Response to reviewer comments for:

“Frost matters: Incorporating late-spring frost in a dynamic vegetation model regulates regional productivity dynamics in European beech forests”

Reviewer 1:

1.

From what I understood, when a frost occur the leaf phenology status is reset to 0 which means that all existing leaves are removed (?). Isn’t this binary behavior not too strong ? Would it not be better to have a more continuous function which could modulate the effect of damage as a function of temperature ? This would be probably more realistic. Indeed for a not too cold temperature (around -2°C) there is probably only a partial damage when for a temperature of -8°C we can guess that damage will be generalized. Especially as micro climate into the canopy (which is not modeled), will induce during night higher leaf temperature in the inner canopy than at the top. Also it could solve, partially, all the discussion in the paper about the choice of threshold temperature. Indeed such continuous function will let the results be less sensitive the the threshold temperature.

Reply: The reviewer brings up several good points. Firstly, the reviewer’s understanding is correct; we model late-frost as a binary function. When a frost occurs, the leaf phenology status is reset to 0 indicating a complete loss of leaves. We briefly describe this behavior in the methods section in lines 121 and 122. In the revised manuscript we will change the sentence to, “... being reset to zero (i.e. complete removal of existing leaves), followed by …" for more clarity.

Indeed, a continuous function might modulate the effect of frost damage in a manner that a binary function cannot. In the development process we have carefully screened the existing literature and published data, leading us to conclude there is a lack of empirical data supporting the implementation of a continuous function to model frost damage. The little data there is comes from climate chamber studies to suggest that the damage to leaves increases with increasingly lower temperatures (Baumgarten et al 2023, Vitasse et al 2014) these thresholds are much lower than *in situ* air temperatures measured during natural frost events (Principe et al 2017, Dittmar et al 2006, Hufkens et al 2012). Additionally, Baumgarten et al. (2023) found that more intense frost, and subsequently more leaf damage, did not necessarily result in higher growth reductions in *Fagus sylvatica*.

Since we were not able to implement a continuous frost function due to lack of empirical data, we instead decided to implement a simpler, stochastic frost threshold for each patch (described in the methods in lines 118 and 119 and in the discussion in lines 297-300) to address this issue statistically. This leads to some patches having a higher frost resistance than others. Since the model state for each gridcell is the average of all patches in that gridcell, this behavior modulates the effect of various levels of damage without the need for a continuous function. This means that some patches will experience frost and consequently lose all their leaves, however, other patches will not experience frost and will not lose leaves. In the aggregate over all patches this results in frost damage between 0% and 100%. If all patches experience frost, the gridcell has 100% frost damage. If none of the patches experience frost, the gridcell has 0% frost damage. If half of the patches experience frost, the gridcell has 50% frost damage. Through this mechanism we approximate a continuous function for frost damage. Ultimately, if more data becomes available a truly continuous relationship between minimum air temperature and frost damage could be implemented in future versions of the model. To clarify the consequences of the stochastic application of frost thresholds to each patch the revised manuscript will include a more detailed description of this behavior starting at line 124.

2.

Tree ring is only an indirect proxy of the simulated frost damage. Indeed it only allows to access the total NPP. Then theses tree rings (and total NPP) are influenced by all the factors during all the growing season making the width also depending of possible drought that will amplify the NPP decrease or on he opposite a very good climate conditions that can dampen it. Then why not use also remote sensing data ? Obviously it will not be possible for the 1953 event. But it will be possible for 2011. In particular remote sensing data can be a good proxy of LAI which will allow to see if the simulated decrease and lagged regrowth after frost is comparable to what is observed from satellite.

Reply: We thank the referee for this comment and agree that tree-rings render a proxy for NPP which is affected by various environmental parameters and that remote sensing information can complement tree-ring based analyses. As we already discussed in the first submission in lines 292-293, the European Forest Condition Monitor featured an ongoing decline in canopy greenness for beech dominated pixels in the year 2011 (cf. Buras et al., 2021). In the revision of our manuscript, we will add a complementary analysis which depicts the relative change of NDVI (expressed as anomalies of proportional NDVI deviations from the long-time median) for Bavaria in 2011 and matches the response seen in both the tree-rings.

3.

We can see on figure 2 the for some years (for instance between 1999 and 2005) the LPJ-GUESS-FROST simulate a annual NPP which is higher than for the standard LPJ-GUESS. As in principle the effect of frost is only negative, how it can be explained ? Is it only related to the fact that, for what I understood, you do a set of patch simulations with could then gives different results ? In other words, two different simulations with LPJ-GUESS could give slightly different means ?

Reply: Thank you for spotting this effect in Fig. 2. Yes, in principle the direct effect of frost in the model is only negative. In years with a considerable number of gridcells across Bavaria experiencing frost this leads to lower mean annual NPP in LPJ-GUESS-FROST as compared to LPJ-GUESS. More indirectly, by reducing NPP late-frost in LPJ-GUESS-FROST alters carbon allocation patterns as seen in Figure 3C. Subsequently, the mean carbon mass in vegetation across Bavaria tends to be lower in LPJ-GUESS-FROST than in LPJ-GUESS. Less carbon mass necessitates less maintenance respiration, consequently the amount of GPP that is lost to respiration is often lower in LPJ-GUESS-FROST than in LPJ-GUESS. In years with only few or no gridcells experiencing LSF, this leads to a slightly higher mean annual NPP in LPJ-GUESS-FROST than in LPJ-GUESS. We will add a short explanation in the Figure 1 caption to describe this effect: “Note that due to lower NPP due to LSF in LPJ-GUESS-FROST, biomass is lower leading to a decrease in maintenance respiration. In none frost years the effect of lower maintenance respiration can lead to higher NPP in LPJ-GUESS-FROST than in LPJ-GUESS."

Reviewer 2:

We thank the reviewer for the editorial comments and will of course include those corrections in the revised manuscript.

1.

26/27: Maybe state explicitly that causally, the increased occurrence of LSF events is an indirect effect that results from a statistically earlier start of the growing season, leading to budburst in deciduous trees at times where the likelihood of frost events is still higher than later in the season.

Reply: This will be stated more explicitly in the revised manuscript by changing the sentence in line 26-27 to, "... under a changing climate, as an earlier start of the growing season leads to the timing of leaf-out and periods with high likelihood for frost to increasingly coincide (Zohner et al. 2020; Ma et al. 2019)."

2.

35/36: Not only beech, but a generally higher share of deciduous broadleaf trees in forests, as mixed deciduous broadleaf forests are perceived as more resilient to climate change and conducive to biodiversity and habitat conservation.

Reply: Good point, we will change the sentence to reflect that this is not only applicable to beech, "... focused on re-establishing a higher share of deciduous broadleaf species, including beech."

3.

45-47: Not to forget other aspects aside carbon sequestration, such as tree health and mortality risk. The data series of the annual forest condition survey in Germany ("Waldzustandserhebung") shows an increase in beech trees with partially to strongly defoliated crowns from 2017 onwards. In 2021 and 2022, only 16 to 21% of beeches in Germany showed no signs of crown thinning, while approx. 45% showed signs of significant crown thinning.

Reply: To clarify that LSF impacts not only carbon sequestration, but also other aspects as mentioned by the reviewer, we will expand this sentence to read, "... of temperate forest ecosystems and underestimating detrimental effects from climate change related to tree health and mortality."

4.

61: "In both cases, freezing damage was observed in European beech." – Add a reference?

Reply: Will be added (Dittmar et al. 2006, Principe et al. 2017)

5.

86-89: Is this the same parameterization for all cohorts within a PFT, or does LPJ-GUESS account for age-dependent variation within a PFT? Understory beeches start leaf-out earlier than mature beeches in the upper canopy layer so that they can profit from a period with reduced shading / light competition. However, this earlier start should also make them more prone to experience LSF events than the mature cohorts, with potentially adverse effects for recruitment success. This could be an aspect to be included in future versions of the model, if not accounted for yet in the LSF scheme.
Reply: We thank the reviewer for this suggestion. As of now, LPJ-GUESS does not consider age-dependent variation in leaf-out times but this is certainly something that could be included in future version of the model and will be discussed in the revised manuscript as an avenue for future model development. In line 310, we will add the following sentences, "... due to radiative cooling. Additionally, due to the strong controls of leaf-out on frost risk, improving the phenological models used in LPJ-GUESS should be a priority. Aside from parameterizing the phenological model for a wide range of broadleaved, deciduous species, future phenology routines should also consider age-dependent variation in leaf-out times."

6.

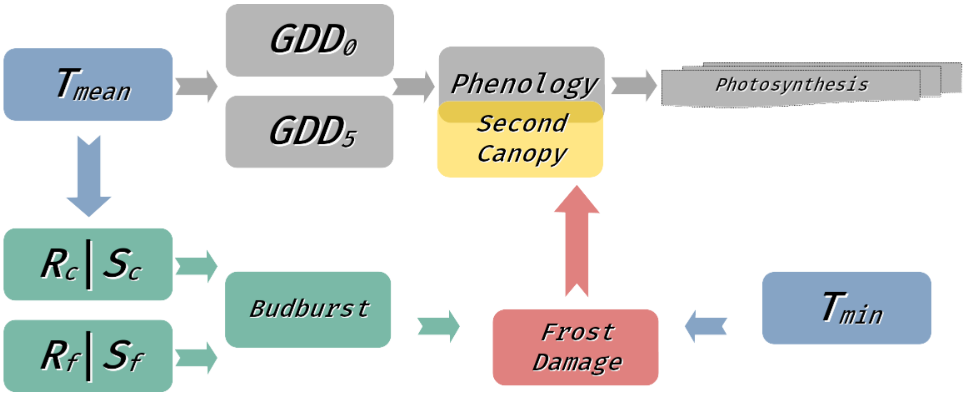
92: Technically / physiologically speaking: LSF and the damage caused to the leaves implies a loss of stored carbon resources, i.e., a reduction in the carbon storage pool, and a re-set or partial re-set of the phenological cycle, i.e., a reduction of canopy leaf area. After having read the paper, I am not sure if the first aspect (loss of carbon resources and need of reallocation from storage reserves to replace lost leaf biomass is implemented in the model. If it is not, this is an aspect that needs to be addressed urgently, because otherwise, the size of the overall effect caused by LSF may be underestimated. Needing to withdraw carbon from storage reserves may not reflect directly on the growth performance of the consecutive growing season. However, a depletion of C-storage reserves makes trees more prone to suffer if additional disturbances occur that require carbon reserves to repair damages. For example, to repair xylem damages caused by cavitation during drought. Resulting carbon debt ultimately may increase mortality risk for affected trees.

Reply: We thank the reviewer for mentioning this crucial aspect. We revised the model to address this aspect by reducing the amount of NPP available for carbon allocation. Carbon allocation in LPJ-GUESS occurs at the end of the year by distributing the accumulated NPP to the various biomass compartments according to a set of allometric constraints. If the accumulated NPP is not sufficient to allocate enough carbon to each compartment to satisfy these constraints, additional carbon can be "borrowed" from a carbon storage pool. This pool must be re-filled when enough NPP is available. The carbon lost due to LSF is calculated as the total carbon allocated to leaves for a given year multiplied by the fraction of canopy coverage at the time of LSF. At the end of the year, before allocation occurs, this fraction of carbon is deducted from the storage pool. A portion of this is immediately "repaid" before allocation, reducing the amount of carbon available to the structural compartments. Over subsequent years, more NPP is allocated to the storage pool until it is completely refilled. In the revised manuscript, Figure 3C will also show the difference in the carbon storage pool between LPJ-GUESS-FROST and the standard model version. We will add a corresponding paragraph with detailed information to the methods section.

7.

96: How about partial leaf-out? Is this discrete, or continuous between 0 and 1 to allow representation of partial leaf-out? Leaf-out happens within a time span of two-three weeks, during which leaf biomass and LAI increase from zero to maximum.

Reply: Thank you for pointing this out, our wording here was a bit unclear. LPJ-GUESS-FROST relies on two parallel, but separate models for describing phenological status. The standard LPJ-GUESS phenological model is continuous from 0 to 1 and describes the daily phenological status as a fraction of full canopy coverage. The newly implemented model, based on Kramer et al 2017, is indeed discrete and simulates the status of bud-burst which we initially described as “leaf-out”. As the term “leaf-out” is somewhat ambiguous we now replace it with the term “bud-burst”. The standard phenological model in LPJ-GUESS serves to simulate the behavior of biomass and LAI increasing from zero to maximum as you mention. The new, “bud-burst” model serves to pinpoint a specific phenological stage after which the unfurling leaves are susceptible to frost. For more clarity, in the revised manuscript we will include additional equations to describe the standard LPJ-GUESS phenology model. Additionally, we will include the following schematic figure in the supplement showing how the two phenological models work in tandem.



Caption: Schematic showing the integration of the new frost module (red, green, and yellow) with the existing LPJ-GUESS phenology model (grey) in dependence on climatic drivers (blue). The LPJ-GUESS growing degree day model simulates continuous leaf development from 0 (no leaves) to 1 (full canopy cover). This phenological status is then used for further model processes such as photosynthesis. The new frost module includes a parallel phenological bud-burst model which simulates a distinct point of bud-burst (i.e. the point at which developing leaves become sensitive to LSF). This model uses a sequential, two-stage approach with a chilling stage (R_c,S_c) and a forcing stage (R_f,S_f) described in Equations 1-4 in the methods section. This bud-burst status is used to determine LSF damage in conjunction with the minimum temperature (T_{min}). In the case of LSF, the continuous phenological status is reset to 0 and a second cohort of leaves has to be rebuilt before photosynthectic activity can resume.

8.

117: This implies that LSF is a yes/no decision. It does not yet allow a quantification of the severity of the frost event (which should be a function of the below-zero temperature value, and maybe additionally the duration of the frost event, as one moderately frosty night will differ in effect size from a several-day-period with strong frost). The stochastic application for individual patches partially addresses this aspect, as far as I understand?

Reply: Yes, that is correct. The reviewer brings up several good points that we had also considered but ultimately decided not to attempt to implement in the model due to lack of supporting, empirical data. Some studies using saplings treated with different temperatures in climate chambers have identified a relationship between severity of leaf loss and increasingly negative temperatures (Vitasse et al 2014, Baumgarten et al 2023). However, Baumgarten et al (2023) also found that more severe frost and therefore more leaf damage, did not necessarily lead to higher growth reductions.
To overcome this lack of conclusive data we apply the frost threshold stochastically for each patch (as described in the methods in lines 118-119 and the discussion in lines 297-300). This leads to some patches having higher freezing resistances than others for a given day. Since the model state of each gridcell is ultimately represented as the average of all patches, this approximates continuous levels of frost severity. When all (half/no) patches in a gridcell experience frost this leads to 100% (50%/0%) frost damage. The method section of the revised manuscript will include a more detailed explanation of the consequences of this stochastic approach starting at line 124.

9.

122: How is the duration of the leafless period determined in the model? An assumed constant (how long?), or a function (depending on what variables?)?

Reply: We thank the reviewer for pointing out that the description of the leafless period is missing. We will add in the manuscript in line 122 that we "implemented a constant leafless period based on observations from several studies (Menzel et al., 2015; Rubio-Cuadrado et al., 2021; Nolè et al., 2018) which found that the time between frost and full development of the second cohort of leaves ranged between ~ 40 and ~ 80 days. Consequently, we implement a 40-day leafless period where trees have no leaves, followed by a 20-day re-greening period where phenology steadily increases to 1 (i.e. full leaf coverage)."

10.

125/126: How long are the time series of tree ring data? Where are they made available?

Reply: We describe the minimum, mean, and maximum length of the tree ring series in lines 138-140 of the methods section (2.3.). For clarity, we will expand this description to include the length of the site chronologies used for comparison with LPJ-GUESS-FROST. Additionally, we will include a supplementary figure showing the chronology RWI and sample depth for each site. Should the revised manuscript be accepted for publication, the tree ring data will be made available in a public Github repository associated with a DOI via Zenodo along with the rest of the data and scripts used for this study.

11.

136: Yes, but climate influence itself is composed of a variety of factors, including growing season water availability and temperature. These other climate effects contribute to the overall signal (the RWI) in combination with the frost effect. Did you attempt to address this issue? Is there a way to separate the frost effect contribution from the overall climate signal?

Reply: The intention of the detrending was to remove age- and size-related trends from the tree ring data. We do not aim to exclude factors such as growing season water availability and temperature since the NPP modeled by LPJ-GUESS is also influenced by these factors (among others).

12.

166: Did you a) detrend the 30 year slice, and b) did you do a blockwise randomization of the detrended years, or did you simply use the years as-is (that often leads to a saw-tooth behavior in the results that is not quite realistic)?

Reply: We detrended the temperature for the 30 year slice and followed the standard protocol for LPJ-GUESS used the years "as-is" without randomization, as the spinup is relevant for the equilibrium of long-term carbon pools (such as soil carbon) and thus does not directly influence the transient simulation runs (starting in the year 1951).

13.

168/169: You used identical spin-up sequences for both LPJ-GUESS and LPJ-GUESS-FROST runs, correct?

Reply: Yes, that is correct. For further clarity, we will amend the description to read, "... we used the identical post-spinup state …".

14.

175 ff: Not clear: did you model multi-species patches including beech, or monospecies-stands with beech only? It becomes clear later on in the manuscript that you simulated monospecific stands, but it would be useful to already clarify this point here in the methods description.

Reply: We thank the reviewer for this suggestion. We will change the sentence in question to read "... to simulate monospecific European beech stands."

16.

191: The direct impacts, yes. However, indirect effects (e.g., a reduction of carbon storage size due to a second leaf-out required to at least partially replace the frost-damaged foliage; an overall reduced growth performance) will put affected trees on a differing growth trajectory in consecutive years.

Reply: Good point, we should have been clearer here. In the context of the resistance index we are only interested in the direct impacts in the frost year. To reflect this and avoid confusion regarding indirect impacts as the reviewer mentioned, we will clarify that, "The direct impacts of LSF are contained to a single vegetation season."

17.

Figure 1: Any idea why the response of LPJ-GUESS_FROST is so much more homogeneous in 2011 than in 1953? And why it is more pronounced than in the observations in 2011, but somewhat less pronounced than in the observations in 1953? (Explanation attempt can be in discussion section).

Reply: We identified an inconsistency in the random number generator used to stochastically apply the frost threshold to each patch which resulted in the extremely homogeneous model response in 2011. This has been fixed and the revised model simulates a more heterogeneous response for the 2011 LSF.

Nevertheless, the model still simulates a more heterogeneous response to the 1953 LSF than the 2011 LSF. This residual difference in responses of LPJ-GUESS-FROST in 1953 and 2011 can be explained by the simulated onset of leaf-out in those years. In 2011, the simulated onset of leaf-out across the 14 sites that experienced LSF ranged from DOY 111 (April 21) to DOY 116 (April 26), well before LSF occurred between DOY 123 (May 3) and DOY 125 (May 5). Subsequently, from a phenological perspective trees at all 14 sites were at risk of frost damage between DOY 123 and DOY 125.

In contrast, in 1953 the simulated leaf-out across the 12 sites affected by LSF varied across a larger range from DOY 117 (April 27) to DOY 142 (May 22). The recorded LSF took place between DOY 128 (May 8) and DOY 131 (May 11). At 3 sites, simulated leaf-out occurred after DOY 131, meaning that of the 12 sites only 9 were phenologically predisposed to frost damage in 1953.

18.

219: I find that a bit surprising, given that Bavaria contains part of the Alps and therefore high-elevation territory where productivity should be considerably lower than at low elevations.

Reply: Our wording in the original manuscript was unclear. In the revised manuscript we will be more clear and state, “The range of NPP across all gridcells in Bavaria varied from nearly 0.3 kg C m^{-2} to around 0.6 kg C m^{-2} in LPJ-GUESS. Introducing late-frost dynamics increased the variation in NPP to range from ca. 0.15 kg C m^{-2} to 0.6 kg C m^{-2} across gridcells, as some regions suffer from heavily decreased productivity in response to late-frost damage (Figure 2).”

Additionally, we will mention the effect the resolution of the input climate has on modulating productivity responses related to elevation in the discussion on the impact of forcing data on the model outputs (see also the response to comment 29).

19.

222/223: Bavaria-wide average loss, or average loss across frost-affected grid cells only?

Reply: Here we refer to the Bavaria-wide average loss. To make this clearer, we will change the sentence to read, “Average across the entirety of Bavaria, the cumulative …".

20.

224: “The lost productivity translates to biomass loss.” _ And a reduced carbon sink strength of affected forests, which has implications for the National GHG inventory reporting (side note).

Reply: We thank the reviewer for bringing this implication to our attention, however, we believe taking into consideration the impacts of LSF on National GHG inventories goes beyond the scope of our paper.

21.

226: “This biomass loss primarily affects the sapwood” - That agrees well with expectations. Did you adapt the carbon allocation scheme within LPJ-GUESS-FROST to achieve this result, or did it emerge without additional adjustment?

Reply: This behavior was emergent and required no alteration to the standard carbon allocation scheme of LPJ-GUESS(-FROST).

22.

232/233: Looking at Figure 2, you actually managed to simulate frost events in a variety of years beyond these two years of special focus, which is a promising result you deserve to highlight as well.

Reply: We thank the reviewer for this encouraging comment. In the discussion of the revised manuscript following line 243, we will highlight that “Aside from reproducing the impact of two, well-known frost events for which tree-ring data was available, LPJ-GUESS-FROST simulates several additional LSF across Bavaria suggesting that LSF is not a rare phenomenon in beech forests.”

23.

243: Thirdly, the phenological representation of the leaf-out process in the model is yet a simplification of real-world processes and variability, and therefore some temporal mismatch between actual and simulated leaf-out can be expected as well. If your simulated leaf-out in 2011 was somewhat earlier than real-world leaf-out, that could explain part of the mismatch as well. Also, if the model indeed represents leaf-out as a nothing-or-all process instead of a continuous process extending over two to three weeks with leaf biomass unfolding and building up during that transition period, in which case it should also matter if a frost event happened in the earlier or later stage of leaf-out. In addition, I'd expect frost severity and frost duration to also modulate the effect size. A light frost of maybe just little below zero for one night should have a less pronounced effect than, say, a night with -5 °C or three consecutive nights with below-zero temperatures.

Reply: We thank the reviewer for bringing up these points. As mentioned in response to comment 17, the simulated leaf-out indeed plays a role in explaining the mismatch between the model and the tree-ring data. We agree that frost severity and duration may play a role in modulating the effect of LSF on productivity, yet current evidence is inconclusive (Baumgarten et al 2023). In the methods of the revised manuscript, we will more clearly state that LPJ-GUESS does indeed simulate continuous leaf-out. Additionally, we will add a clearer separation between the separate phenological models used to 1) simulate the full cycle of leaf development from 0 (no leaves) to 1 (full canopy coverage) and 2) the bud-burst model designed to specifically pinpoint the timing of bud-burst as the beginning of the period when developing leaves are susceptible to LSF. As mentioned in the response to comment 7 we will also add a schematic to the supplement showing how the two models work together.

24.

261: Do you plan to ultimately also implement LSF effects for other deciduous broadleaf species in LPJ-GUESS? It should matter in a similar way for other early-budding European species, such as maple or hornbeam. It should even affect some of the coniferous species, as their development of new shoots to some degree is also sensitive to frost. With an earlier end of winter dormancy, the trees lose their frost hardiness earlier and become more prone to LSF. Tree species at risk from late frost are primarily fir, beech, chestnut and - although late bloomers - also ash and walnut.

ReYes, that is planned for the future. We will add a corresponding statement to the discussion in which we provide an outlook on further potential refinements.

25.

271/272: For how long exactly does the dormancy last?

Reply: This dormancy or leafless period is based on observations by multiple studies (Menzel et al., 2015; Rubio-Cuadrado et al., 2021; Nolè et al., 2018) and is comprised of a 40 day period where phenology is set to 0 (i.e. no leaf coverage) followed by a 20 day re-greening period where phenology steadily increases to 1 (i.e. full leaf coverage).

26.

276/277: This should also be a challenging endeavor, because it would require tree stands that experience identical environmental conditions except for experiencing frost or not. Otherwise frost effects are always integrated with additional climatic and non-climatic effects on tree ring growth.

Reply: Thanks for pointing this out. In the revised manuscript we will expand upon the sentence in question to reflect this, "... effect of late-frost on tree biomass. This would require forest stands with identical environmental conditions aside from late-frost, which is not possible in a natural setting but can be simulated using DVMs."

27.

278/279: Integrated over that time period, or in comparison in the final year of the simulation period?

Reply: We thank the reviewer for pointing out this ambiguity. We refer to the difference in vegetation carbon between LPJ-GUESS and LPJ-GUESS-FROST in the final year of the simulation period. To clarify this, we will change this sentence to read, "In the final year of our 69-year simulation period the difference in vegetation carbon between LPJ-GUESS and LPJ-GUESS-FROST amounted to a five percent reduction due to the effects of LSF."

28.

291 ff: Likely, frost damage across all leaves within a canopy follows a statistical distribution, with some of the most protected leaves within the canopy suffering hardly at all and some of the most exposed leaves being lost to frost damage entirely. Integrated across all leaves within a canopy, this results in a continuous effect nature, not a yes-or-no effect nature.

Reply: We fully agree with the reviewer, however, since LPJ-GUESS models the canopy with a big leaf approach we cannot simulate the distribution of frost damage within the canopy.

29.

305/306: Which poses a particual challenge for predictive modeling of future dynamics. Especially because the commonly used (downscaled) climate forcing from GCM output is unlikely to catch such regional effects.

Reply: Good point, we will include this aspect in our discussion on future challenges related to modeling microclimate and the discrepancy between measured 2m air

30.

312: "carbon costs for re-building the canopy should not be ignored" - Are they ignored so far?! I implicitly assumed that producing leaf tissue biomass involves reallocation from carbon from a storage pool to the new biomass (including growth respiration losses)? If this mechanism is not yet part of the model, it should be addressed sooner rather than later. Producing leaves must come at a cost, carbon-wise!

Reply: As mentioned in response to comment 6, the revised version of the manuscript includes re-allocation of carbon from the storage pool to account for the loss of biomass due to LSF. As of yet, this is a relatively simple representation of carbon storage and the discussion in the revised manuscript will highlight the need to refine the representation of carbon storage dynamics in future versions of the model.