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Biogeosciences Discussions

Interactive comment on "Effects of shrub cover increase on the near surface atmosphere in northern Fennoscand" *by* Johanne H. Rydsaa et al.

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Firstly, we would like to express our sincere gratitude towards the two anonymous referees for taking the time to review our study, and for the constructive suggestions and comments to improve the manuscript. See point-by-point replies to the comment below (some technical comments are grouped together), answers are given below each cited comment.

Anonymous Referee #1 Received and published: 28 November 2016

"Rydsaa et al. present an interesting investigation into changes to the near-surface atmosphere resulting from vegetation change, with a particular focus on near-surface

temperatures. They use the WRF model to compare simulations where the vegetation extent is (i) based on present day climate distributions, and (ii) relating to a 1K increase in summer temperatures, relative to the current vegetation distribution. The authors also considered the sensitivity of this response to inter-annual variability. Based on the results presented in this manuscript, the authors suggest that tall shrubs are key to a summer warming feedback but that the main impact of shrub expansion is on advancing the onset of snowmelt in the spring, thus inducing a positive feedback to spring temperatures. In terms of inter-annual differences, the authors propose that their results show that the warm summer-tall shrubs feedback is consistent across warm and cold seasons. They finish by proposing that their findings show "a clear potential for a so-called vegetation-feedback tipping point"."

We are glad that the reviewer finds the study interesting. The reviewer has clearly taken the time and effort to get to know our study very well, and we truly appreciate this and the following thorough review of the manuscript.

"In order for this paper to be acceptable for publication in Biogeosciences, the following major revisions are required:

1. Ideas are not always introduced in a logical manner, and the text is frequently hard to follow. Moreover the writing style needs to be more concise to improve clarity and flow of ideas (See detailed line-by-line comments for examples). It would also be nice to see some hypothesis or specific research questions clearly stated in the introduction and these used to structure the subsequent results and discussion. This would greatly facilitate the overall readability and coherence of the work, but will require some major structural changes to the manuscript to be achieved."

As the reviewer suggests, the manuscript will undergo a thorough revision with emphasis on improving the writing style and structure for improved readability. Based on the comments from both reviewers, we realize that the purpose and ideas behind this study should be more clearly presented for the readers. Although as the reviewer

points out, some large structural changes are necessary to achieve this, we agree that these changes to the manuscript are vital to put our study in better context. The reviewer kindly proposes a more clearly stated hypothesis or list of research questions in the introduction, which is a great idea and will be added. A clarification of the primary research questions motivating this study and the corresponding experimental setup is presented below;

1. The warmer climate is causing more shrubs and low trees to grow in the northern Fennoscandia area, how does this feed back to the atmosphere in the region? More specifically: a. How will the feedback be influenced by varying shrub areal extent and shrub heights? b. Which season will be more affected and experience the strongest feedback; spring or summer? c. How sensitive is the feedback to different conditions, such as snow cover or temperatures?

In order to answer these questions, we run a fine scale atmospheric model (WRF) with prescribed and manually altered perturbations to the vegetation cover, and compare the atmospheric response. The perturbations reflect a spatial increase in shrub and tree cover in addition to an increase in shrub heights in some areas. To respond to the research questions in point 1a, the existing shrub cover as described in the model, was split into three sub-categories in order to distinguish the atmospheric sensitivity to varying shrub heights. In two different experiments shrubs and low trees are re-distributed in accordance with some "simplified bioclimatic envelopes" that were derived for this study. Based on an extensive literature review, mean summer temperatures were selected as the key environmental criteria used to guide the perturbations applied to the shrub and tree cover. In order to take into account some of the uncertainties inherit in the shrubs' response to summer temperatures, one bioclimatic envelope is based on present day summer temperatures, and one based on a 1K increase in mean summer temperatures.

In order to answer the research question in point 1b, we chose to focus on spring and summer. This is based mainly on the findings of previous studies, showing that these

two seasons were the ones experiencing the largest atmospheric feedbacks resulting from shrub and tree increase. Furthermore, as the atmospheric response may vary under different climatic conditions (e.g. warm vs. cold, snow rich vs. snow poor, present vs. future), we chose to run each set of vegetation distributions for two contrasting years, spanning the natural variability across a 10-year period with respect to temperature and snow cover in the study region. This setup allows us to investigate how particular conditions influence the vegetation feedbacks (research question 1c), and based on this, to make some careful assumptions regarding what may be expected under future versus present climate conditions.

"2. Central to this work is the assumption that published climate envelopes for vegetation types in Norway are sufficient to predict changes in future vegetation when mean summer temperatures are 1K warmer. However, the authors show significant discrepancies between the present-day vegetation distribution and that expected from the climate envelopes based on present day climate. This suggests that either (i) the climate envelopes are inappropriate, or (ii) the present-day vegetation is out of equilibrium with the present climate – perhaps due to warming that has already occurred. The former case presents obvious difficulties for the use of these climate envelopes. In the second case, it seems somewhat unrealistic that the vegetation will have had time to adjust to the scenario indicated by the climatic envelopes under 1K warming, given the timeframe over which 1K warmer summer temperatures will be achieved. As it stands, this study is limited in how much can be drawn from the 'future' distribution based on the climatic envelopes associated with a 1K increase. There needs to be significantly more discussion of the limitations of using climatic envelopes and justification of their use."

As pointed out by the reviewer, we realize that our use of climate envelopes in this work has not been properly introduced and explained, and the background for each of the vegetation distributions not well enough distinguished. As mentioned in the manuscript (but not adequately emphasized), the vegetation distribution in the reference simula-

tions are based on the MODIS land use dataset (Broxton, 2014), which represents present day vegetation distribution (which one can only speculate to which degree is in total equilibrium with present day climate or not, as several other factors are also influencing the shrub cover, as explained in the introduction). As a satellite based dataset, it is not specifically linked to summer temperatures or bioclimatic envelopes and cannot be expected to be in complete equilibrium to the 10 year mean summer temperature based bioclimatic zones developed for the purpose of this study. Although this vegetation distribution in our opinion serves well as a reference point for our vegetation perturbations, one original limitation to this dataset with respect to our study, is that it has only one shrub vegetation category representing the tundra area of interest in our study (with shrub heights of 0.5m). To study the effects of different shrub heights on the atmospheric response (research question 1.a), we found it necessary to split this shrub class into three sub-classes with different heights; sub alpine, low alpine and mid alpine shrubs. In order to distribute these across the shrub covered area as defined by the MODIS dataset, we applied the simplified "bioclimatic envelopes" based on the key criteria of mean summer temperatures, in combination with empirically derived temperature-vegetation relationships from the region (as further explained in the Methodology section).

We realize that the distinction between the use of the MODIS dataset (which is not based on bioclimatic envelopes) and the vegetation perturbations applied to it (which are based on a key bioclimatic criteria; summer temperatures which represents a simplified bioclimatic envelope) was not properly introduced in the manuscript, and appeared confusing. This will be properly explained and clarified in the revised manuscript. We hope the reviewers agree that given this distinction, there is no discrepancy in the use of bioclimatic envelopes between the reference simulation and the perturbed simulations, rather bioclimatic envelopes are used as a refinement on the original, satellite-based dataset. However, following the reviewer's suggestion, this side of the study and its potential limitations will be discussed further in the revised manuscript.

With respect to the 1K "future" scenario, we do agree with the reviewer in that results from this experiment should be interpreted with care (as highlighted in the Discussion section). The manuscript will be rewritten to emphasize this, and to more clearly highlight the actual purpose of this experiment; The vegetation perturbation produced from the 1K perturbation to the mean summer temperatures were applied as a sensitivity experiment (adding to the aforementioned 0K bioclimatic perturbations), rather than to represent a pseudo-realistic future scenario for vegetation distribution in the area. As such, we have made no assumptions of a specific timeframe for this vegetation distribution. However, as a temperature increase is a very likely part of future climate conditions in this area, the loose term "future scenario" was used to describe it, yet the aim was rather to take into account an assumption of uncertainty in the shrubs' response to summer temperatures as a key environmental condition. The description of this experiment will be clarified and the discussion reframed in this context to avoid confusion.

"3. It is stated that only the vegetation distributions are altered and that the simulations are identical in all other respects. This suggests that your model is being forced with present day climate for both the reference and 1K runs, i.e. you are measuring the strength of the vegetation feedback under today's climate. However, of interest is the strength of the vegetation feedback in a 1K warmer climate. To assess this, surely the driving meteorological data need to reflect this 1K warming (and associated changes in winter climate and snow cover)? I suggest that you run a new 1K reference simulation with the present-day vegetation distribution and met data reflecting the 1K warming. This would still allow you to isolate the vegetation feedback, under a more meaningful scenario."

We agree with the reviewer's opinion that the strength of the atmospheric feedback might vary under different climatic conditions. This was exactly our reason for choosing to simulate our reference and perturbed vegetation distribution under varying climatic conditions, by choosing two contrasting years with respect to snow cover and summer

temperatures. The contrasting response between the two years will give an indication of how sensitive the feedback strength is to variations in the climatic conditions, whether they arise as part of the natural present climate variability, or represent some future mean state or condition. However, one distinction must be made clear; although the perturbations to the vegetation distribution in the two sensitivity experiments are based on a shift in the bioclimatic envelopes corresponding to a 1K difference in mean summer temperatures, the goal of investigating feedbacks under varying climatic conditions is not particularly linked to a 1K general warming of the climate. The temperature difference between the two contrasting years chosen here more than covers the 1K temperature difference chosen to perturb the vegetation cover (as shown in the results section). Rather than representing a particular shift in temperature, it represents the natural variability in temperature in this area over a 10 year period. However, our motivation is that the difference in response particularly across the warmer versus the colder year, may serve as an indicator of potential differences in feedback mechanisms that dominate in a warmer versus a colder climate.

The reviewer suggests an approach to investigate this aspect of the feedback sensitivity, by making another reference simulation with met data reflecting a 1K warming. It is not clear whether the suggestion inherits a perturbation of met data (which could prove problematic in comparison with the other simulations in principle, as this would force the regional model with "unrealistic" meteorological conditions), or if the reviewer in fact suggests a similar approach as the one we have chosen yet apparently failed to properly communicate. We acknowledge that this side of the setup/approach has not been clearly introduced in the manuscript, and that more emphasis should be put on this aspect of the setup in both the introduction, results section and in the discussion. The different response across the two contrasting years could be more emphasized and put in closer context with the two different vegetation distributions. We hope the reviewer agrees that this will be a sound approach to answer this research question. The revised manuscript will be altered accordingly following the reviewer's comments.

"4. The introduction highlights the importance of soil properties in determining the distribution of shrubs and their response to changes in climate, in particular drawing attention to soil moisture content, in addition to mean summer temperatures, as key drivers of shrub expansion. This study explores the effects of increased summer temperatures (by 1K). However, it is not clear that the influence of soil properties is taken into account regarding the perturbed vegetation simulations, although this will surely be an important constraint on future distributions. "

As referred to in the introduction, both soil moisture content and summer temperatures have been shown to be important factors in regulating shrub expansion. In this study we have chosen to use only mean summer temperatures to derive our "simplified bioclimatic envelopes" used to perturb the vegetation distribution. This will be clarified in the revised manuscript. The effect of soil moisture in the system is taken into account in the model simulations, and feedback to the soil moisture is briefly shown in the results. However, in the "simplified bioclimatic envelopes" as defined and used here, the soil moisture content is not a determining factor. We completely agree with the reviewer (and cited literature) that in a more realistic future scenario it would certainly be an interesting factor to include. Also, in the study region of interest here, other factors such as herbivory by reindeers could possibly play and equally important role, however a further investigation into these factors is not the aim of the present study (as also noted in point 1 by Reviewer#2).

Detailed comments

Abstract "P1L11 Specify that you are evaluating the sensitivity of near surface atmosphere / temperatures P1L12 Specify that these are model experiments P1L21 Shortwave radiation instead of SW would be clearer P1L22 "shrub and tree heights, which lower the surface albedo" P1L28 Be more specific –a role in what?"

We agree and will alter the abstract according to the reviewer's suggestions.

Introduction "P1 L34-6 Writing style needs to be more concise"

A thorough review of the language will be conducted throughout the manuscript.

“P2 L6 You mention biochemical effects here but nowhere else. Can you provide some references for this opening sentence? P2 L7-8 The increase in radiation absorption is due to the decrease in surface albedo –please structure the sentence to reflect this. P2 L12 “influence the melt and sublimation” this sentence is quite vague –can you specify what this influence is (i.e. does it enhance or reduce melting/sublimation) P2L15-16 Provide a reference for this. P2 L16 Missing punctuation. P2 L21 “speed the melting season” –this is unclear, do you mean that the onset of melting is advanced or that the melting season is shorter and more intense? P2 L24-39 Provide more information regarding the climate scenarios these vegetation increases related to (i.e. how many degrees increase in temperature) –this will provide better context for your own study P3 L4 coupled “with” not “to” P3 L9-12 Please provide a reference(s) to support/illustrate this”

We appreciate the reviewer’s suggestions and will make alterations to the manuscript accordingly.

“P3 L31 “Also based on dendroecological observations in northern Scandinavia” is misleading as the study discussed just previously (Myers-Smith 2015) was based on data from across the circumpolar region, not just northern Scandinavia.”

This is a good point, and we acknowledge that this was not made clear. It will be adjusted as suggested.

“P4 L 6-7 This spatial resolution cannot resolve “fine scale features of vegetation change”, which will be occurring on much smaller scales than the model grid size”

This is of course a valid objection, and this statement was written in comparison with previous, coarser scale studies in mind. However, the sentence will be rewritten for clarity and the role of resolution more appropriately addressed.

“P4 L12-18 This paragraph could be clearer in its presentation of the main aims of the

study. In the methodology you state that differences between seasons are of particular interest, but this is not mentioned in this paragraph. You should list the hypotheses that are tested in the manuscript here (this will also help provide a structure to your discussion section, relating yours results to the research questions).”

We agree with the reviewer that a more clear presentation in this paragraph will greatly benefit the total readability and re-structuring of the manuscript. As mentioned in point 1. above, a more clear structure in the presentation of both the purpose and corresponding setup will be added to the revised manuscript, and followed up throughout the presentation and discussion of the results, following the reviewer’s suggestions.

Methodology “P4 L22-24 This needs to be explained more clearly, i.e. how do the vegetation change simulations differ from one another P4 L36 Requires references to said studies”

Adjustments will be made accordingly.

“P6 L10-11 “Alterations in the atmosphere results from the biophysical changes related to the applied vegetation perturbations alone” –does this mean that in simulations where the vegetation is prescribed based on a 1k increase in summer temperature, you do not adjust the forcing met data to reflect this?”

As discussed in the points above, yes, the reference and perturbed simulations are run with the same meteorological forcing to isolate the effect of vegetation perturbations on the atmosphere. However, the sensitivity of the feedbacks related to variations in climatic conditions such as the temperature are investigated by choosing two contrasting years (2003 and 2008) with respect to temperature and snow cover.

“P6 L19-23 This is not clear”

Will be rewritten for improved clarity.

“P6 L19 The authors define vegetation categories according to “empirically derived climatic vegetation zones” –they cite Bakkestuen et al 2008 who develop a model for

vegetation variation in Norway. It is not clear during the methodology section whether the “empirically derived climatic vegetation zones” are from Bakkestuen et al. 2008 or are derived by the authors.”

It will be clarified in the revised manuscript that we have followed a comparable approach as Bakkestuen et al, in deriving our simplified bioclimatic zones. However, whereas Bakkestuen et al. derived their bioclimatic zones from a multitude of climatic and other variables (temperature, precipitation, snow cover, geology, topography etc), the presented zones were purely based on summer temperature.

“P7 L4 Should be “e.g. see” P7 L23 Specify the increase in JJA 2 m temperatures applied”

Adjustments will be made accordingly.

“P7 L34 I’m not sure what you mean here P7 L36-38 Shouldn’t the forcing met data reflect the temperature increase in the Veg1K simulation?”

As explained above, the feedback sensitivity to temperature is investigated using the two contrasting years of met forcing data.

Results “P8 L2-3 This should be explained properly in the methodology P8 L8-10 Refer to table 2 here P8 L25 Remove “also” P8 L27 Refer to specific plots, e.g. using lettered plots P8 L35 Reference to Fig. 7 not Fig. 6 P9 L4 Reference to Fig. 4 not Fig. 3”

These are all good points, and corresponding adjustments will be made to the revised manuscript.

“P9 L14 “These areas” –do you mean areas with low alpine shrub expansion?” Yes, this will be clarified in the revised manuscript.

“P9 L22-23 “. . . the small albedo decrease associated with the low-alpine shrub increase. The areas with taller shrubs and trees on the other hand, are characterized by a decrease in snow cover throughout the spring and summer seasons due to a

stronger albedo decrease (Fig. S4)” –I can’t see how this figure specifically shows the different albedo effects associated with these vegetation types (i.e. low-alpine shrub vs. tall shrub and tree)”

The spatial differences in mean seasonal albedo changes are shown in the bottom panels. Each area with vegetation changes can be recognized by comparing with e.g. Fig. 1 (bottom panel); however, we acknowledge that this might be unclear. The figure can be amended by adding numbers or a bar plot for clarity, which will separate each area with vegetation change from each other.

“P9 L27 Add parenthesis”

Will be added.

“P9 L29-30 “The increased SH mainly acts to heat the lower atmosphere within the boundary layer, while the LH is also released above the PBL height” –it’s not clear where this result comes from”

This is not specifically shown here, but more a reference to general meteorological processes. This will be rewritten for clarity.

“P9 L37-39 The figures you refer to do not show the results you present in the manuscript text here (net not incoming SW and LW)”

This is not specifically shown here, but provided as additional information to explain the results. This will be clarified in the revised manuscript.

“P10 L3 You refer to “increased shrub cover”, do you also mean increased tree cover here too? Later on in this paragraph you refer to “vegetation changes” and on L38 you talk about “increased shrub and tree cover” –are you using these three phrases interchangeably or do you mean something different in these instances? It is not clear. Also, please specify which simulation these results are from (I presume Veg0K – RefVeg).”

Yes, the three phrases are, somewhat confusingly used interchangeably, as the re-

viewer points out. We will adjust the manuscript towards a more coherent presentation of the vegetation changes applied.

“P10 L 5-6 It is not clear from just looking at Fig. 7 that the low cloud cover increase is predominantly occurring over areas of vegetation change –you should at least refer to the bottom panel in Fig. 1 that shows this or include it again in the empty plot of Fig. 7 for easy reference. P10 L8 Provide p value”

Suggested changes will be added.

“P10 L13-14 “This indicates”. If the only thing that you changed between the two simulations was the vegetation cover, then surely then all the precipitation change must be attributable to this? What else would have caused it if all other variables were kept constant?”

We acknowledge that this is vague, as the referee correctly points out, the changes are caused by vegetation changes and feedback mechanisms related to these. The sentence will be rewritten to clarify this.

“P10 L15-18 What do you mean by “summarized”? Looking at Table 2, the 2.2% increase is the averaged change over all areas with vegetation changes and over both cold and warm summer seasons. You only provide the warm spring increase in precipitation (1.1%), why not the change averaged over both warm and cold seasons in this case? This is not consistent with your presentation of the summer result. The 1.4% increase in snow and ice appears to be from the cold summer season (looking at Table 2), why did you select this specific value? Per Table 2 this is not a statistically significant finding, yet the p value you present in this paragraph is (p = 3.19 x 10-9).”

The presentation of these results will be revised for clarity.

“P10 L20-25 Be clear that you are discussing the RefVeg simulations here P10 L 22 “and a 3.1K warmer 2 m temperature, on average.” Looking at Table 2, the difference seems to be 2.97K ? P10 L27-28 Be clear that you are discussing the RefVeg simula-

tions here P10 L28 Be more specific –how many days earlier? P10 L39 Spatial pattern of snow cover shown by Fig. S3 not the spatial pattern of snow depth P11 L11 Please indicate the subplots of interest here, e.g. Fig. 10 c & d”

Adjustments to the manuscript according to these suggestions will be applied.

“P11 L21-26 The temperature values presented here do not match those given in Table 2. I presume this is because the Table values are means over areas with vegetation change only whereas in this paragraph you are presenting values for the entire model domain –is this correct? It is not clear why you are not consistent here, particularly as for precipitation you refer to Table 2 rather than continue with giving whole-domain values.”

The numbers presented here are not particularly related to the experiments or the areas with vegetation changes, as they are given as a summary of the mean differences in the climatic conditions between the two contrasting years in the area as a whole. Therefore, they are given as domain averages (only land areas) and not related to areas with vegetation changes specifically. We acknowledge that this should be specified more clearly in the revised manuscript.

“P11 L 36-38 If snow conditions are important then surely you need to take into account that temperature increases during the winter months are projected to be much greater than 1K in your Veg1K simulations.”

This paragraph will be restructured to put more emphasis on the differences between the two contrasting years reflecting different snow cover conditions, simulated here. The temperature difference in temperature feedback resulting from the vegetation distribution perturbations across the two years will give a good indication of the sensitivity of the system in this respect and will be discussed in more depth.

“P12 L2-4 This would benefit from a figure illustrating this change in the vegetation, i.e. such as in the bottom row of Fig. 1 P12 L11-12 This is confusing as both vegetation

simulations (Veg0K and Veg1K) represent a “future” scenario? Or at least, Veg0K does not reflect the present-day vegetation distribution but the distribution that one would expect given our present-day climate.”

Good point. See discussion in the points above. Clarification of this will be added to the revised manuscript.

“P12 L14-16 The second sentence (“Therefore average spring season heating is therefore strongest in areas with the tallest vegetation”) does not logically follow on from the sentence preceding it. Also, over-use of “therefore”. P12 L16-18 But what about the spread of temperatures. So, the highest temperature is found in Summer but in Fig 12 it looks as though this is very localized and that during the Spring more of the domain experiences higher temperatures.”

This is a good observation and a more detailed discussion will be added to the revised manuscript.

“P12 L20 Why is this not included in the supplementary material? P12 L28 Start your discussion off with a summary of your major findings in the order they were presented as hypotheses in the methods section.”

We appreciate the reviewer’s suggestion and will rewrite the discussion in accordance with the revised introduction as suggested.

“P13 L 17-19 Needs re-wording P13 L21 The authors don’t change the greenness factor of each grid cell between the simulations, this seems strange as you would expect a ‘greening’ effect with the 1K increase?”

The reviewer makes a good point, and we acknowledge that there are many possible ways to make perturbations to the vegetation cover within this model framework. Here, our choice of only altering the type of vegetation is that this will indirectly lead to a modelled alteration of vegetation properties related to greenness (i.e. LAI, height, shading factor etc.), all properties that we through a thorough review of the literature

have sound scientific basis for changing. Also, the perturbations made here are sufficient to give answers to the research questions in focus here. The “greenness factor” variable in this model setup is related to the overall density of vegetation in a grid cell, i.e. is based on an entirely different satellite dataset and also has a monthly varying distribution, and is used to scale other vegetation-type specific variables in time. We found it difficult to base any alterations to this distribution on empirical or theoretical arguments. Although, as the reviewer points out, one could expect a change in what this variable represents, it is hard to estimate to which the degree this would occur, and whether it would be in addition to, or instead of, the changes already taken into account. Also, another reason for making the perturbations as simple and concise as possible is the interpretability of the results, and as such, we found that changing the vegetation type (and corresponding properties) was more beneficial. However, the results are carefully interpreted with the model setup and its possible limitations to this in mind. A short discussion of this issue will be included in the manuscript, with reference to up-dated publications.

“P13 L30 “. . .areas with increased tall vegetation” P13 L31 “. . .related to increased low shrub cover. . .” P13 L32 “enhanced” rather than “added”. What is the balance between these two factors during the spring season?”

We appreciate the reviewer’s suggestions and corresponding adjustments to the manuscript will be added.

“P13 L 36 What do you mean by “despite the snow masking effect in winter”? Also, you did not analyze winter months in this study. The final part of this sentence doesn’t make sense: “the deciduous nature of the northward expanding shrubs and trees in this study, which is based on what is observed in the study region””

This will be rephrased for clarity.

“P13 L38-40 They haven’t allowed for expansion of needle leaved trees –is this reasonable?”

In this study the aim was to look at vegetation changes related to the expansion of shrubs (area and height) and low trees in the tundra region specifically. Also, the northern Fennoscandia region is dominated by mountain birch forest, which is deciduous. Whether the simultaneous northward migration of evergreen needle leaved trees would give a more realistic vegetation distribution given our climatic conditions would certainly be interesting to look at, but is besides the aim of this study. This choice of limitation will be mentioned briefly in the revised manuscript.

"P14 L18 Clarify that you are talking about changes in SW and 2 m temperature, i.e. a reduction in early summer P14 L21 Remove "also" P14 L26 "we note that they observed a substantially larger response in soils temperatures than was shown in our results""

Suggestions are appreciated and adjustments to the manuscript will be added.

"P14 L36-37 Can you provide the equivalent percentage shrub increases for your simulations to aid comparison with the studies discussed here?"

We could add an area extent or a percentage number for comparison as the reviewer suggests, however we are reluctant to do so for the following reason; The papers cited here have looked at the entire circumpolar area, and made adjustments to the vegetation cover that differ substantially in nature from the ones applied in our study. A percentage number relating the areal extent of changes to the entire study domains would as such aid little in comparing the studies, and on the contrary give rise to an unfounded expectation of similarities in the results. As the studies share a similar aim (i.e. to study the feedback effects of high latitude vegetation changes on the atmosphere), an overall comparison of the atmospheric effects are defendable. However, a more close and qualitative comparison of the applied changes in vegetation distribution between the studies could potentially be more misleading than beneficial, in our opinion.

"P15 L1 "The response of shrub expansion" –this doesn't make sense; the response of what to shrub expansion? P15 L2-3 More moderate than what? P15 L6 Remove "were

related to" and change to "are occupied by""

Will be rephrased for clarity.

"P15 L18 Change 0.04 to 0.05 as per Table 2 P15 L14 "we find" This is the first time a time lag is mentioned. What sort of time-lag –provide an estimate. P15 L33 Remove "have" P15 L34 Change "in evaluating" to "to evaluate" P15 L35 Remove "have" P16 L12 You stated in your results that this increased snow cover was due to "increased snow fall in the cold season and possibly the increased shading effect of the shrubs" whereas here you are implying it is entirely down to shrub expansion –this seems to be a contradiction."

Will add an explanation of time-lags, and rephrase the sections according to the reviewer's suggestions.

"P16 L35-36 Repetition of P15 L31-33"

Figures "Figure 1. The following changes would improve the clarity of this figure: Labelling sub-plots (e.g. a, b, c, d) would be beneficial for clearer linking between the text and the figure (this comment applies for further figures also). The temperature limits shown by the contour lines are unclear. The axis labelling of the fourth subplot is slightly inconsistent with the others. Why does the vegetation classification change in the final subplot? For instance in the top panels, Tall shrubs are 0.5-2m whereas shrubs of this height are classed as Low alpine shrubs in the bottom panel. It would be helpful to see a subplot like the one at the bottom of this figure for the other vegetation perturbation, i.e. Veg1K – RefVeg. Why have you not included this?

Figure 2. You have shown temperatures in degrees Celsius here but throughout the manuscript you refer to temperature changes in Kelvin, this should be kept consistent.

Figure 3. If you re-ordered your figures so that figures 2 and 3 precede Figure 1, this would make Figure 1 clearer as it reflects the order that you present the related concepts in the manuscript text.

Figure 5. Refer to Fig. 4 not Fig. 3

Figure 6. This Figure is too small and trying to show too much, which makes it unclear and difficult to extract the key information. Why did you use that particular cross section? It is hard to see the stippled lines What is the difference between the inset scale and the main figure scale? Why are they not consistent?

Figure 7. The middle row of figures would be easier to interpret if the scales were the same. Not clear from the figure caption which simulation we are looking at (i.e. Veg0k – RefVeg)

Figure 8. On the right plot, label the two seasons as 'warm' and 'cold' or 'RefVegwarm' and 'RefVegcold' instead of the year, as this is how you refer to them elsewhere in the manuscript. The title of the left plot is too long and so is hard to read where it overlaps the left axis labels.

Figure 11. In the all other figures showing anomaly distributions across the domain, you state that the figure is "only showing significant results at the 95% confidence level" –why do you not do that here?

Figure 12. Inconsistent use of "2 M" and "2m" throughout figures in the manuscript Specify that these are inter-seasonal means

Table 2. Responses are presented inconsistently: Why are precipitation, snowfall and low cloud coverage changes shown as percentages whereas the actual values are given for the other variables? Why is the mean value for RefVeg MAM Low cloud coverage 0.31 when the mean values for the warm and cold years are 0.29 and 0.29? (this applies to other values presented in the table) Why are you only averaging over areas with vegetation changes? Cloud cover and precipitation effects might not be limited to the atmosphere directly above the vegetation change for instance."

We appreciate this thorough review of the figures and constrictive suggestions for improving them. We realize some adjustments are needed and will be made accordingly.

Reference list "P20L1-12 Duplication of reference: Myers-Smith et al. 2015a appears to be the same paper as Myers-Smith et al. 2015b"

Will be corrected.

Supplementary material "Figure S1. Consistent scales would be better Figure S5. In the text preceding this figure, it is not clear why "(Veg0K-RefVeg)" is included at the end. "

Will be corrected.

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