The importance of RCP scenarios increased towards the end of the simulations, catching up to management impact at Hyytiälä in mid-century and representing the most important factor during the last period. The parametric uncertainty was the least influential factor for both JSBACH and PREBAS, at both sites. We will next examine the grouped indicator results.

~~Redundancy indices calculated separately for the different indicator groups.~~

3.1 Biomass distribution

The site-level differences in biomass stock uncertainties largely arise from the management actions (Fig. 2 and 3) and the management and RCP scenario impacts reflect the redundancy indices calculated with all ecosystem indicators (Fig. 1) for PREBAS. The RCP scenario influence increases for both sites towards the end of the simulations and the climate model and parameter uncertainty is negligible for both sites and all periods. There is an anomaly for Sodankylä reference period, where management has a very large impact. This situation arises due to minimal (0.1 m^3/ha), but systematic difference in harvested volume – the difference is so small it is not visually evident (Fig. 3). The rest of the Sodankylä reference period variables are nearly identical, so the small change in harvesting results in high correlation, which is captured by the CCA.

The differences in site-specific variables due to the management actions, can already be seen from the reference period indicators (Fig. 3). The ~~DEL~~ delayed ecosystem logging (DEL) scenario has approximately 10 % larger stand volume than ~~BAU~~ business as usual (BAU) for Hyytiälä, but there is practically no difference for Sodankylä. The management actions start to have a noticeable impact for Sodankylä simulated variables at mid-century, but this impact is much smaller than that of the RCP scenarios. The management effect is much more pronounced at Hyytiälä, where both actions follow separate pathways.

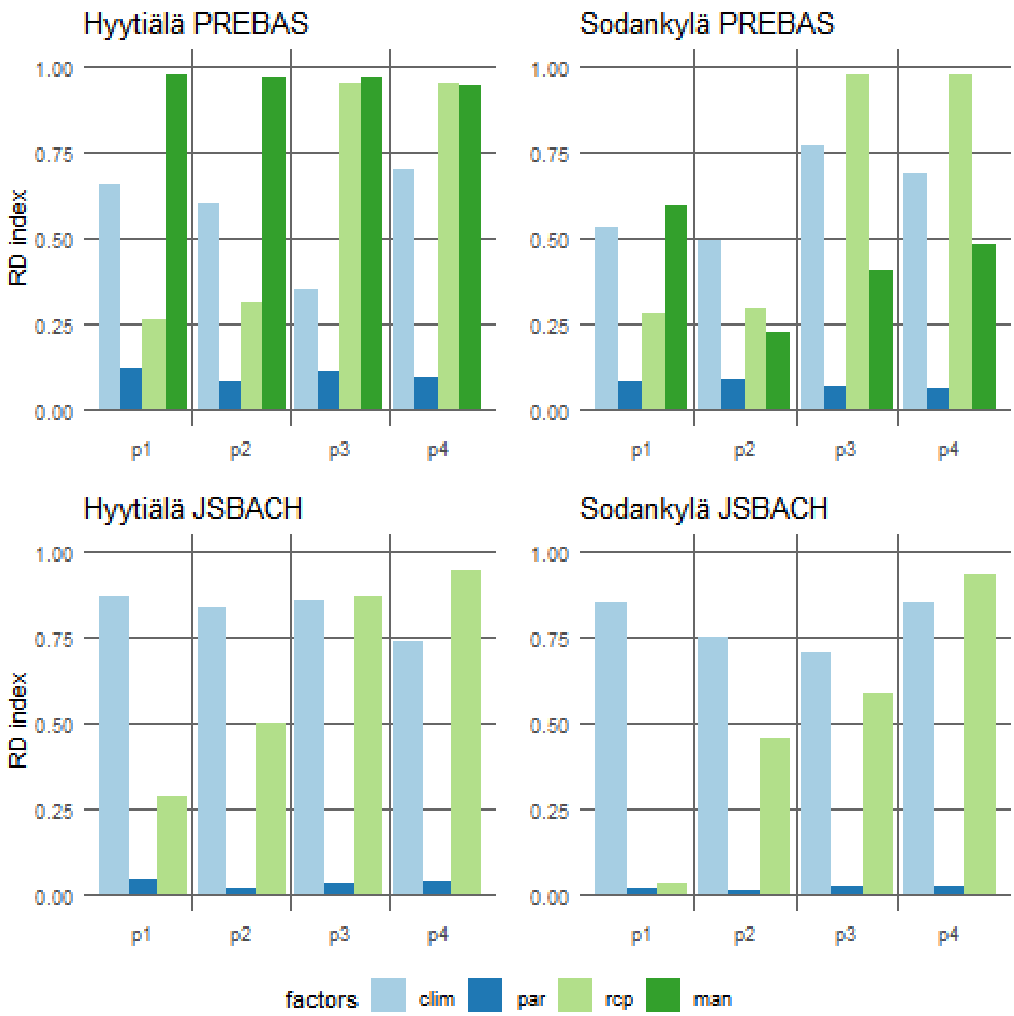

Figure 1. Redundancy indices for the different uncertainty factors, calculated using all ecosystem indicators using values from 1980–2009 (p1), 2010–2039 (p2), 2040–2069, (p3) 2070-2099 (p4). Exact values in a supplementary table.

3.2 Ecosystem carbon exchange

The ~~bifurcation of~~ divergence in the annual GPP and respiration in JSBACH illustrates the separation of the RCP scenarios at about the midpoint (2040) in the simulations (Fig. 4). These two variables that comprise the net ecosystem exchange (NEE), have strong temporal linear correlations for both RCP scenarios ($\cancel{r2 \approx 0.95}$$r^2 \approx 0.95$). The respective linear regression lines for GPP [g(C)/m²d] yield an increase of 1.3 and 2.4 (RCP4.5 and 8.5) in 100 years for Hyytiälä and similarly 0.6 and 0.8 for Sodankylä. Likewise, the increases in respiration are 1.6 and 2.6 for Hyytiälä in 100 years and 0.8 and 1.2 for Sodankylä. GPP uncertainty was larger at the beginning of the simulations, but levelled with respiration at the end of the period. Relatively, the increased radiative forcing yields a stronger increase in GPP for Hyytiälä and respiration for Sodankylä. Some of the flux variables, such as Sodankylä GPP (Fig. 4), suggest a bi-modal value distribution in the the last 30 years of the simulations. This is caused by the different climate models yielding separate modes to the otherwise nearly identical value distributions. Most of the GPP and respiration value distribution (Fig. 4) reflect the variation in model parameterisations. This variation is not the parameter uncertainty, which is reflected in how the value distribution changes over time (after removing the effects of the climate models and RCP scenarios).

As the ~~bifurcating~~ diverging GPP and respiration fluxes signal, the RCP scenarios were important sources of uncertainty for the ecosystem carbon exchange variables at both sites, with importance growing over time (Fig. 2). However, it is noteworthy that management induced uncertainty for ecosystem carbon exchange was the most influential factor for Hyytiälä when it is accounted for in the model. The Sodankylä flux variation seems to be only dependent on the RCP scenario for both models, while the climate models were the most important factors at Hyytiälä during the first two periods for JSBACH.

3.3 Ecosystem seasonality

The seasonal indicators depict the length of the vegetation active period and the snow melting period as well as the amount of soil water (and the recurrence of summer drought). The CCA analysis (Fig. 2) indicates that growing season indicators respond to changes in both climate models and RCP scenarios for both models, but the indicators are not sensitive to management actions. The snow melting period uncertainty for JSBACH is dominated by the climate models for the first half of the simulations for Hyytiälä, after which the RCP scenario is more influential. The situation is a bit different for Sodankylä snow melt, where the climate model uncertainty reduces radically after the reference period and then remains the same – the RCP scenarios gain effectiveness as simulations progress and reach the climate model influence at mid-century. The uncertainty related to the water balance for JSBACH is not ~~explained by any of the examined factors~~ captured by CCA and the uncertainties for PREBAS are also low.

The vegetation active period is lengthening at both sites (Fig. 5). The displacement of the trendline start of (vegetation active) season (SOS) for JSBACH is approximately -8.1 days in 100 years for Hyytiälä (-11.3 for RCP8.5) and -7.6 days for Sodankylä (-10.9). Likewise, the end of season (EOS) displacement is 3.3 days for Hyytiälä (5.1 for RCP8.5) and 3.5 days for Sodankylä (5.2). The SOS and EOS temporal correlations are typically strong ($r^2 \approx 0.8$). The increase to the length of VAP is very similar for both sites, regardless of the different annual GPP.

The Mann-Kendall tests report a decreasing trend (earlier occurrence) for start of the snow melting period, first snow-free date and the length of the snow melting period (Fig. 6) in all simulations, except for Sodankylä RCP8.5 where the Mann-Kendall signifies the absence of trend for the melting period length. The simulations indicate that at the end of the century, the annual amount of snow in Hyytiälä will be radically diminished, and that Sodankylä winters will be similar to present day Hyytiälä winters (especially in the RCP8.5 scenario). Relatively, the first snow free date is catching up to the start of the snow melting period (Fig. 6). The snow starts to melt approximately 20.7 days earlier in 100 years time for Hyytiälä RCP4.5 and 24.9 days earlier in RCP8.5, whereas the snow free dates appear 29.8 days (RCP4.5) and 41.7 days (RCP8.5) earlier. The corresponding values for Sodankylä are 12.2 (RCP4.5) and 25.1 (RCP8.5) for the start of snow melting period and 20.0

(RCP4.5) and 28.2 (RCP8.5) for the snow free dates. The correlations vary widely: $r^2 \approx 0.7$ for snow free dates, $r^2 \approx 0.5$ for the start of the melting period and $r^2 \approx 0.2$ for their difference.

The initial distributions of the summertime soil moisture values (Fig. 7) are unimodal for Hyytiälä and bimodal for Sodankylä for all climate models. This structure is still evident for the RCP4.5 scenario (of the last 30 years) but breaks down for the RCP8.5. Moreover, Hyytiälä RCP8.5 demonstrates some bimodality for two of the climate models whereas the RCP8.5 for Sodankylä seems to be losing the bimodality and is becoming (in appearance) more similar to the Hyytiälä reference period. The ~~model parameterisations result in highly similar soil moisture distributions for~~ soil moisture value distributions are nearly identical for all climate models at both sites during the reference period, but there are clear differences (distribution modes and shapes) for the last 30 years.

The averaged drought events (Fig. 8) seem to be repeating at a roughly constant rate although the different model parameterisations result in wide soil moisture distributions (Fig. 7) at the end of the simulations. The average cumulative values correspond reasonably well with the drought indicator threshold in Appendix B1 (5 % of 92 summertime days, accumulated for 120 years would result in 552 days). The temporal correlations for the individual climate model and RCP specific simulations is poor ~~(r^2 ranging from 0.12 to 0.5~~ – Mann-Kendall test for individual simulations indicated some positive, few negative but mostly no trends (Table 3). The cumulative drought day distributions at the end of the simulations (Fig. 8) are strongly skewed with wide "tails" and high-value outliers (outside the figures) of approximately 2600 drought days for Hyytiälä and 3700 for Sodankylä. Interestingly, one of the climate models (~~brown~~CNRM-CM5) markedly reduces the amount drought days for the RCP8.5 at both sites when compared to RCP4.5. Neither the accumulated drought day variations or those of the soil moisture values (Fig. 7) are reflected in the CCA analysis of the Water group (Fig. 2). This is largely result of low correlation among the simulations.

Table 3. Classification of trends according to Mann-Kendall test in annual drought days for all simulations.

	Hyytiälä	Sodankylä
positive	35.7 %	6.1 %
negative	0.7 %	3.2 %
no trend	63.6 %	90.7 %

3.4 Ecosystem indicator value comparison

The comparison results (Fig. 9) for soil moisture and ET indicate very small changes in the average values for both models but the JSBACH simulations manifest substantially larger variation. The JSBACH model yields more elevated levels of relative GPP, NPP, NEE and ecosystem respiration for Hyytiälä, but the situation is (mostly) reversed for Sodankylä. These differences likely reflect the effect of the management actions and distinct site characteristics. The managements result in clearly different pathways for these variables at Hyytiälä, but only yield small differences at the end of the simulation for Sodankylä.

The SOS is roughly identical for both models, whereas both PREBAS versions have a larger effect on the EOS – initially the EOS for PREBAS occurs much earlier (roughly 15 days) than for JSBACH, which is diminished to a few days at the end of the simulations. The PREBAS extends the VAP more evenly from both "ends", whereas JSBACH focuses more on the SOS. These differences are reflected in the length of the VAP, which is merely the difference between EOS and SOS. Additionally, we note that the largest value spreads (deviations as represented by the length of the "whiskers") appear during the values representing the last 30 years of the RCP8.5 simulations – this merely reflects that the simulation uncertainties are increasing towards the end of the simulation (as expected). Overall, the model responses to the different inputs is very alike, which results in linear dependencies between the variables (Fig. 9).

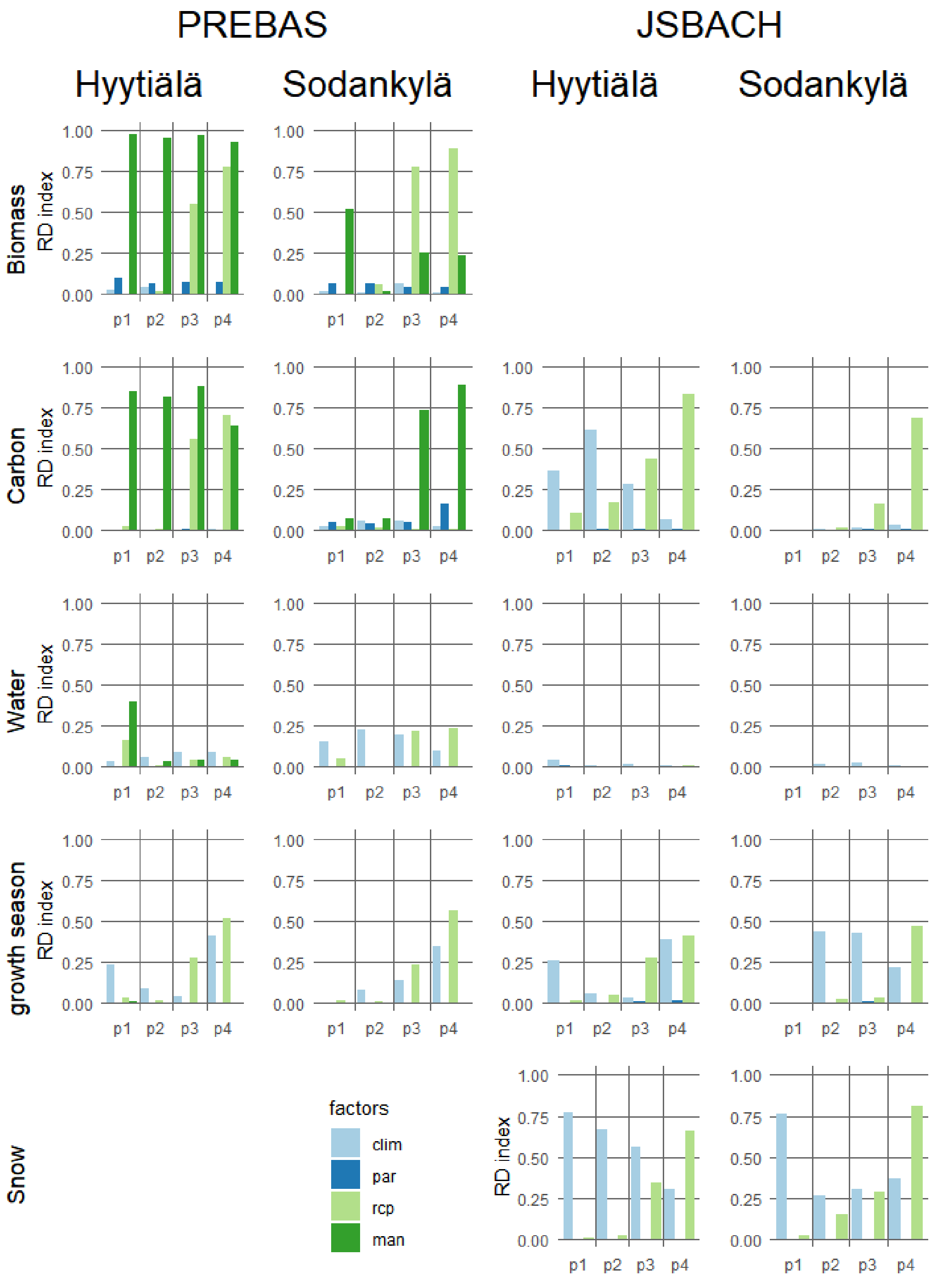

Figure 2. ~~Selected ecosystem indicators from the PREBAS biomass factors, averaged~~ Redundancy indices for the ~~30-year long periods. The y-axis "whiskers" at each point represent the point specific~~ different uncertainty ~~: one standard deviation amongst the corresponding simulations. We use lighter shading for the earlier periods~~factors, ~~a different colour~~ calculated separately for the ~~RCP scenarios and a~~ different ~~marker to separate the management actions~~indicator groups using values from 1980–2009 (p1), 2010–2039 (p2), 2040–2069, (p3) 2070-2099 (p4). Exact values in a supplementary table.

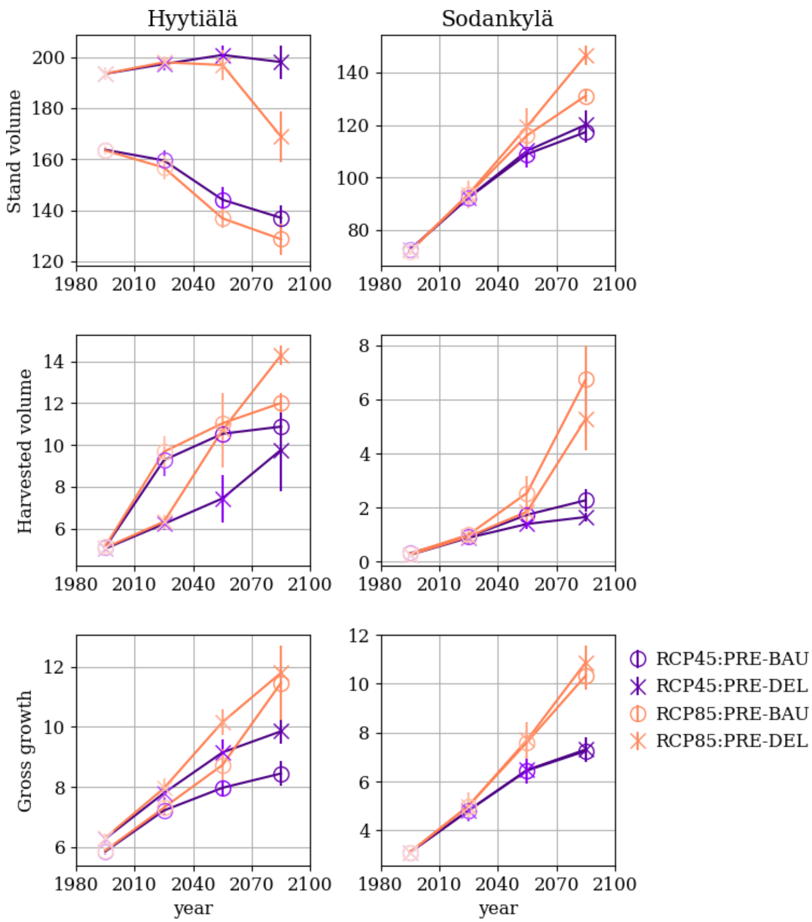

Figure 3. Selected ecosystem indicators from the PREBAS biomass factors, averaged for the 30-year long periods. The y-axis "whiskers" at each point represent the point specific uncertainty: one standard deviation amongst the corresponding simulations. We use lighter shading for the earlier periods, a different colour for the RCP scenarios and a different marker to separate the management actions.

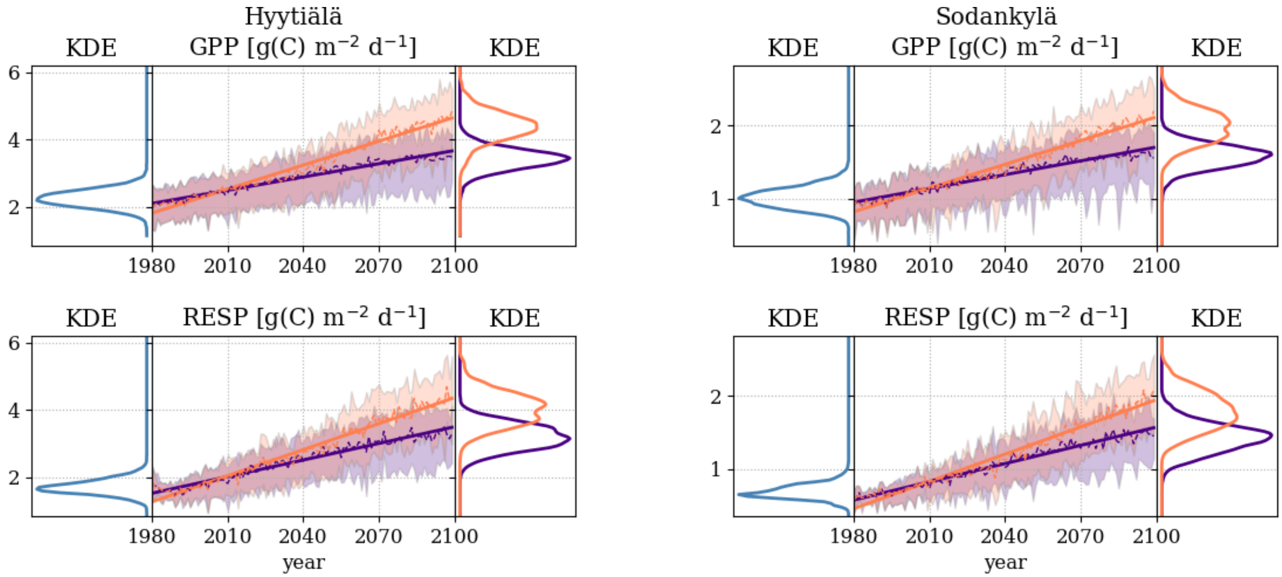

Figure 4. JSBACH predicted annual values of GPP and ecosystem respiration for RCP4.5 (purple) and RCP8.5 (orange) scenarios. The shaded area represents all RCP-specific simulations, the dashed line is the annual mean and the solid line is the trend line. The KDE estimates on the left side of each image represents the distribution of the reference ~~päeriod~~ period values of both RCP scenarios (blue), whereas the KDE on the right side consists of RCP specific values from the last 30 years of simulations.

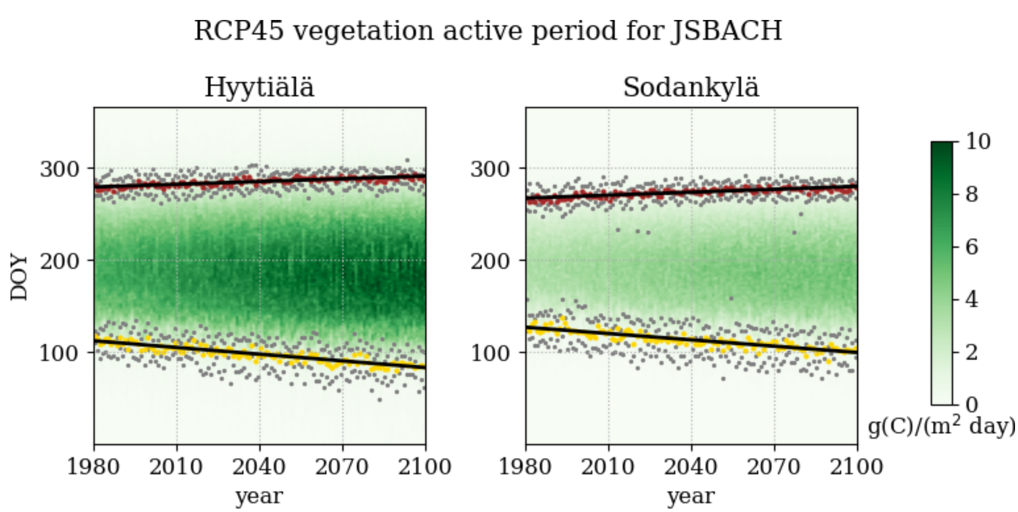

Figure 5. Average vegetation active period for JSBACH RCP4.5; yellow dots are the SOS values, red dots are the EOS values and the grey dots are the minimum and maximum SOS/EOS from all simulations. Also presented are the trend lines and the daily GPP as the green amplitude.

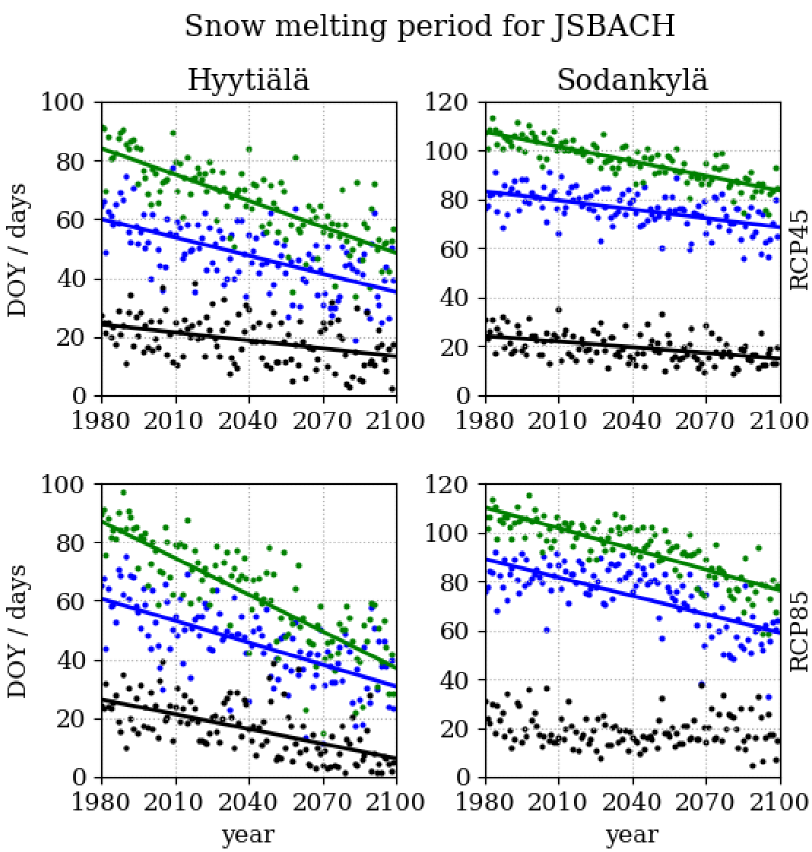

Figure 6. The average snow melting period for the JSBACH model; presented are the average annual values for the start of the snow melting period (blue), the first snow free day of the year (green) and their difference (black) as well as trend lines (calculated from the shown values) for these variables (when applicable).

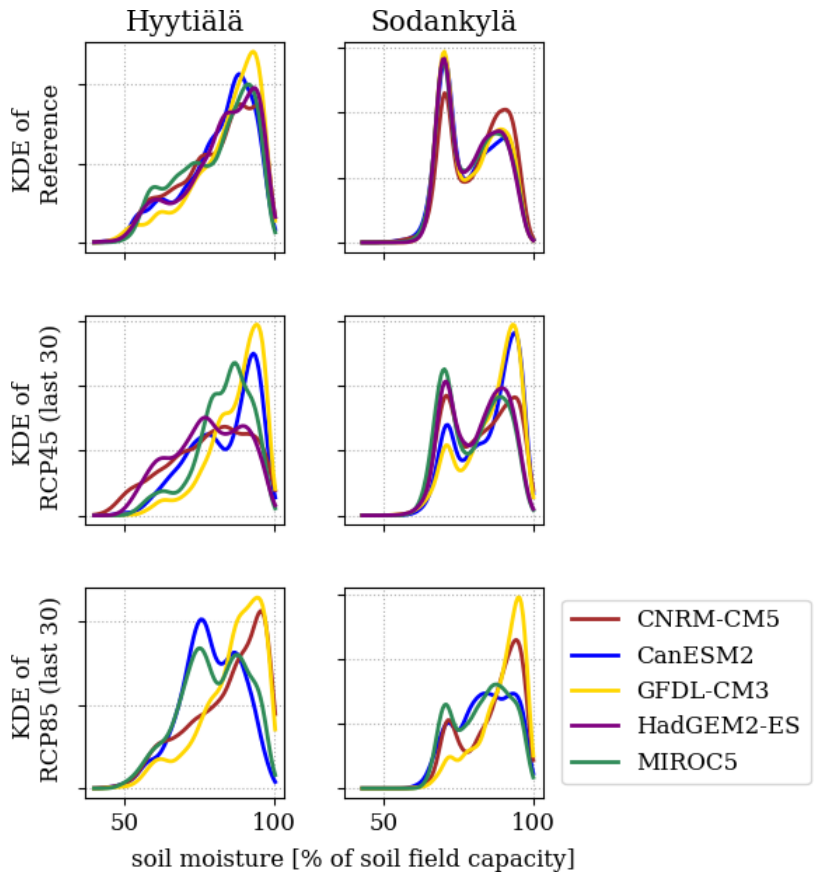

Figure 7. KDE estimates of the JSBACH soil moisture values (relative to soil field capacity) for the reference period and the last 30 years of simulations. Each colour represents the average summertime (June-August) soil moisture, produced with one of the climate models using all parameterisations.

~~Accumulated summer drought days scatter plotted for each climate model, averaged over model parameterisations with minimum and maximum increment visualised as y-axis whiskers. The gray line is the average of the simulations. The KDE estimates on the right side depict the distribution of the accumulated drought days with the different parameterisations at the end of the simulation. The KDE figures have been cut at 1250 accumulated days.~~

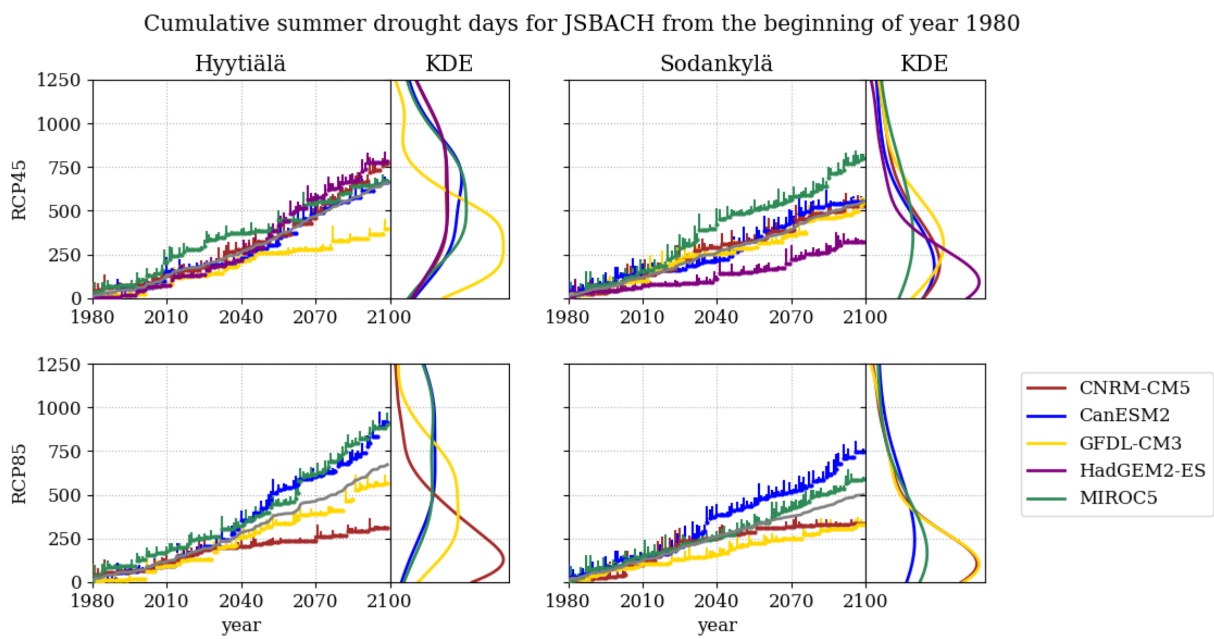

Figure 8. Accumulated summer drought days scatter plotted for each climate model, averaged over model parameterisations with minimum and maximum increment visualised as y-axis whiskers. The gray line is the average of the simulations. The KDE estimates on the right side depict the distribution of the accumulated drought days with the different parameterisations at the end of the simulation. The KDE figures have been cut at 1250 accumulated days.

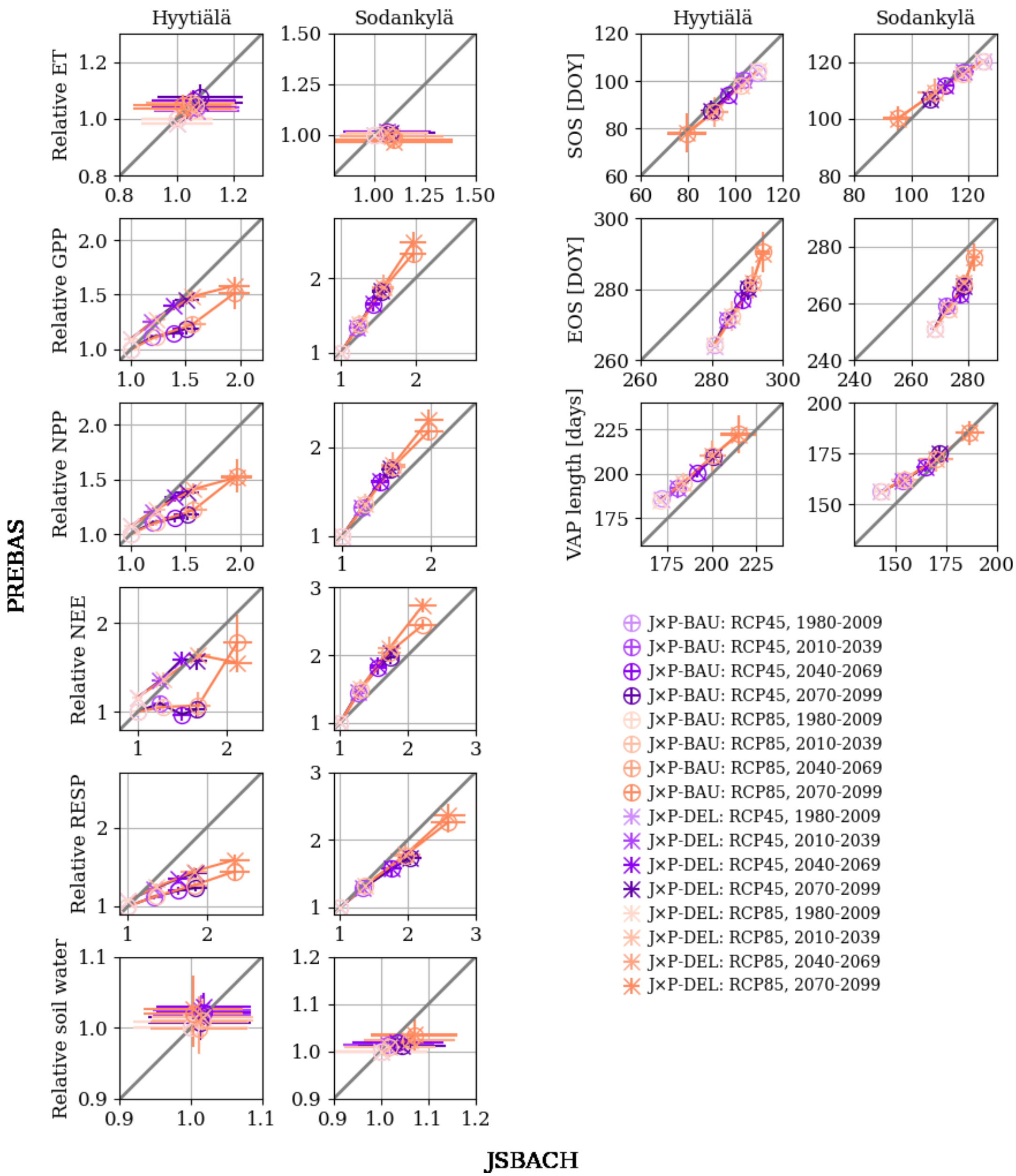

Figure 9. Average simulated values for shared ecosystem indicators between JSBACH and PREBAS, plotted for each 30-year period and both RCP4.5 and RCP8.5 scenarios. The values for JSBACH are divided by the average of the reference period values, and the values for PREBAS by the average of the BAU scenario reference period values. The “whiskers” at each point represent the point specific uncertainty: one standard deviation amongst the corresponding simulations. We use lighter shading for the earlier periods.

4 Discussion

In this paper we present an assessment on the importance of the different uncertainty sources, simulated on boreal forests for the 21st century. The JSBACH and PREBAS models yield similar uncertainty estimates (Fig. 1) and have a similar response to many of the examined ecosystem indicators ~~of climate change~~ (Fig. 9)~~. The~~ , when we take into account that PREBAS simulations included forest management. Further differences in modelled variables can be explained by the different model structures (e.g. soil moisture and evapotranspiration)~~or the inclusion of PREBAS management actions (ecosystem carbon fluxes)~~. Forest management plays an important role in the estimates of ecosystem variables and their uncertainties. This importance is underscored by the lack of management in many land-surface components of climate models.

4.1 ~~Impact to ecosystems~~Ecosystem indicator sensitivity

According to **?**, the long-term eddy-covariance measurements (1997–2017) at a boreal coniferous forest in Hyytiälä indicate a significant increase of gross-primary productivity (+10.5 [g(C)/m² year]), which is only partly compensated by an increased ecosystem respiration (+4.3g [g(C)/m² year]). As a result, the annual CO_2 sink has increased by about 6.2 [g(C)/m² year]. The GPP increase is dominated by an increase in LAI (from 4.1 to 4.6), while rise in the atmospheric CO2 concentration (from 360 ppm to 410 ppm) contributes only about 10 % to the rising GPP trend (**??**). It has to be noted that Hyytiälä forest was thinned in 2002, temporarily reducing LAI to 3.4. However, in few years the forest recovered to similar steadily increasing LAI trend than before thinning. The observed rise in the GPP is better replicated by the RCP8.5 scenario (Fig. 4) that yields an increase of +8.8 [g(C)/m² year] for Hyytiälä; whereas the increase in ecosystem respiration is more closely reproduced by the RCP4.5 scenario (+5.8).

The RCP scenarios have a strong impact for growing stock and wood harvesting (Fig. 3), but the effect pales in comparison to the examined management actions. This underlines the importance of proper forest management for provisioning services (**??**). This is illustrated by the relative NEE pathways (Fig. 9) that are roughly ~~convex~~ concave for BAU and ~~concave~~ convex for DEL management actions. The simulations also indicate linearly lengthening VAP (Fig. 5), with high variation towards the end of the simulations (Fig. 9). This can be interpreted as beneficial for nature tourism and recreational activities, but on the other hand are the adverse effects of shortened snow melting period (Fig. 6) and potentially increased droughts (Fig. 8), also investigated by **?**. These effects are also detrimental for winter harvesting and wood quality, as suggested by **?**.

? reported lengthened snow melting periods for some regions in Finland for 1982–2016. We analysed the reference period (1980–2009) snow melt in more detail and found that roughly 30 % of parameter specific simulations for Hyytiälä, and 20 % for Sodankylä, resulted in increased length for the snow melting period. We note that our simulations are restricted to site level, whereas regional experiments include lakes, rivers etc. that can significantly affect the outcome – this type of an uncertainty source is not considered in our simulations.

4.2 Simulation uncertainty sources

The overall uncertainty associated with the management actions differs for Hyytiälä and Sodankylä (Fig. 1). This is due to the more abundant harvesting effect at Hyytiälä (Fig. 3), whereas most of the biomass in Sodankylä is left to grow. Sodankylä stand volume increases as simulations progress whereas Hyytiälä stand volume remains the same or even decreases for the BAU scenario. This underlines the importance of proper forest management, as the impact of these relatively similar actions is strong – especially when taken into context of e.g. clear cuts.

As expected, the uncertainty related to the RCP scenarios increases systematically (**?**) for all ecosystem indicators and grouped variables (except for the Water group) as the simulations advance further in time. This is similar to results by **?**. The RCP scenarios are the most dominant factor in explaining the JSBACH and PREBAS uncertainties for both sites at the end of the simulations. The RCP uncertainty also dominates the Carbon, Growth and Snow variables at both sites and Biomass variables for Sodankylä. The RCP scenarios tend to gain effect at mid-century (e.g. Fig. 3), although there are some earlier affects, e.g. snow variables for Sodankylä (Fig. 6).

The effect of the climate models to the redundancy indices is the most varied among the examined uncertainty sources. The climate models tend to have more impact in the two earlier periods, although the overall climate model uncertainty remains roughly the same throughout the simulations. This can be seen ~~as arising from~~ to reflect the internal variability of the climate system (**?**) and the consequent variation in the climatic drivers. The combined variation of climate models and model parameters may not be fully captured due to non-linearity within the simulated variables. This is noted to emphasise the importance of the parameter uncertainty, as stated by **?**. The parameter uncertainty is expected to be small when compared to the selected RCP scenarios that have a significant impact on the ecosystem (see **?**, Fig. 2). Most of the ~~examined parameter distributions~~indicator value distributions, induced by the parameterisations, are highly alike for all climate models (Fig. 4), especially during the reference period (Fig. 7). The combined climate model and parameter uncertainty is on par with the RCP scenario uncertainty towards the end of the simulations (Fig. 1).

4.3 Validity of estimates

The JSBACH model calibration (**?**) was originally used in comparison of various submodel components (stomatal conductance functions) and the PREBAS calibration (**?**) utilised permanent growth and yield experiments. Both of these examinations rely on hindcasting with relatively recent meteorological measurements or datasets, and the resulting parameter distributions emulate the current climate conditions well. The ~~examined~~ JSBACH model was calibrated with data throughout the boreal zone and the parameterisations can be viewed as to be representing all evergreen coniferous forests where as the PREBAS model was extensively calibrated for the whole of Finland. The sites in this study are representative of southern and northern boreal pine forests and the ecosystem indicators were ~~also~~ chosen to reflect the calibrated parameters and processes. We note that model calibration and the parameter distributions also compensate and reflect for missing and imperfectly modelled processes.

The CCA analysis and model comparison focuses on the relative differences in the ecosystem indicators, and thus less importance is given to the absolute indicator values. The CCA analysis only accounts for linear dependencies (**?**) between the input and output uncertainties, and even though the redundancy index (**?**) considers the (correlated) variance between the variables, the nonlinear effects may be underestimated. We reduce the annual variation and linearise the variables by averaging and separating them into four consecutive 30-year long periods. Additionally, we also examined the PREBAS redundancy indices without the RCP2.6 – these results differ only marginally from those with the RCP2.6 included, which increases the validity of the JSBACH results.

This linearisation may not be enough to capture all variation, as is the case with the JSBACH Water group uncertainties (Fig. 2) and the wide spread of soil moisture values (Fig. 7) and cumulative drought days (Fig. 8). The different parameterisations and climate models have a prominent variation, but due to adverse effects the correlations remain small. For example, the RCP8.5 radically increases precipitation (see **?**, Fig. 2) and therefore increases the soil moisture (Fig. 7) and reduces the amount of drought days (Fig. 8). The strength of this effect varies among the climate models, but the model parameterisations still enable even radical increases to the number of drought days. This major source of uncertainty, investigated by e.g. **?**, is not captured by CCA. However, when the indicators are reasonably correlated (as is the case for most of the presented indicators), the ~~estimates are reliable~~CCA method is applicable.

The CCA analysis was performed for indicator groups to ensure robustness of the approach – this was not successful in every case, as a minimal but systematic difference in Sodankylä reference period harvested volume led to a large management scenario impact (Fig. 2). The situation arises as all of the other indicator values were nearly identical and thus a small systematic change that was relatively large, had high correlation and impact in CCA. This event was not replicated with the other groups.

5 Conclusions

~~Our~~ Although this study is limited to only two sites, our simulations indicate that the management actions have the greatest influence to simulated ecosystem indicators ~~of climate change. A similar impact is achieved by the RCP scenarios towards~~ in Finland. When taken into account that the considered management actions are very alike, more emphasis should be given to forest management when simulating future ecosystem conditions. Towards the end of century, the RCP scenarios achieve a similar impact as the management actions. The combined climate model and parameter uncertainty is also an important factor for the whole duration of the simulations due to internal variability of the climate system, but these effects can be easily underestimated due to non-linear or adverse effects. The examined uncertainties are comparable for both models.

Long-term measurements and simulations indicate considerable increases to GPP and ecosystem respiration, with a slightly larger emphasis respectively for the southern and northern boreal forests. While the effect of management to these variables is linear, the impact on NEE is more complex and would be of interest in further studies. The snow melt is occurring several weeks earlier in all simulations and the length of the snow melting period appears to be decreasing, although the results for Sodankylä are not conclusive. Similarly, the length of the vegetation active period is expected to increase linearly for both sites by a few weeks. Sodankylä soil moisture is expected to increase, while the effects for Hyytiälä are varied. The scenarios do not constrain the recurrence of drought as the parameterisations enable varied outcomes.

We have successfully estimated the roles of different uncertainty sources on overall ecosystem indicator sensitivity at representative boreal forest sites. The study provides material to steer further analysis to relevant uncertainty sources as well as justification to further examine the effect of forest management. The analysis of results is based on CCA that is able to capture the uncertainties when the outputs are correlated. The linearity assumptions in CCA limit its applicability, so other methods e.g. random forest as in **?** should also be consider in cases with highly non-linear variables. The uncertainty analysis would also benefit from a larger model ensemble with different model process implementations. In such a case, instead of different model parameterisations, the factorial design could be extended to include different model components or parameterisations representing different functionalities or local management practices. This would still keep the number of simulations reasonable while allowing a robust uncertainty estimation.

Code and data availability. The underlying JSBACH model version (branch: cosmos-landveg-tk-topmodel-peat, revision: 7384) can be obtained from the Max Planck Institute for Meteorology (MPI-M), where it is available for scientific community under the MPI-M Software License Agreement (http://www.mpimet.mpg.de/en/science/models/license/). The model modifications have been uploaded to Github, and they can be accessed by contacting the authors at jarmo.makela@fmi.fi. The R package (Rprebas), containing the PREBAS model, is available on GitHub (https://github.com/checcomi/Rprebas). The periodically averaged indicator values as well as the redundancy index values in Fig. 1 and 2 are available as supplements.

Appendix A: Model parameters

~~The~~ Pre-existing JSBACH and PREBAS model ~~uncertainties are represented by a~~ calibrations (??) were deemed suitable to represent parameter uncertainties in the simulations described in this paper. A set of parameter ~~vectors (available as supplements). The different parameters and their distribution means and deviations are given in Tables A2 and A1~~values was extracted from the model calibrations to preserve parameter interdependence. The PREBAS parameter values were ~~evenly sampled~~ drawn at fixed intervals from the MCMC chains in ?. ~~The JSBACH parameter values were taken from the~~ This is a standard approach that results in an approximation of the parameter posterior distributions. The JSBACH calibration was done with adaptive population importance ~~sampler~~ sampling (APIS)~~simulations using the Bethy stomatal conductance formulation in ?. The bulk of these (100) vectors consists of APIS location parameters at 20 iterations~~, which produces a posterior estimate at each iteration. The estimate at 20-iterations (40 ~~samples)~~ parameter combinations) was complemented with 15 additional combinations at each of 40, 60, ~~which are complemented by later draws to reflect the sampling process~~80 and 100 iterations. All parameter descriptions, as well as sample means and deviations are given in Tables A1 and A2.

~~JSBACH model parameter descriptions as in ? with distribution mean and standard deviation.~~

Appendix B: Calculation of ecosystem indicators

Most of the ecosystem indicators in this paper are directly produced by the models, but few are derived from other variables.

B1 Drought days

The drought days are calculated as the amount of days when average soil moisture (of the combined 2nd and 3rd soil moisture levels in a 5-layer JSBACH scheme) is below a certain threshold. Only summertime (June, July, August) values are used and the threshold for Hyytiälä was set as the 5th percentile of all soil moisture values during the reference period. This value is approximately 33 % of the soil field capacity in Hyytiälä, which compares well with the parameters θ_{tsp} and θ_{pwp} for the Hyytiälä drought period optimisation in (?). Thus, the number of dry days is a reasonable measure for Hyytiälä. We used the same percentile to set a similar value for Sodankylä although the site characteristics differ (different soil compositions and field capacity etc.).

B2 Vegetation active period

The dates for the start of season (SOS) and end of season (EOS) for the vegetative active period are calculated from simulated daily GPP. First we extracted the value corresponding to the 90th percentile of the daily GPP, from all of the simulations during the reference period, and then multiplied this value by 0.15. The SOS date is considered to be the first day of the year (DOY), when the daily GPP is consistently above this threshold. The consistency here means that, when we consider the daily GPP values, starting from the 30th DOY, to twice as far as the date of the SOS event, the GPP must be above the threshold for at least half of the days. The date for EOS is calculated similarly, when GPP is below the threshold and starting from 230th DOY.

Table A1. JSBACH model parameter descriptions as in ? with distribution mean and standard deviation.

Parameter description (units)		μ	σ
Farquhar model maximum carboxylation rate at 25 °C (μmol (CO_2) m^{-2} s^{-1})	$V_{\mathrm{C,max}}$	42.8	1.94
Farquhar model efficiency for photon capture at 25 °C.	α	0.30	0.013
Multiplier in momentum and heat stability functions.	c_{b}	4.9	0.7
Ratio of unstressed C3-plant internal/external CO_2 concentration.	f_{C3}	0.81	0.025
Exponential scaling of water stress in reducing photosynthesis.	q	0.65	0.19
Volumetric soil water content above which fast drainage occurs.	θ_{dr}	0.79	0.09
Fraction depicting relative surface humidity based on soil dryness.	θ_{hum}	0.23	0.02
Volumetric soil moisture content at permanent wilting point.	θ_{pwp}	0.19	0.03
Volumetric soil moisture content, above which transpiration is unaffected.	θ_{tsp}	0.43	0.1
Fraction of precipitation intercepted by the canopy.	p_{int}	0.29	0.04
Depth for correction of surface temperature for snow melt (m).	s_{sm}	0.05	0.025
Maximum water content of the skin reservoir of bare soil (m).	w_{skin}	2.7×10^{-4}	7.3×10^{-5}
LoGro-P: memory loss parameter for chill days (days).	C_{decay}	15.7	5.3
LoGro-P: minimum value of critical heat sum (°C d).	S_{min}	18.0	6.4
LoGro-P: maximal range of critical heat sum (°C d).	S_{range}	189.0	49.9
LoGro-P: cutoff in alternating temperature (°C).	T_{alt}	6.0	1.8
LoGro-P: memory loss parameter for pseudo soil temperature (°C).	T_{ps}	15.8	5.3

B3 Snow melting period

The snow depth in model simulation varies on a year-to-year basis. We also encounter some years without any snow cover for Hyytiälä. Hence we first aggregate the snow depth over the model parameterisations and climate model simulations to produce average site and RCP scenario specific time series. This approach yields robust estimates of the snow cover, where the actual time series is smooth enough to allow calculation of the beginning of snow melting period and the first snow free date. We take a similar approach as in Manninen et al. (2019) and fit a sigmoidal function to identify the starting date of snow melt. The snow is considered to have melted, when the snow cover has consistently vanished. This means that there is no snow cover for at least half of the days during ±10 days of the snow clear date.

Table A2. PREBAS model parameter descriptions as in **?** with distribution mean and standard deviation.

		pine		spruce		birch	
Parameter description (units)		μ	σ	μ	σ	μ	σ
Maintenance respiration rate of foliage (kg(C) kg^{-1}(C) yr^{-1}).	$m_{\mathrm{F,ref}}$	0.2	0.003	0.2	0.005	0.3	0.061
Maintenance respiration rate of fine roots (as above).	$m_{\mathrm{R,ref}}$	0.23	0.023	0.24	0.036	0.33	0.064
Maintenance respiration rate of sapwood (as above).	$m_{\mathrm{S,ref}}$	0.03	1.4×10^{-4}	0.03	3.0×10^{-4}	0.03	1.4×10^{-3}
Growth respiration rate (as above).	c	0.29	0.005	0.25	0.023	0.24	0.027
Leaf longevity (yr).	$\nu_{F,\mathrm{ref}}$	4.0	0.02	9.7	0.27	1.1	0.09
Fine root longevity (yr).	ν_{R}	0.9	0.03	1.7	0.07	1.2	0.19
Homogeneous extinction coefficient.	k_{H}	0.25	5.4×10^{-4}	0.25	8.8×10^{-4}	0.31	9.7×10^{-3}
Specific leaf area (m^2 kg^{-1}(C)).	s_{LA}	20.0	0.036	20.1	0.072	41.0	2.94
Parameter relating to reduction of photosynthesis with crown length.	s_1	0.011	6.1×10^{-4}	0.006	9.7×10^{-4}	0.031	0.011
Wood density (kg (C) m^{-3}).	ρ_{W}	197	2.82	183	2.48	226	20.9
Ratio of fine roots to foliage.	α_{Rs}	180	0.18	201	0.55	105	4.44
Foliage allometry parameter.	z	1.8	0.020	1.7	0.001	1.9	0.012
Ratio of total sapwood to above-ground sapwood biomass.	β_0	1.28	0.014	1.27	0.018	1.48	0.056
Ratio of mean branch pipe length to crown length.	β_{B}	0.4	4.5×10^{-4}	0.5	8.7×10^{-4}	0.4	0.048
Ratio of mean pipe length in stem above crown base to crown length.	β_{S}	0.39	0.006	0.46	0.007	0.46	0.024
Light level at crown base that prompts full crown rise.	C_{R}	0.22	0.008	0.16	0.004	0.17	0.013
Reineke parameter.	N_0	856	3.0	1040	7.4	998	68.6

Appendix C: Canonical correlation analysis

We carried out canonical correlation analysis (CCA) to quantify the impact of the different factors on the ecosystem indicators. These factors are parametric uncertainty (pars), management scenarios (man), climate models (clim) and rcp scenarios (rcp). CCA is a multivariate extension of correlation analysis that allows identifying linear relationships between two sets of variables (**?**). It's use is similar to multiple regression but it is more appropriate when there are multiple intercorrelated variables such as model outputs. A more detailed description of CCA is provided in (**?**).

We consider two sets of variables, ~~X~~ $X \in \mathbb{R}^{n_f \times s}$ (the different factors) and ~~Y~~ $Y \in \mathbb{R}^{n_e \times s}$ (ecosystem indicators)~~. These are of dimensions N_p and N_q, where N is~~, where n_e, n_f are the number of ~~realisations for the variable and p, q are~~ factors and ecosystem indicators and s is the number of ~~variables~~simulations, presented in Table 1. Each factor $f_i, i \in \{1,...,n_f\}$, or indicator $e_j, j \in \{1,...,n_e\}$, can be interpreted as a row-vector of X or Y, respectively. In CCA we construct ~~the linear composites~~ linear composites of the input factors ($U_1 = a^T X, a \in \mathbb{R}^{n_f}$) and output variables ($V_1 = b^T Y, b \in \mathbb{R}^{n_e}$). We choose a,b as to maximise the (canonical) correlation (~~called canonical variates) $U_1 = a^T X$ and $V_1 = b^T Y$ by maximising the correlation between them. The~~ Rc_1) between the composites U_1 and V_1~~form~~:

$$Rc_1 = \text{corr}(U_1, V_1). \tag{C1}$$

This forms the first pair of canonical variates U_1 and V_1. The second pair is formed similarly but it is required to be uncorrelated with the first pair (and so forth for the following pairs). The first pair accounts for the highest amount of variance between the two sets of variables and has the highest canonical correlation (~~Rc~~$Rc_k, k \in \{1,...n_k\}$) – the variance and correlations diminish for each consecutive pair. In our analysis, we use three pairs for JSBACH (n_k=3) and four pairs for PREBAS ($n_k = 4$).

The ~~correlations between the individual variables (factors or indicators) and the respective canonical variates~~ simple linear correlations between an independent variable (f_i or e_j) and a respective canonical variate (V_k or U_k) are called canonical loadings (~~CL), whereas the correlations with the~~ CL_{ik}, CL_{jk}). Similarly, the correlations between an independent variable and its opposite canonical variate (f_i and U_k or e_j and V_k) are called canonical cross-loadings (~~CcL). These loadings are needed to~~ CcL_{ik}, CcL_{jk}). To summarise the CCA results via the use of ~~the~~ a redundancy index (Rd)~~that~~, we need the canonical loadings of the ecosystem indicators (CL_{jk}) and canonical cross loadings of the uncertainty factors (CcL_{ik}).

$$Rd_{ik} = \frac{1}{n_e}\sum_{j=1}^{n_e}(CL_{jk}^2)Rc_k^2. \tag{C2}$$

The redundancy index (Rd_{ik}) expresses the amount of variance ~~of~~ in a set of variables (ecosystem indicators) explained by another set of variables (uncertainty factors) (**???**).

$$\cancel{Rd_{iv} = \frac{1}{n_i}\left(\sum(CL_{iv}^2)\right)Rc_v^2}$$

~~Above i is a placeholder for one of the two sets of variables, factors (f) and ecosystem indicators (e) ; v indicates a canonical variate; n_i is the number of variables in the i-th set and Rc are the canonical correlations.~~

The square of the canonical loadings (CL_{jk}) expresses the proportion of variance accounted for each variable – computing the average for each variate provides an indication of the overall variability explained by the variate. The squared ~~Rc~~ Rc_k represents the variance shared by the canonical variates of the two sets of variables~~– it is the bridge between the two sets. The redundancy index can be summed up across the canonical variates to have an overall measure of the bi-multivariate covariation of the two sets of variables.~~

. In our analysis, we wanted to quantify the importance that each factor have on the ecosystem indicator uncertainty (RdF). We quantified the redundancy index of the indicators for each canonical variate and then multiplied it by the squared canonical cross-loadings between factors and variates.

$$RdF_{fvik} = Rd_{evik} CcL_{fvik}^{2} \tag{C3}$$

$\cancel{CcL}$ CcL_{ik} represents the proportion of variance shared between the factors ($\cancel{f}$ f_i) and the canonical variates of the ecosystem indicators ($\cancel{e}V_k$). The ~~RdF of the different factors can be summed up across the variates to obtain the overall weight that each factor has on the ecosystem indicator uncertainty~~overall redundancy and the full weight of uncertainty for each factor f_i are derived by summing over the canonical variates. This produces an overall measure of the bi-multivariate covariation of the two sets of variables.

Author contributions. J. Mäkelä and F. Minunno are respectively responsible for the JSBACH and PREBAS simulations. J. Mäkelä prepared the manuscript, with contributions from all co-authors, whereas F. Minunno provided the CCA and redundancy index calculations and analysis.

Competing interests. The authors declare that they have no conflicts of interest.

Acknowledgements. This work has been supported by Jenny and Antti Wihuri Foundation and the Ministry of foreign affairs of Finland (IBA-ForestFires, PC0TQ4BT-53) as well as the Academy of Finland Center of Excellence (272041), OPTICA (295874), the Strategic Research Council at the Academy of Finland (STN-SOMPA, 312932), ICOS Finland (281255) and MONIMET (LIFE12 ENV/FI/000409).