Response to reviewers by Zhang et al.

We thank the reviewers for their thoughtful and constructive comments, which have greatly helped improve this manuscript. We have made the following modifications to address the reviewers' main concerns.

1. We have restructured the section 4.4 to discuss four perspectives to improve regional Earth system models over the Arctic: a) interaction with ocean components; b) importance of including permafrost C feedback and how biogeophysical feedback will affect the permafrost vulnerability; c) how to improve vegetation distribution; and d) the importance of including nutrient cycles.

2. We now mention the limitations of using C3 grass plant functional type (PFT) instead of tundra and shrub-specific PFTs.

3. We now compare atmospheric heating change due to the changed albedo and latent heat change due to the changed vegetation with other studies (such as Euskirchen et al., 2009; Kasurinen et al., 2014).

4. We have edited our language to be more concise and clear, improved the legends of figures, and we have corrected typos pointed out in the specific comments.

We hope that our revised manuscript will satisfy comments of the reviewers. Please find below our detailed responses (colored in blue), following each reviewer's comment.

Response to Anonymous Referee #1 (www.biogeosciences-discuss.net/11/C1977/2014/)

This manuscript presents the results of a study to understand how biogeophysical feedbacks of vegetation in the Arctic might influence climate and carbon dynamics in the Arctic. The analysis uses RCA-GUESS as a tool to conduct this study, and relies on the comparison of outputs from simulations with fixed vegetation and dynamic vegetation. I really like the design of this study. However, there are some issues/short-comings in the analysis that should be addressed in a revision: (1) the lack of consideration of shrub tundra, (2) no treatment or discussion of the permafrost carbon feedback issue, (3) the need for more discussion/comparison of the magnitude of albedo/latent energy feedbacks with other analyses that have been published, and (4) some rough text in certain places in the manuscript. Below I explain my concerns with these issues and finish off the review with specific comments.

The lack of consideration of shrub tundra

When I was asked to review this paper I was really looking forward to the analysis as I was thinking that it follows nicely onto the analysis of shrub tundra dynamics in Zhang et al. (2013, ERL). However, I was quite disappointed to find out on page 6722 that the analysis involved 6 global PFTs and not PFTs (such as shrub tundra) that are quite relevant to the region. The shrub tundra issue was highlighted in Chapin et al. (2005), which was cited in the manuscript, because shrub tundra has much lower albedo than graminoid tundra. Also, as pointed out in Figure 1 of this manuscript, an expansion of shrub tundra has the possible positive feedback to warming through snow masking. To me, the analysis represented in the paper is much less interesting without having the shrub issue represented and seems like a Bonan/Foley circa mid-1990s type of analysis with respect to dealing with mostly a C3 grass representation of tundra in the context of arctic/boreal biogeophysical feedbacks to climate. The shrub issue is mentioned in passing on page 6735 late in the manuscript, and warrants more discussion. Not sure what else to recommend here – just seems like a missed opportunity to build on the progress in Zhang et al. (2013) with respect to having considered shrub tundra dynamics considered in the analysis.

We agree with the referee that it would have been ideal to follow the progress in Zhang et al. (2013) inter alia employing the same Arctic tundra PFTs in RCA-GUESS as in the customized Arctic version of the offline model LPJ-GUESS. This should enable biogeophysical feedbacks from the transitions among tundra shrubs and dwarf vegetation to be captured in a more realistic way. However, we are still underway with developing RCA-GUESS to fulfill this purpose. On the other hand, the more generalized global PFT configuration we used, which is identical to the standard global version of LPJ-GUESS, has been evaluated and proven robust in numerous published studies, especially with respect to terrestrial carbon cycle variations and dependencies on drivers (e.g. Piao et al., 2013; Ahlström et al. 2012a). In addition, Ahlström et al. (2012b) estimated the net ecosystem exchange using LPJ GUESS driven by CMIP5 climate outputs. As our study mainly focuses on the impacts of biosphere-atmosphere coupling on carbon fluxes, the aforementioned publications, based on the same PFT configuration and biogeochemical representations, provide a useful baseline for comparison to the results from our study. These studies are now cited on p7, L186-188, and p19, L579-583 as we do in section 4.4 of the Discussion.

No treatment or discussion of the permafrost carbon feedback issue

My understanding is that the version of LPJ-GUESS used in this study does not represent the carbon stored in permafrost, and therefore is not capable of considering the permafrost carbon feedback in this analysis. The small increases in soil carbon storage in Table 2 could easily be large decreases (potentially much larger than the increases in vegetation carbon storage in Table 2). There has been a lot published on the permafrost carbon feedback in recent years (e.g., Schuur et al. 2013. Expert assessment of potential permafrost carbon feedback to climate change. Climatic Change 119:359-374. doi:10.1007/s10584-013-0730-7). The permafrost carbon feedback issue warrants at least a paragraph of discussion late in the paper, probably in section 4.4. Also, the conclusion that 8.5 Pg C feedback is considerable (page 6734, line 8, as well as the abstract) doesn't seem very considerable to me compared to the possible magnitudes of the permafrost carbon feedback.

We agree that this is an important and relevant issue and have added discussion of it in our revised paper, as p18-19, L552-571 in section 4.4. However, any comparison of our estimate with permafrost C release must be done with care. Firstly, the positive permafrost carbon feedback will change ambient CO_2 concentration which will bring extra fertilization effects on vegetation productivities. In particular, the biogeophysical feedbacks seen in our study could potentially influence permafrost carbon dynamics through changes in regional temperature and precipitation. We will elaborate on this issue in section 4.4.

Comparison of albedo and latent energy feedbacks to other analyses

There are other time-dependent analyses of changes in albedo and latent energy feedbacks in the boreal and tundra regions. I had expected to see the magnitude of the albedo and latent energy feedbacks compared with these analyses (e.g., Euskirchen et al. 2009a and 2009b).

Euskirchen, E.S., A.D. McGuire, T.S. Rupp, F.S. Chapin III, and J.E. Walsh. 2009a. Projected changes in atmospheric heating due to changes in fire disturbance and the snow season in the western Arctic, 2003 – 2100. Journal of Geophysical Research – Biogeosciences 114, G04022, 15 pages, doi:10.1029/2009JG001095.

Euskirchen, E.S., A.D. McGuire, F.S. Chapin III, S. Yi, and C.C. Thompson. 2009b. Changes in vegetation in northern Alaska under scenarios of climate change 2003-2100: Implications for climate feedbacks. Ecological Applications 19:1022–1043.

In our study, we find that the change of atmospheric heating (the sum of net long-wave and net short-wave radiation) in the summer is around 5-10 W m^{-2} on a seasonal basis for 2071-2100 relative to 1961-1990. This estimate is similar to the magnitude reported by (Euskirchen et al., 2009b) 0.34 $\pm$0.23 W m^{-2} $decade^{-1}$ in the summer due to increased shrub expansion. However, Euskirchen's estimate is based on an off-line simulation. By including the effects of climate-vegetation interaction, their estimates may become larger. We mention this comparison in the revised manuscript as p16, L486-498 in section 4.3.

Some rough text in certain places

Most of the writing in the manuscript is pretty good from a grammatical perspective. However, there are places in the manuscript where the text is pretty rough and there is a need for the co-authors to step up to the plate and fix it. In particular, there are sentences in section 4.1 that make little sense. There were also some confusion in my mind about what was being depicted in some of the figures, and this could probably be avoided by more articulate description in the figure legends (see specific comments below).

Specific comments

Page 6716, line 11: Should "an GCMs" be "a GCM"?

Yes, modified as "an EC-Earth" (p1, L21).

Page 6718, line 16: Should "efficient transports of momentum" be "efficient transport of momentum"?

Yes, changed as suggested (p3, L77).

Page 6720, line 2: I think "CO2 fluxes measurements" should be "CO2 flux measurements".

Agree, changed as suggested (p4, L116).

Page 6720, line 6: I think "boreal forests productivities" would read better as "boreal forest productivity".

Agree, changed as suggested (p4, L119).

Page 6720, line 23: I suggest changing "This increases" to "These responses increase".

Agree, changed as suggested (p5, L136).

Page 6721, lines 9-12: This sentence should be rewritten, as it is pretty awkward.

We have deleted this sentence and instead reformulated the whole paragraph to more clearly articulate the aims and approach of our study (p5, L139-154):

"In this study, we highlight the importance of including interactive vegetation dynamics in simulations of the future Arctic climate. To this end, we employ a regional ESM (RCA-GUESS) that couples a regional climate model (RCA4) with an individual-based dynamic vegetation-ecosystem model (LPJ-GUESS) to study the coupled evolution of climate, vegetation and ecosystem C balance across the pan-Arctic. By comparing simulations with and without interactive vegetation dynamics forced by lateral boundary conditions from a GCM under a strong future warming scenario (RCP8.5), we analyze how biogeophysical feedbacks arising from distributional and structural change in arctic tundra and boreal forest may impact the Arctic climate and terrestrial C balance. Specifically, we investigate the following questions:

1. How well does RCA-GUESS simulate Arctic climate, vegetation and C fluxes in the recent period?

2. How do biogeophysical feedbacks affect Arctic climate and terrestrial C balance in a warmer, high-CO2 future climate?

3. What aspects of vegetation change are particularly associated with changes in terrestrial C balance?"

Page 6722, line 21: Change "of world" to "of the world"; add "and" before "Arctic".

Agree, changed as suggested (p6, L185).

Page 6722, lines 27 and 28: Please explain what you mean by "intolerant". I don't think

that is an adjective that is widely used in the community to describe PFTs.

We modified it as "shade-intolerant" (p7, L193-195).

Page 6723, line 25: "comprising" should be changed to "composed of".

Agree, changed as suggested (p8, L220).

Page 6724, line 25: Note that "PNV has not yet been defined, so it should be spelled out here.

We now define it the first time we mention it (p6, L184).

Figure 4c: You need to explain how you calculated percent difference as there are two different ways to calculate it. Also, is it possible to have the colors in Figure 4c consistent with the colors in Figures 4a and 4b?

We agree, and we have added this sentence "The latitudinal percentage difference for each aggregated vegetation type between the composed map and the simulated map is quantified by the number of grid cells in which the simulation over- or underestimates each vegetation type divided by the total number of grid cells in each latitude band." on p9, L252-256 in the section 2.3. We have also made the color consistent with each sub-plot.

Page 6727, lines 20-23: It is not clear in this sentence that the estimates (500-600 g C m-2 yr-1) are for the entire CORDEX region. Please state this explicitly if this is the case.

Agree, we have added "European forest" before "NPP" to clarify that this refers to European region only (p11, L321).

Page 6726, line 26: Add "for arctic tundra" after "inversion models". Also, explain in Figure 5b that the estimates are just for arctic tundra.

Agree, changed as suggested (p11, L328).

Figure 8: I need more explanation about how Figures 8b and 8d were generated.

We now mention the equations and have also added them to the legend as below.

Fig. 8. Normalized phenology index anomalies (%) $C_p=(LAI_{eg}-LAI_d)/(LAI_{eg}+LAI_d)$ Wramneby et al., 2010) quantified by the shift in the relative abundance between evergreen (eg) and deciduous (d) PFTs due to (a) climate change from the period 1961-1990 to the period 2071-2100; (b) the effects of biogeophysical feedbacks for the period 2071-2100. Normalized physiognomy index anomalies (%) $C_p=(LAI_w-LAI_h)/(LAI_w+LAI_h)$ quantified by the shift in the relative abundance between woody (w) and herbaceous (h) PFTs due to (c) climate change from the period 1961-1990 to the period 2071-2100; (d) the effects of biophysical feedbacks for the period 2071-2100.

Figure 9a: Is it an NEE anomaly that is really plotted in Figure 9a? If so, what is the period to which the anomaly is referenced (1960-1990 perhaps)? But I don't see why an anomaly needs to be plotted here, as plotting the actual values of NEE makes more sense.

We agree that it is more informative to show the actual values of NEE to indicate the magnitude of carbon uptake in Gt C. We have changed this in the revised manuscript.

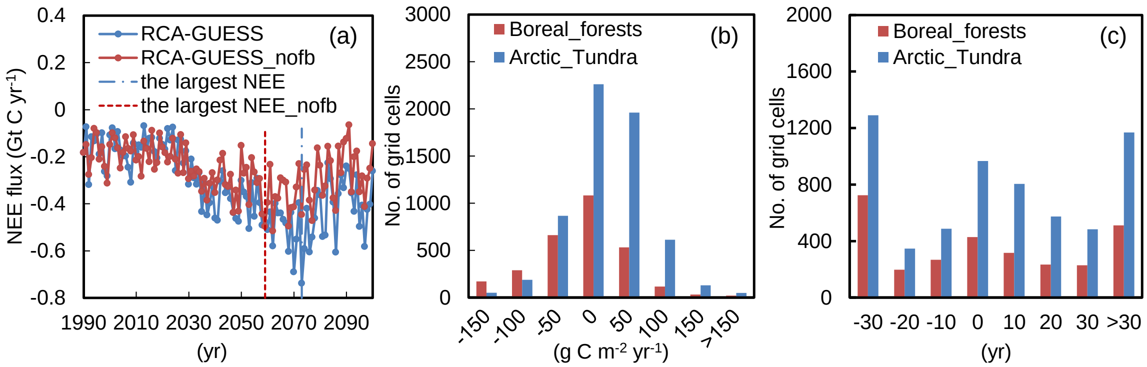


Figure 9b and 9c: These panels need units on the x axis. Also – the legend for Figure 9b doesn't seem appropriate.

We agree, and have added units to the x axis. . The x axis (g C m^{-2} yr^{-1}) for Figure 9b means how much the peak C uptake will be reinforced or ameliorated due to the biogeophysical feedbacks, in both tundra or boreal forests. The x axis (yr) for Figure 9c means how many years the peak C uptake will be postponed or advanced by due to the biogeophysical feedbacks, in both tundra or boreal forests.

Page 6729, sentence spanning lines 21 and 22: There is not enough information here for me to understand how you sorted the grid cells and what is actually depicted in Figures 9b and 9c.

We now mention it on p13, L375-377 in section 3.3.

Page 6730, lines 2-4: Sentence is pretty rough, and needs to be rewritten.

We have reformulated the rough sentence: "Biogeophysical feedback accounts for about 22% of the increase in net C uptake, around 8.5 Gt C. The majority (83.4%) of this extra C uptake comes from areas simulated as Arctic tundra in the modern climate." (p13, L412-414). We further discuss it on p17, L521-531 in section 4.3.

Section 4.1: This section is really pretty rough and needs to be rewritten.

We have rewritten this whole section and hope it is now better.

Page 6734, line 8: As mentioned earlier, I challenge whether 8.5 Pg C over a century is a very significant feedback. It is equivalent to one year of current fossil fuel emissions and is likely to be quite small in relation to the permafrost carbon feedback.

We now state: "The additional C sinks arising from biogeophysical feedbacks correspond, at around 8.5 Gt C, to global anthropogenic emissions for about one year under present conditions (Table 2), relatively modest compared to some estimates of the potential losses of C from thawing permafrost across the Arctic (Schuur et al. 2013)." (p17, L522-525)

Page 6734, lines 11-14: I don't know how one can make this argument that vegetation dynamics (not actually succession) plays a more important role than a prolonged growing season since these issues were not analyzed relative to each other in the study.

We do not present an explicit analysis, but are confident, based on experience with the model and by the spatial patterns emerging e.g. in Fig 5 and 8, of the large role played by carbon sequestration in the stems of growing trees. We elaborate this spatial aspect more clearly in the revised text (p17, L521-531):

"The sensitivity of vegetation distribution to the effects of biogeophysical feedback seems relatively modest (figure 8b and d). The additional C sinks arising from biogeophysical feedbacks correspond, at around 8.5 GtC, to global anthropogenic emissions for about one year under present conditions (Table 2), relatively modest compared to some estimates of the potential losses of C from thawing permafrost across the Arctic (Schuur et al. 2013). A prolonged growing-season, denser forest covers and invasion of trees into tundra are the factors resulting in a further enhanced vegetation productivity, which postpones the arrival of the peak C uptake rate for Arctic terrestrial ecosystems. In our study, dramatic changes were found in the transition from herbaceous to woody vegetation occurring in Arctic tundra (figure 8c). These changes appear to primarily account for the simulated increased C storage in areas classified as Arctic tundra in the present climate."

Response to Anonymous Referee #2 (www.biogeosciences-discuss.net/11/C3575/2014/)

General comments:

Zhang et al. used the regional model RCA-GUESS to simulate biogeophysical feedbacks in the Periarctic region. In particular, the authors focus on the carbon cycle and on how the biophysical feedbacks could potentially affect the carbon stocks in high latitudes in the context of a global warming. The authors effectively present interesting results, showing how biogeophysical feedbacks in high latitudes are important in order to determine the land carbon sink and the vegetation distribution. The article is generally well written, and the authors are clear in explaining the results which are well supported by images and tables. On the other hand there are some few general comments that require a revision, as these issues should be addressed in a more complete discussion, which would explore the limitations of the study. The main issue is the lack of discussion about the importance of the representation of permafrost and freezing/thawing processes in the RCA-GUESS model and the lack of discussion of this potential limitation in the paper. It is not clear how the model used in the present study can deal with permafrost-related processes. This issue is particularly relevant in the region of focus in the present study, and the implication of this model feature should be addressed. Permafrost and permafrost-related processes are fundamental drivers of hydrology, energy balance and carbon cycle in the Periarctic region. Some of these issues are well discussed, e. g., by Koven et al. (2011), Permafrost carbon-climate feedbacks accelerate global warming. PNAS, doi:10.1073/pnas.1103910108. The influence of permafrost-related processes can also affect the size of the terrestrial carbon sink (due, for example, to permafrost-related processes, such as cryoturbation). The magnitude of the permafrost-climate feedback should therefore not be underestimated, and the lack of representation of these processes can deeply affect the results published in this paper. In particular, the magnitude of the effects of the biogeophysical feedbacks the authors find are in the same order of magnitude of the permafrost-carbon feedback recently found in MacDoughall et al. (2012), Significant contribution to the climate warming from the permafrost carbon feedback, Nature Geoscience, doi:10.1038/ngeo1573. I understand that the biogeochemical effects are not the focus of the paper, but their presence/absence should be considered in a more complete discussion.

We agree that impacts of permafrost retreat are an important issue not encompassed by our approach. We have added a paragraph discussing permafrost-mediated C-cycle feedbacks in the Discussion on p18-19, L522-571 in section 4.4.

Other issues/questions to be addressed:

The article presents results from simulations of a regional model forced with boundary conditions from climate projections under the RCP 8.5 scenario. Why did the author choose only this scenario for the boundary conditions?

We chose an RCP 8.5 scenario because the strong CO_2 and warming forcing was expected to give a clear signal in terms of vegetation dynamics, biogeophysical feedbacks and C balance change. As our focus is on analyzing the feedback mechanisms, as opposed to making policy-relevant projections, we did not consider it a priority to include scenarios based on multiple narratives of socio-economic change.

In the 6 PFTs described in Section 2.1 there is no mention of mosses/shrubs, which on the other hand is relevant to the region of focus. Could the differences in albedo with C3 grasses and the insulating effect of mosses potentially affect the results the authors show in the paper?

We agree the simplification of lumping mosses and graminoids into one generic "C3 grass" could have some quantitative effect on the results, e.g. concerning albedo. However, Matthes et al., (2011) found that effects of vegetation shifts on 2m air temperature were much larger than the effects of freezing/thawing of soil moisture or the effect of insulation by top organic soil horizons (p17, L513-520). In our revised manuscript, we further compare the atmospheric heating change due to albedo change with other studies on page 16, L486-498:

What is the role of the competition for nutrients in this study? Are N and P cycles considered? How would the results of the simulations without dynamical vegetation change by considering the nutrient cycles? Goll et al. (2012), Nutrient limitation reduces land carbon uptake in simulations with a model of combined carbon, nitrogen and phosphorus cycling, Biogeosciences, doi:10.5194/bg-9-3547-2012 showed how relevant is the impact of nutrients for the estimation of the land carbon sink. Once again, I understand that this one is not the focus of the paper, but this other potential limitation should be mentioned in the discussion.

The model version adopted for this study does not include nutrient feedbacks, although N cycling is included in the most recent offline version of LPJ-GUESS. Clearly, limitation of productivity due to slow mineralization rates for N is very important in high latitude ecosystems. However, simulated NPP is generally realistic for present conditions, and N limitations of a future increase in productivity will be offset by increased mineralization rates in warming soils. We have added a paragraph to discuss it in the section 4.4.:

"The model version adopted for this study does not include nutrient feedbacks to vegetation growth, although N cycling is included in the current offline version of LPJ-GUESS (Smith et al. 2014). Nitrogen mineralisation rates in the cold soils of boreal and Arctic ecosystems are known to limit the productivity of vegetation in these areas. Simulations with N-enabled global carbon cycle models generally suggest that C sequestration under a future high CO2 climate will be lower globally when N-cycle feedbacks are accounted for (Zaehle & Dalmonech 2011). However, increasing mineralisation rates in warming soils will reduce N-limitation, allowing substantial productivity increases as growing seasons become longer and warmer. In addition, trees colonising tundra areas rendered accessible by a milder climate constitute a temporary, new sink for carbon until stand carrying capacity is reached and mortality matches biomass growth. As shown for the N-enabled version of LPJ-GUESS by Wårlind et al. (2014), these effects will counteract any tendency for N availability to inhibit an increase in C storage by high-latitude ecosystems in a warming, high-CO2 climate. Baseline (1961-1990) NPPs simulated by RCA-GUESS across the Arctic are within the range of variability of observations (Fig 5a). Although the present study does not include N limitation, the simulated increase in ecosystem C storage across the Arctic may be realistic. How nutrient cycling effects may impact biogeophysical land-climate interaction remains unclear and needs further investigation."

Specific comments: The paper is generally well written, and I have only very few comments on the text.

Page 6716, line 11: "an GCMs CMIP5: : :" should read "a GCMs CMIP5: : :"

Modified as "an EC-Earth CMIP5….. (p1, L21)"

Page 6719, line 9: I am not sure about the citation of Rietkerk et al. (2011). The authors of that paper showed how small-scale vegetation-climate interactions could potentially affect larger scales, and they referred to small-scale soil and vegetation features and to their effect on land-atmosphere fluxes. These small-scale features are not resolved in GCMs, but neither they are in RCMs, despite the increase in resolution.

This scaling issue is indeed of interest, and it could also be addressed in the discussion. The use of a RCM, though, in my opinion does not address the small surface heterogeneities, such as the ones highlighted by Baudena et al. (2013), Vegetation patterns and soil-atmosphere water fluxes in drylands, Advances in Water Research, doi: 10.1016/j.advwatres.2012.10.013 for drylands, and for the Arctic environment by Cresto Aleina et al. (2013), A stochastic model for the polygonal tundra based on Poisson-Voronoi Diagrams, Earth System Dynamics doi:10.5194/esd-4-187-2013. In this way the citation is misleading, as this issue of scales remains unresolved also in the approach used by the authors.

We agree. We have deleted this citation. And, in the next paragraph, we write "Kueppers et al. (2005) showed that the RCM-based climate is more suitable to predict potential shifts in species' range than the GCM-based climate in California, where land surface, topography, climatologically distinct ecoregions, local climate varied with the distance from the coast are better resolved in the regional climate outputs." (p4, L99-103) to emphasize why it is important to revolve climate in a regional scale.

Page 6720, line 2: "CO_2 fluxes measurements" should read "CO_2 flux measurements"

Agree, changed as suggested (p4, L116).

Page 6720, line 23: I guess that adding a noun near "This" would improve readability.

Maybe "This effect"?

Agree, we have changed it to "These responses" (p5, L136).

Page 6721, line 9: Something is missing after "but". Maybe "but we made this choice

in order to..."?

We have deleted this sentence and instead reformulated the whole paragraph to more clearly articulate the aims and approach of our study:

"In this study, we highlight the importance of including interactive vegetation dynamics in simulations of the future Arctic climate. To this end, we employ a regional ESM (RCA-GUESS) that couples a regional climate model (RCA4) with an individual-based dynamic vegetation-ecosystem model (LPJ-GUESS) to study the coupled evolution of climate, vegetation and ecosystem C balance across the pan-Arctic. By comparing simulations with and without interactive vegetation dynamics forced by lateral boundary conditions from a GCM under a strong future warming scenario (RCP8.5), we analyze how biogeophysical feedbacks arising from distributional and structural change in arctic tundra and boreal forest may impact the Arctic climate and terrestrial C balance. Specifically, we investigate the following questions:

1. How well does RCA-GUESS simulate Arctic climate, vegetation and C fluxes in the recent period?

2. How do biogeophysical feedbacks affect Arctic climate and terrestrial C balance in a warmer, high-CO_2 future climate?

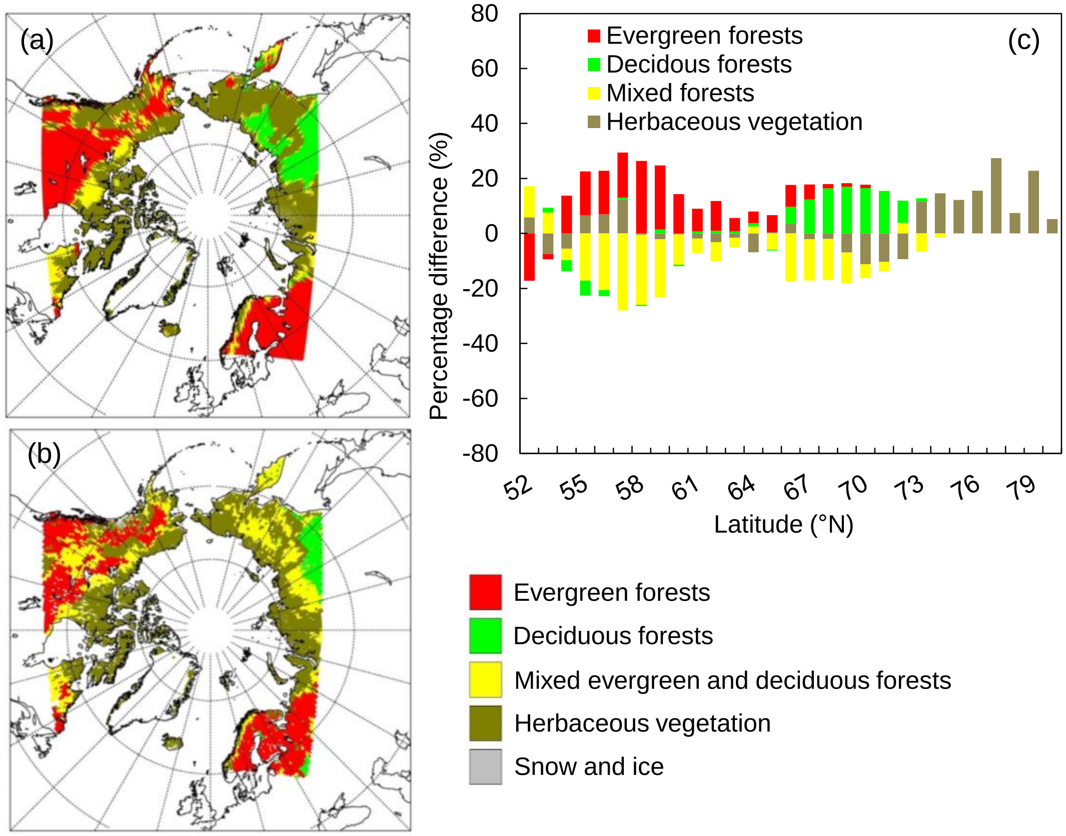
3. What aspects of vegetation change are particularly associated with changes in terrestrial C balance?"

Figures:

The figures are generally understandable and well discussed in the text, but:

In Figure 4 (c) colors are not consistent with the other two panels.

We change it as suggested.



In Figure 9 (b) and (c) lack of labels on the x axis. At least the units (which are in the label) should be shown. In the figure label I do not understand the sentence "...for both the peak C uptake rate ...". I guess something is missing here.

We will articulate it in the legend. The revised legend will be

Fig. 9 (a) The inter-annual variation of NEE flux (Gt C yr^{-1}) in both RCA-GUESS feedback and non-feedback runs from 1990 to 2100 for Arctic tundra. (nofb: the non-feedback run; negative value: carbon sink; the vertical dash and dash-dot lines denote the year with the largest NEE over the whole period). (b) Distribution of the number of grid cells (total: 9032) for the shift of the peak C uptake rate (g C m^{-2} yr^{-1}) in both boreal forests and Arctic tundra (positive: increase; negative: decrease). (c) Distribution of the number of grid cells for the shift of the year (yr) with the peak C uptake rate in both boreal forests and Arctic tundra (positive: delay; negative: advance).