

Response to Referee #1

We thank R1 for this detailed review, especially for going through the equations, which has enabled us to significantly improve the description of the new process implementation in our article. We apologize for the erroneous formulations of several equations and have corrected them in the revised manuscript. We double-checked in the code that the lines of code correspond exactly to the revised formulation of equations. Enclosed please find a detailed explanation of the revisions we made based on R1's comments. For your convenience, comments are in bold and our response is in italic. Revisions we made in the manuscript are presented in italic with grey background.

This paper represents a great amount of work in model development, and in general it is well justified, well written, and the availability of such a model will contribute towards science both through using the improved model and informing other model developers. Therefore I recommend that it should be published in this journal, but with some clarifications and a bit of consolidation.

Firstly, the paper is rather long. I am not convinced that separating the analysis in figures 8-10 into different continents (Europe/Asia/America) is really relevant to the model developments here. Differences between the PFT's should still be visible in the aggregate results. Consolidating these would reduce the figures and you could remove some of the discussion of inter-continental differences from the text. These are interesting but the paper would benefit from being a bit shorter.

We are aware that the article is rather long: this is due to our wish to introduce together the two or three vegetation types needed to improve the current representation of Artic vegetation in the ORCHIDEE model. As the reviewer suggests, we removed the division by continent for figures 8-10 and the analysis associated (in Sect. 3.2 & 4.2), which was replaced by the Fig. 11. The old figures and analysis by continent is moved to the supplementary material (Figs. S1 to S3).

Throughout the manuscript you have used the word "summergreen", which I have never heard before and we always use "deciduous". I'm not sure summergreen is really a word in English and maybe you should use deciduous instead? Sorry if I'm wrong here.

In the model ORCHIDEE, the use of the word summergreen is required to compare the deciduous summergreen and raingreen (present only in tropical climates, as presented in Table 1). Considering that we are working only on boreal landscapes, it seems simpler, as suggested, to use the word "deciduous" in this article (p3. l.14-16, p5. l.25, p.19 l.28, p.24 l.32, Tables 1 & Table 2 and Fig. S3)

Specific comments

*** P1 Line 17 what you mean by "a larger phenological plasticity" isn't entirely clear to me. Maybe because I am not a specialist in vegetation but I think this will be read by other 'general' land surface modellers so could maybe be a bit clearer. Do you mean the phenology varies more in the season? Or more quickly over time?**

"Phenological plasticity" means that the phenology of the plant can be shifted under hard climatic constraints, without causing its death. To be clearer, in the article we added a short description (in brackets p.1 l.17-18): "(i.e. adaptability and resilience to severe climatic constraints)".

*** P1 Lines 23-26. Please check all of these numbers for the percentage changes. I can't find them all in the main text or they don't seem to be consistent - for example, the change in roughness is quoted as 25% in the main text (page 20, line 33), but 41% in the abstract.**

We have checked all numbers (value and %) present in this article. We have corrected the mistake (p.20 l.34 "decrease of 41% from 55°N" and we added in the main text: p.19 l.33-34 "For example, the NPP is lower by 31% north of 55°N", p.20 l.20 "+3.6% North of 55°N", p.21 l.1 "(-33% from 55°N), as expected mainly during ...", p.21 l.17 "(+11% with 140 km³.y⁻¹ north of 55°N)".

*** P5 line 6 "coefficients a1 and a2" - should be "b1" instead of "a2" as it seems to be called b1 in the table. Furthermore, you said you chose values so that stomatal conductance would not depend strongly on VPD but then the multiplier of VPD (b1) takes a larger value for NVP's than for the original grasses so this seems a bit counter-intuitive. Could you add a bit more explanation here?**

Indeed, as you have pointed out, the coefficient should be " **b_1** " instead of " a_2 " (p.5 l.19). For the second comment, as you noted, the objective was to reduce the dependency of stomatal conductance to the humidity and CO_2 concentration, so to reduce the second term of eq. (1). The only adjustable constants are in eq. (2) (with the calculation of f_{VPD}): to reduce f_{VPD} we had to increase the term " $1/(a_1-b_1.VPD)-1$ ", and so to reduce " $a_1-b_1.VPD$ ". Our choice to modify b_1 is based on the fact that a_1 is the same constant for all PFTs, when b_1 was already dependent on the vegetation type (trees, C3 grasses or C4 grasses). We propose here not to add more detail to the article, which is already too long.

*** Section 2.2.3: For the NVP's, when you have negative NPP you induce a biomass loss function. But presumably the negative NPP itself should also lead to a biomass loss. I am interested to know how this works - are these are somehow linked or are they two separate loss terms?**

This is a very good point. In ORCHIDEE there is no explicit biomass loss when the NPP is negative. If NPP is negative, this means $GPP < Ra$ (respiration) and this leads to a loss of biomass by the respiring tissues (to support Ra). But here, for NVPs we added a new explicit (and unlinked) loss term, to compensate for a reduced leaf biomass mortality (compared to the C3 grass PFT used as the starting point) due to the suppression of seasonal leaf fall and the increase of leaf longevity. Moreover this loss of biomass appears also if the NPP is null (not necessary negative).

*** Section 2.2.3 and Figure 1. Why did you reduce the turnover again after a certain amount of time? (ie why does the line on figure 1 decrease again after it reaches its maximum?) It would be helpful to provide some evidence from the literature or some more scientific justification here.**

The aim of this turnover, presented in section 2.2.3 Eq. (3) and Fig. (1), is to represent the behaviour of NVPs in extreme conditions, such as snow cover or dryness, during a long period (more than 1 month). If the turnover was maintained at the maximum (k_{lmax}) when there is no NPP, rapidly most of the biomass would be removed and the plant would die. But that doesn't correspond to general observations of the presence of NVP biomass after snow removal, or after long very dry periods (with the desiccation process). To account for this resilience, we propose to reduce the biomass loss after a certain period of severe conditions. Note that there is still some biomass lost due to senescence. As suggested, we added a small description p.6 l.10-12: "After a maximum, the turnover decreases in order to represent the induced

resistance and thus survival to extreme conditions, i.e. under snow cover in winter or under dryness”.

*** P6 A few issues around equation 4 (which is labelled as 3 by the way!). Underneath the equation you wrote "b is the daily leaf biomass" but this is in units of gCm^{-2} , which doesn't have any units of time, so it isn't 'daily'? Do you mean the value gets updated daily? I suggest removing the word 'daily' here. However, there should be some units of time in the turnover rate and I think these might actually be in l_{coef} , which you have given as no units, I think this should maybe have units of day^{-1} or similar? Difficult for me to tell from the information here but please check it. Another point about this equation, why does it only apply when $LAI > LAI_{max}$ instead of $LAI > LAI_{lim}$? Using LAI_{max} means it will jump from zero when you reach LAI_{max} , whereas if you start turning over when it reaches LAI_{lim} , it will increase smoothly from zero. Maybe this was a typo, but if not, can you explain why you do it? Thanks!**

As you suggest, the confusion came more from a lack of information/description than from real mistakes. We thank the reviewer a lot for these comments. Here are all the changes we made:

- *The label of equation 4 was changed (p6. l.27).*
- *The "daily" was removed (p6. l.28), because it stood for "updated daily" and that could be confusing.*
- *We added the unit of l_{coef} : " (d^{-1}) " (p6. l.28 and table 2).*
- *There was some confusion between LAI_{max} used for the photosynthesis and LAI_{lim} . So we checked the LAI_{xxx} and changed the syntax when that was necessary (p6. l.25-28).*

*** P8 Equation (10). This is quite a complicated equation and it would be really useful to see what the moisture function actually looks like. I suggest you add a plot of this. I looked in the paper that you referred to but it was not easy to immediately see it, and the moisture function for respiration is important so would be great to include the plot here.**

Indeed, this equation is very complex. We followed your recommendation adding a new figure (Fig. 4) in order to have a better understanding of the new function and some text in p.9 l.1: "Equation (10) and Fig. 4 describes..."

*** P9 line 4/5 says that albedo and roughness were set the same as C3 grasses. I guess for NVP's the roughness could be quite different from grass? Could you add a comment on possible differences? Either here or in the discussion.**

The roughness of NVPs can probably be considered to be of the same order of magnitude (compared to shrubs and trees), because they are both less than few tens of centimetres. However the albedo is very different, because their colour can vary widely especially depending the hydric status. We add in the discussion p.23 l.29-33 some precision about this issue: “The albedo of the new boreal vegetation is still considered the same as that of the PFTs they are derived from, although the colours of these PFTs may vary substantially, with important impact on the albedo. In particular for NVPs (Porada et al., 2016) the colour may vary according to the relative humidity of the plant (Hamerlynck et al., 2000), an effect linked to the temporal dynamics of surface moisture that is difficult to capture with global models”.

*** P10 Equation 11a) The text says it’s a logarithmic function, but this does not seem to be the case? Equation 11b) Bottom line of fraction should have D^{γ} not D^2 Given these equations, I am not sure it makes sense to fix the crown area but still vary the biomass and height. This means that the allometric relations don’t hold (for the case without dynamic vegetation), because the allometric relations are basically the relationship between height and area (or diameter-but these are related), yet you are varying the height and not the area. Could you comment on this? Are you assuming that the number of individuals changes in order to keep the crown area fixed? If so, please make that clearer in the text.**

Equation 11.a) it not expressed as a logarithmic function, but in order to describe the appearance of this function, we can consider that the usual function closest to eq. 11.a is the logarithmic function: starting from 0, increasing similarly to the logarithmic function and assuming a maximum (H_{max}). To be clearer, we propose to replace the “is” by “resembles to” (p.10 l.1).

We corrected equation 11.b. (“ D^{γ} ” in place of “ D^2 ”), p.10 l.9.

The last part of this comment is about a fundamental choice of the developments performed in this article with the aim to obtain a realistic height of the vegetation to compute roughness, albedo or the height of shrub above the snow. The two strongest constraints were that i) without activating the dynamical vegetation (DGVM) module the total area of each PFT was fixed and ii) to be consistent, the equations with and without DGVM have to be the same. In order to have the vegetation height as a function of the biomass, we chose to implement a dynamical height depending on the biomass, following these equations (Eq. 11). Thus, as noticed by the reviewer, to account for vegetation height and diameter variations within a fixed area, the number of individuals has to vary. As a consequence, we can have only few tall shrubs or many short shrubs for a given area and biomass. To be clearer in

the text, we added p10. l.5-6: “and the number of individuals is adapted in order to keep the crown area fixed (Eq. (11.c. & d.))”.

*** P10 Section 2.3.2 In the introduction you said that shrubs accumulate more snow in winter than trees (p3 line 13), but in this section you seem to treat them both together. What is the reason for this?**

The initial aim was to represent differences of snow accumulation on vegetation, not usually represented in ESMs. In this paper we started with the most significant difference between woody and non-woody species. In order to represent the differences between shrubs and trees, we would need to take into account precisely the spatial heterogeneity (vegetation coverage...), the phenology (evergreen and summergreen) and the wind effects. Given the complexity of the involved processes, it was beyond the scope of this already long paper and we thus focused only on the woody vs non-woody species difference. The sentence in the introduction is general and defines the ultimate objective.

*** P10 equation (13) I can guess what you are doing here - assuming that with very few shrubs they'll be spread out so they won't accumulate much snow, and with a lot of shrubs of course the snow will be the same as the grid box mean because they are covering the whole grid box. But what is the justification for peaking in the middle? Maybe with just a few shrubs they would still accumulate snow? Did you get this function from somewhere or did you come up with it yourself? Could you either (in the first case) add a reference or (in the second case) give a bit more explanation of the physical reasoning?**

This comment is very constructive. As mentioned above, we did not find a simple and robust approach in the literature to take into account the differences of snow accumulation on vegetation. The best solution would have been to separate the snow accumulation (and the energy balance) by vegetation type, but this was not possible within the scope of the study. We thus chose a simplified approach, as explained by the reviewer. However, in light of your comment, we realize that we probably over-simplified the equation: indeed few shrubs should still accumulate snow. With this suggestion we could revise the threshold used in Eq. 13 and define a new equation:

“ $1+4 \cdot f_v$ ” if $f_v < 0.2$ and “ $2 \cdot f_v$ ” if $f_v \geq 0.2$.

That may produce more realistic snow depth variations, with a peak of snow depth for high vegetation if its fractional cover is 0.2 instead of 0.5. However, given the small overall impact that is expected with such change and the

difficulties to launch again the optimization and validation we choose to keep the initial formulation but to add a comment in the text p.11 l.4-5 “Note that this equation is a heuristic formulation discussed in section 4”. In the discussion p.22 l.19-25 we added: “However, the snow-shrub interactions may be underestimated; Eq. (13), with a maximum snow depth obtained for a grid-cell fraction of high vegetation of 0.5, may underestimate the impact of shrubs on snow in the case of low shrub cover. Having only few shrubs still leads to significant snow accumulation (McFadden et al., 2001; Sturm et al., 2001). Further investigation of the sub-grid scale parameterization of snow-shrub interaction is necessary, possibly using similar equations but optimising the shrub cover fraction for which the snow depth is maximum (currently 0.5 but possibly significantly smaller).”

*** P11 Equation (15) I am not sure I agree about the form of this. Because you are integrating, the mortality rate (as a fraction of biomass) depends on the height of the shrub. Imagine your temperature is just constant with z , then the mortality rate will be proportional to $(H-H_{min})$ and thus higher for a taller shrub - despite both being at the same temperature. Is this something you wanted to include in the model? If so, you should discuss it. If not, I would suggest you instead divide the RHS of the equation (15) for M_{ce} by $(H-H_{min})$.**

We thank the reviewer for spotting the inconsistency. We indeed forgot to divide the RHS in equation 15 by the height. However, we do not divide RHS by “ $H-H_{min}$ ” but by “ H ” (Eq. (15), p.11 l.22), because we consider that the mortality is not applied below “ H_{min} ”. If the temperature is constant with z that means the mortality is applied only on the fraction of the vegetation above h_{min} : $((H-H_{min})/H)$.

*** P12 first paragraph: I don’t quite understand what f_{v_max} is. Do you prescribe a certain fraction of the grid cell to be occupied by a PFT but then it doesn’t necessarily occupy that whole fraction? Please explain this term a bit more.**

F_{v_max} is the maximum fraction of the grid cell occupied by each vegetation type (PFT), prescribed in the case of no dynamical vegetation. However, for grasses (and NVPs), which don’t have woody parts, we consider that the real fraction of vegetation cover can differ from F_{v_max} . The idea is to take into account, for roughness and albedo, the lack of leaves in winter. We use the Leaf Area Index (LAI) as a proxy for the vegetation cover, as usually done in global models, with an exponential decay. In order to improve the text, we added two sentences: p.12 l.6 “The fraction of vegetation (f_v) is used” and p.12

l.9-10 "to take into account the variation of leaf cover (for example absent for grasses in winter)".

*** P12 equation (17) - you do the weighted average in terms of 'log's, I assume this is standard procedure from somewhere but I haven't see it before. Please add a reference.**

Indeed, it is a standard simplified way of doing it, as detailed in "Vihma and Savijärvi, 1991" (p.12 l.15). The main principle follows from turbulence theory and the computation of the so-called drag coefficient that is a log function of the roughness length.

*** P13 L21-24 not sure what you mean by these things: - "survival or establishment limits" - limits in terms of what? Temperature? - "a cumulated degree-day threshold for the development" - maybe here you mean "..for the development of leaves"?**

We agree that the terms that we used were inaccurate. We added p13. l.25 "temperature" and changed the word "development" p13. l.26 to "plant growth".

*** P14 line 1, talks about methods for wetlands, but surely not all of your sites are wetlands?**

The published and unpublished data provided by Peregon et al. are more about lowlands. We take these data because we did not find any other data with total living biomass and productivity, on different sites, with multi-annual observations, and for the three new PFTs. Aware of this limit, we added an evaluation with biomass measurements from two other transects, one in Eurasia (Walker et al, 2011a) and one in North America (Walker et al, 2011b; and previous reports since 2007). The evaluation of the model with these observations is supported by a new figure, Fig. 9, and associated comment:

P.16 l.35-39 and p.17 l.1: "We further compare the simulated biomasses with two other Arctic transects. The first one is the North America Arctic Transect (NAAT). It is situated in a continental area, and includes eight field locations (70°N 149°W to 79°N 100°W) sampled from 2002 to 2006 (Walker et al, 2011b) chosen as representative of zonal conditions. The second, located in a marine-influenced area, is the Eurasian Arctic Transect (EAT). It includes six field locations (58 to 73°N, between 67 to 81°E) sampled from 2007 to 2010 (Walker et al., 2008, 2009a, 2009b, 2011a)."

P.18 l.23-35: “Carbon stock with two Arctic transect

To evaluate the modelled biomass in other Arctic sites (not used in the calibration step), including uplands and lowlands, Fig. 9 shows scatter plots of observed and simulated biomass along two transects: the NAAT (North America) and the EAT (Eurasia) Arctic Transect. The NVPs and shrub biomasses are relatively well reproduced by the model (i.e. within the error bars). For both PFTs, the standard deviation of the observations includes the 1:1 line, but the observed biomasses are on average higher than the simulated biomasses. Simulated shrub biomasses are biased low for the NAAT transect but not for the EAT transect.

In contrast, the mean value of observed biomass for boreal C3 grasses (Fig. 9.c) is low compared to the simulated biomasses for both cases. For half of the sites the simulated low biomass is in accordance with the observations, but for the other half the values are much larger ($> 300 \text{ gC.m}^2$ whereas the observations do not exceed 54 gC.m^2). Despite the optimisation with observations from western Siberia (Fig. 7; leading to a decrease of biomass compared to temperate C3 grasses) there is likely an overestimation of the biomass for boreal C3 grasses, probably associated with an overestimated productivity.”

Walker et al, 2011a: Vegetation of zonal patterned-ground ecosystems along the North America Arctic bioclimate gradient. Applied Vegetation Science 14, 440–463. Doi: 10.1111/j.1654-109X.2011.01149.x

Walker et al, 2011. 2010 Expedition to Krenkel Station, Hayes Island, Franz Josef Land, Russia, Data Report, Alaska Geobotany Center, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK. 63 pp.

*** P14 line 32/33, it seems odd that the Arctic grasses are assigned to cold climates but then they all end up in the South! Have you checked this?**

We have checked again the distribution of the vegetation, and we obtain the same result. That corresponds also to the “boreal trees” limit around 50°N and to mountainous regions. Note that our definition of the boreal region, based on Koppen Geiger climatic zones, has a relatively large extent given that we grouped several “continental cold climate” zones of the Koppen Geiger classification.

*** P15 line 7/8 What was the justification for these new distributions, especially with the grass fraction. Why did you include grass but not include any shrubs? Also a bit concerning that your percentages don't add up to 100%. What is the rest?**

In the standard ORCHIDEE version, the sparse vegetation class (from the ESA map) was distributed into 25% of trees + shrubs, 35% of bare soil and the rest as grasses; the NVPs were not considered. As explained in section 2.5, the too

small cover of NVPs in the satellite – derived product, led us to propose a new interpretation of the sparse vegetation class for boreal regions (based on other arctic land cover maps), i.e. 45% of sparse vegetation class is considered as NVP cover. Thus we removed 15% of bare soil and 30% of grasses to represent NVPs (see Table S1). To be clearer in the text, we added p.15 l.16-18: “The remaining fraction of sparse vegetation (25%) has not been modified and is considered as a mix of trees and shrubs”.

*** P16 : last sentence in section 2.6.1 talks about simulations and spin-up with no context (eg forcing data, soil characteristics?). I assume that the same simulation protocol as described in 2.6.2 is used for these simulations, and you extract the closest grid cells? But then the start of the simulation that it refers to at the end of Section 2.6.1 is not the same as described in Section 2.6.2. You need to more clearly explain what simulations are done/used for the parameter optimization.**

Indeed, the lack of details could lead to confusion. We did not include enough explanation about the set up of the simulations for the optimisation, which is different than for the evaluation step. The biggest differences come from the spinup (as already explained) and the spatial scale (at 0.5° for the optimisation). We clarified that in the text by adding p.16 l.34-36 and p.16 l.20-22: “The simulation for the optimisation was done with CRU-NCEP meteorological forcing (Wei et al., 2014; Viovy, 2015), at 0.5° resolution”.

*** Section 3.1 - the first 3 lines here are more like methods than results. Can you make this an extra (final) section in the methods perhaps?**

This is a good point. We have changed accordingly (p.17 l.10-13).

*** P17 line 23 How do you know the water stress in the model is too large? Could you show some evidence for this, or that it was seen in previous studies with ORCHIDEE?**

The text was probably confusing, as we did not pretend that the water stress in the model is too large, in Arctic or elsewhere. We only have few grid points corresponding to the “forest-steppe”, where the observations indicate a substantial vegetation development, when the model simulates a low development (low biomass). This forest-steppe ecosystem is situated at the foot of a mountain region (in the south), with less rainfall. So probably the local observation site has more soil water available for the plants than the large-scale (2°) mean soil water. To avoid misunderstanding (without much text increase), we add p.17 l.35-36: “due to a too large water stress... at 2° resolution in a mountainous region”.

*** P20 line 3/4 "too low LAI seems to be simulated in western Siberia" This looks more like the middle of Siberia to me?**

We now write "in the central-west of Siberia" (p. 19 l.1).

*** P22 line 14 "plant resistance to water stress" - I thought you added something that made the NVP's recover more slowly from drought, and lose biomass, rather than resist the drought. Sorry if I missed the point here - do the other types of plants instead die in those circumstances? If so, could you clarify this?**

This is complex, and given your comment, we realize that it was not clear enough in the manuscript.

For NVPs, first we removed the leaf fall and decreased the senescence. To partly compensate for that, we added a biomass loss when $NPP \leq 0$, but only during the first weeks in order to represent the cost linked to a resistance to extreme conditions. With this cost, the plant becomes more resistant and is able to survive during severe conditions. We made this more explicit (p.5 l.34-35 "extreme conditions introduced by lower leaf senescence and no leaf fall" and p.6 l.10-12 "After a maximum, the turnover decreases in order to represent the resistance induced and the survival, i.e. under snow cover in winter or under dryness").

Moreover, we reduced the maintenance respiration of NVPs in case of dryness (section 2.2.4) to represent the desiccation and the ability to resist efficiently to dryness. We added a reminder to these two processes p.22 l.10: "(through resistance to negative NPP (Sect. 2.2.3) and desiccation (Sect. 2.2.4))"

*** P22 line 32 "especially for NVP's" - Not sure about this. Aren't NVP's less nitrogen limited than other plants?**

Indeed, the interest to introduce the NVPs is to be able to represent the vegetation in stressful condition. We wanted to insist that simulating in a realistic way any stress condition is important to estimate and model the ecological advantage of NVPs. To be clearer, we changed the "especially for NVP's" by p. 25 l.9-11: "This is especially important for NVPs, which have an ecological advantage in these stressful conditions (such as poor nitrogen availability)".

*** P22 at the bottom of the page, you are talking about splitting shrubs into different types. It would be helpful to add in a comment about why it would be useful to do this? (What impact it might have?)**

Such split would be useful to represent evergreen shrubs, which represent nearly half of shrubs cover in Arctic. Separating evergreen from deciduous

shrubs can have important consequences, especially for the albedo in winter. We added in the text p.24 l.35-36: “evergreen phenology type, which represents more than 48% of shrubs North of 55°N according to the CCI product and Table S1”

*** P23 line 14/15, you are talking about how the seasonal cycle of NVP productivity differs from the vascular plants in the model, but there is no comment about whether these differences are realistic. You also mentioned earlier in the paper about ‘representing the observed temporal dynamics of lichen and bryophyte biomass’, but no reference to actual observations. It would be helpful to refer to some studies to discuss whether the behaviour of the model is realistic.**

We agree that important ecological functionalities have to be justified by observations, using the literature. We thus have changed the text by adding p.23 l.7-9: “This behaviour corresponds to the observation that NVPs are, compared to vascular plants, most active during the shoulder seasons, due to less severe water stress and reduced competition for light (Williams and Flanagan, 1996; Campioli et al., 2009)”

*** P23 line 37/38, “the new PFTs are more sensitive to climate change than the original ones” - the plots do not seem to fully support this. The fractional changes are maybe larger with the new PFT’s, but the ‘old’ PFT that you show on the plot (boreal broad- leaved trees) seems to have the largest absolute change and so potentially the biggest impact on the carbon cycle. I recommend modifying this discussion to account for this.**

We agree that we have overstated the response of the new PFTs to climate change. We have to put into perspective the larger fractional changes, and the relative “absolute” contribution. To clarify that, we added p.23 l.25-26: “even if their overall contribution (productivity and biomass) remains lower”

*** P25, Acknowledgements - I suggest you add more details of the projects, not just the acronyms i.e. full names and project numbers.**

We add p.26 l.2-5: “The authors acknowledge financial support by the European Union Seventh Framework Programme (FP7/2007-2013) project PAGE21, under GA282700, as well as a French – Swedish program that has funded the first author’s PhD, through the GAP project”.

*** P38 Table 5. I think it is interesting that one of the calibrated parameters (b) was calibrated to zero. This appears to remove the acclimation behaviour from the photo-synthesis model. Could you add**

a comment about this in the text? Do you think it's because the air temperature never gets very warm so acclimation isn't necessary?

*We thank the reviewer for this interesting suggestion. We therefore added p.22 l.29-33: "Moreover, the parameter that control the so-called entropy factor for photosynthesis rates (**b** in eq. (20)) was optimised to zero (Tables 5 and S2), involving de facto the removal of seasonal temperature dependence of photosynthesis. This results highlight a potential limit of the Yin and Struik (2009) expression for carboxylation rate and could be due to the fact that the air temperature never gets warm enough to induce seasonal acclimation."*

Technical comments (In general the writing is good but I picked up some gram- mar/typos on the way through so will list these here.)

All of these technical comments were taken into account in the new version of the article.

- * P1 Line 24, "transpiration (+33%)" -> "transpiration (-33%)"
- * P2 Line 23/24, "is relatively simple and discretized on few" -> "has been relatively simple, with few"
- * P2 Line 26 "either trees or grasses PFTs." -> "either trees or grasses."
- * P2 line 27 "in the reality" -> "in reality"
- * P2 line 36 "interactions part" -> "interactions as part"
- * P3 line 4, I'm not sure about how you have referenced the CAVM, you have written "Mapping Team et al.", I wonder if it should just be "Mapping team" (and then the names listed are the members of the mapping team, not additional people?)
- * P3 line 7 "does not allow to" -> "does not allow it to"
- * P3 line 9 "mosses and lichens and shrubs" -> "mosses, lichens and shrubs"
- * P3 line 12 "more resistant for hydric" -> "more resistant to hydric"
And "or for nitrogen limitation" -> "or to nitrogen limitation"
- * P3 line 15 "to warming whereas trees" -> "to warming, whereas trees"
- * P4 line 16 "C3 grasses plants" -> "C3 grasses"
- * P6 line 1 "cold temperatures" -> "cold temperature"
- * P6 line 33 "(use in ORCHIDEE)" -> "(used in ORCHIDEE)"

- * P7 line 13 "when NVP get desiccated." -> "when NVPs get desiccated."
- * P7 line 30 "NVPs layer" -> "NVP layer"
- * P8 line 24 "to define the control litter" -> "to control litter"
- * P9 line 12 "processes as trees." -> "processes to trees."
- * P9 line 22 "additional shrubs types" -> "additional shrub types"
- * P11 line 2 "dynamically the vegetation distribution" -> "the vegetation distribution dynamically"
- * P11 equation 16 Change 'else' to 'otherwise'
- * P12 line 6 "there is no woody" -> "there are no woody"
- * P12 line 27 "equation described previously" -> "equations described previously"
- * P12 line 27 "as well as few" -> "as well as a few"
- * P12 line 29 "Cold climates" -> "Cold climate"
- * P12 line 34 "themselves function of" -> "themselves functions of"
- * P13 line 12 "list of variable" -> "list of variables"
- * P13 line 31 "observations located in" -> "observations are located in"
- * P16 line 9 "number of iteration" -> "number of iterations"
- * P18 line 12 "referred as" -> "referred to as"
- * P20 line 25 "occur in early spring" -> "occurs in early spring"
- * P20 line 27 "impact the albedo" -> "impacts the albedo"
- * P20 line 34 "Contrariwise" -> "Conversely"
- * P21 line 14 "5mmd-1" should be "0.5mmd-1" ?
- * P21 line 20 "permanent frozen soil" -> "permanently frozen soil"
- * P22 line 27 "implies to introduce" -> "implies introducing"
- * P22 line 30 "availably" -> "availability"
- * P23 line 19 "on the same time" -> "at the same time"
- * P24 line 7 "in liason with" -> "in conjunction with"
- * P24 line 13 "ecosystem occur" -> "ecosystems occur"
- * P24 line 23 "permafrost extension" -> "permafrost extent"
- * P24 line 33 "soil water dynamic" -> "soil water dynamics"
- * P25 line 5 "and reach around" -> "and reaches around"
- * P25 line 11 "reduce locally" -> "locally reduce"

*** P25 line 12 "snow dynamic" -> "snow dynamics"**

*** Table 2 (df) "Maximum number of day for this extra turnover" -> "Maximum number of days..."**

*** Table 3 caption "values are choose" -> "values are chosen"**

Response to Referee #2

We thank R2 for this detailed review. Enclosed please find a detailed explanation of the revisions we made based on R2's comments. For your convenience, comments are in bold and our response is in italic. Revisions we made in the manuscript are presented in italic with grey background.

Druel et al. include a number of new processes and parametrizations into the land surface model ORCHIDEE that are thought to be important in high latitude ecosystems including * parameter optimization of C3 grass, * implementation of a new shrub PFT, and * implementation of a new PFT representing lichens and bryophytes.

Several additional relationships and processes have been also included, such as * shrub-snow interactions, * vertical soil organic matter profile, * moisture dependence of heterotrophic respiration and anoxic conditions, * moss effects on thermal diffusivity.

In general, I fully agree with the importance to advance the LSMs in these respects and I would like to see such important model development published soon. The authors also use a number of site-level observations and a formal parameter calibration procedure for this model development. However, I have some serious concerns about this manuscript which should be addressed prior to publication.

Most importantly, there are too many different topics treated in this single manuscript which then are themselves mostly only superficially addressed and which even may not have any relation to each other (in the model). I strongly suggest to focus the paper on 1-2 research questions and a reduced amount of new processes added. I would agree with a presentation of new shrub, moss and C3 grass parametrizations. After a thorough model evaluation, some model application could be presented e.g. to understand the relation of their carbon balances to each other and to trees as well as their effects on soil temperature. Still, I believe individual papers for shrub and moss functions and effects would be more clear. If all topics should stay within one paper, then substantial additional text and figures/tables are required in order to i) explain the research question and importance of processes using literature, ii) evaluate new (and

sometimes old if affected) model functions, iii) present and discuss results with recent literature, and maybe apply the model to address a research question.

The organization of the manuscript was an important step ahead of actually writing this article. And as you suggest, we had to decide between isolating in different articles the different boreal vegetation types (PFTs), or writing an article about the global improvement of boreal vegetation (including all PFTs). We chose this second option in light of its submission to GMD, to focus the article on the model implementation at a global scale and not on a model application with in-depth investigation of a scientific question. It must enable users or developers of other LSMs to understand our developments, compare or integrate processes in order to improve global vegetation modelling.

In this context, it seems to us that splitting into different articles may reduce the interest of the study, especially in view of the fact that an overall and comprehensive evaluation (with global data) of the implementation would be difficult to split. Similarly, limiting the number of processes described could preclude the global consideration of the new boreal PFTs, and importantly, prevent reproducibility of our developments – being a venue for comprehensive descriptions of new model developments is an important goal of this journal. Finally, to reduce the size and complexity of this article, we chose to keep the application of implementations you suggest, such as the vegetation dynamics, the impact on soil carbon stocks or climate changes, for later articles.

However, as you suggested, we have added substantial additional content, especially in the introduction to highlight the research question and appropriate references to the existing literature (p.1 l.31-33, p.2 l.7-12,15,20,23,26-35,38-40 and p.3 l.6-7,32-36), in the results to provide evaluation on other sites (Fig. 9, p.16 l.35-39, p.17 l.1, and p.18 l.22-35), and in the discussion (from p.22 l.4) to compare our results with more recent studies (in particular Porada et al., 2016). Moreover, in order to clarify and reduce the size of the article, we decided to move the results split by continent (ex figs. 8 to 10 and associated texts) into the supplementary material (Figs. S1 to S3), and to substitute them by Artic-wide averages (Fig. 11).

Overall the paper should be considered primarily as a model description with a main focus on non vascular plants and shrubs, while the improvement for C3 grasses reduces to parameter optimization. The evaluation of the new developments at local to continental scales should thus only be considered as a first step to evaluate the potential of a more realistic description of boreal vegetation in a global model and not as an exhaustive evaluation/validation of the carbon, water and energy balance of these ecosystems. Such exhaustive

evaluation is not compatible with an in-depth model description in a single paper and is thus left for a subsequent study. However, we have tried to better justify in the paper our choices for the selected evaluation diagnostics (and not all available observations).

Some detailed important issues:

0) It is unclear to me how the authors can neglect the recent publication by Porada et al. (2016) which presents a process-oriented and dynamic representation of bryophytes and lichens in the land surface model JSBACH in introduction and discussion.

Indeed, Porada et al. (2016) is one of the first descriptions of non vascular plants in an ESM, with a process-based implementation. We missed the paper as it only came out after we had already completed our first draft. We thus added this reference in the introduction when describing the current state of boreal PFT in ESM model p.3 l.5-7: “a first description of lichen and bryophytes was implemented in the JSBACH model (Porada et al., 2013), improve recently with a process-based implementation (Porada et al., 2016)”. We also compare our results with those of this latter article (in the discussion and conclusion sections) in order to put into perspective our findings.

1) Mosses have an important function in Boreal forests and the forest ground is usually covered by mosses and lichens. Usually we can expect a NVP cover of more than 50% in Boreal forests and more in tundra (Rapalee et al., 2001; Porada et al., 2016). The approach in this study is to treat NVPs as separate PFT with a separate tile results in minor coverage in most regions. (The color scale in fig 5 is not useful to evaluate the shrub and moss cover, please improve). Hence, there will be a strong bias in moss and lichen effects on the heat balance and biogeochemical ecosystem functions using such model. That limitation should be discussed in detail.

In the version of ORCHIDEE used in this article there is no possibility to take into account and model explicitly the understory vegetation cover (the sum of all PFTs fraction ≤ 1). We agree that this poses a severe limitation to fully assess the impact of shrubs and NVPs on ecosystem functioning, and more particularly in boreal landscapes. However, we chose to make a first step with the current model structure, treating NVPs and shrubs as separate PFTs like for the 13 standard PFTs. We should notice that in boreal landscapes the forest cover is relatively sparse with significant gaps, by comparison to temperate or tropical forest cover, thus allowing light to reach the ground more easily. As a first approximation we can thus estimate that NVPs are only

partially controlled by the surrounding trees and that the biotic interactions with the other strata are limited.

Additionally, treating explicitly the understory vegetation, with a process-based approach, is more complicated as it requires a treatment of the radiation transfer within the canopy that accounts for forest gaps distribution and for the intra-canopy climate. Indeed air humidity and temperature are significantly different above the forest canopy than near the ground. Naudts et al. (2016) made a first crucial step in that direction with the addition in ORCHIDEE-CAN of a 2 streams radiative transfer scheme including a “gap” model and Ryder et al. (2016) further added a multi-layer canopy scheme (for energy, water and carbon fluxes) accounting for intra-canopy climate gradients. Our paper should thus be considered as a first step, describing the main biogeochemical features of NVPs and shrubs (as standalone PFTs), before a more complete and comprehensive integration is made within a vertically discretized canopy model (i.e. the ORCHIDEE-CAN version). We thus decided that the available model structure (at the time of the study) was not sufficient to treat explicitly understory NVPs/shrubs.

In this context we agree that the original land cover maps derived from satellite observations largely underestimate the fractional cover of NVPs and shrubs. However, we made an attempt using existing boreal land cover maps to partly correct for this bias. Note also that Peckham et al. (2009) showed that mosses represent a large cover fraction of burned areas, with thus potentially significant year-to-year variations of NVP cover at regional scale. Overall, it was difficult to increase more substantially the NVP/shrub fractional cover without having unrealistically low tree cover. Our study thus represents a lower estimate of the potential impact of NVPs and shrubs on boreal ecosystem functioning.

Note finally that the colour scale of Fig. 5 has been improved.

*Peckham, S. D., Ahl, D. E. & Gower, S. T. Bryophyte cover estimation in a boreal black spruce forest using airborne lidar and multispectral sensors. *Remote Sens. Environ.* 113, 1127–1132 (2009).*

*Ryder, J., Polcher, J., Peylin, P., Otlé, C., Chen, Y., Gorsel, E. V., ... & Valade, A. (2016). A multi-layer land surface energy budget model for implicit coupling with global atmospheric simulations. *Geoscientific Model Development*, 9(1), 223-245.*

*Naudts, K., Ryder, J., McGrath, M. J., Otto, J., Chen, Y., Valade, A., ... & Ghattas, J. (2015). A vertically discretised canopy description for ORCHIDEE (SVN r2290) and the modifications to the energy, water and carbon fluxes. *Geoscientific Model Development*, 8, 2035-2065.*

2) I agree with the authors that the global model can hardly cover small-scale variations in NPP and biomass of shrubs and mosses and lichens. Therefore, I suggest modify Fig 6 such that we see one dot for each climatic zone representing the model and data means but including error bars representing their std. Then one can discuss where the model fails to reproduce natural variance within one climatic zone and natural variance among zones. Fig 7 shows importantly that there is hardly any latitudinal variation in the measurements while the model shows a strong variation. Please, discuss in detail.

We agree with the reviewer that Figure 6 would benefit from grouping the individual measurements within restricted climatic/geographic zones. We have thus followed this advice and grouped them according to the six subzones.

Indeed there is a strong latitudinal variation in the model simulations (Fig. 7). However, it seems to us that the latitudinal variation in the measurements is as strong, considering the important variation in the mean as well as in the standard deviation. We therefore regret that we do not understand this comment.

3) It seems, model calibration and evaluation at site level has been performed with the same data. If you have too little data to split the dataset into representative parts for calibration and evaluation, then please repeat the site-level model evaluation with a bootstrap method: iteratively remove data for calibration and evaluate respective model results at these sites.

We agree with the reviewer that optimally we should always split the dataset into a calibration and evaluation parts. However in our case several constraints arose from i) the relatively small size of the initial dataset for such split and ii) the large computing time necessary for the model calibration which complicates any bootstrap approach (i.e. the calibration took several weeks with the Genetic Algorithm that is used). Given these constraints we searched for additional datasets to fulfil several requests from the different reviewers. We thus now apply the following strategy:

*1) we keep the original Western Siberia dataset to perform the optimization.
2) we use the observations from two new transects in North America and Eurasia (with appropriate biomass data) to perform the model evaluation.*

We added a new figure (Fig. 9) for the model evaluation with associated comments reported below. Note that we indicate in the text the potential shortcomings due to the use of mainly lowland data for the calibration of a

global model, p.14 l.22-24: “Note finally that using a single dataset in Western Siberia (mainly lowlands) for the model calibration may introduce some biases, which will have to be evaluated.”

P.16 l.35-39 and p.17 l.1: “We further compare the simulated biomasses with two other Arctic transects. The first one is the North America Arctic Transect (NAAT). It is situated in a continental area, and includes eight field locations (70°N 149°W to 79°N 100°W) sampled from 2002 to 2006 (Walker et al., 2011b) chosen as representative of zonal conditions. The second, located in a marine-influenced area, is the Eurasian Arctic Transect (EAT). It includes six field locations (58 to 73°N, between 67 to 81°E) sampled from 2007 to 2010 (Walker et al., 2008, 2009a, 2009b, 2011a).”

P.18 l.23-35: “**Carbon stock with two Arctic transect**

To evaluate the modelled biomass in other Arctic sites (not used in the calibration step), including uplands and lowlands, Fig. 9 shows scatter plots of observed and simulated biomass along two transects: the NAAT (North America) and the EAT (Eurasia) Arctic Transect. The NVPs and shrub biomasses are relatively well reproduced by the model (i.e. within the error bars). For both PFTs, the standard deviation of the observations includes the 1:1 line, but the observed biomasses are on average higher than the simulated biomasses. Simulated shrub biomasses are biased low for the NAAT transect but not for the EAT transect.

In contrast, the mean value of observed biomass for boreal C3 grasses (Fig. 9.c) is low compared to the simulated biomasses for both cases. For half of the sites the simulated low biomass is in accordance with the observations, but for the other half the values are much larger ($> 300 \text{ gC.m}^2$ whereas the observation do not exceed 54 gC.m^2). Despite the optimisation with observations from western Siberia (Fig. 7; leading to a decrease of biomass compared to temperate C3 grasses) there is likely an overestimation of the biomass for boreal C3 grasses, probably associated with an overestimated productivity.”

Walker et al, 2011a: Vegetation of zonal patterned-ground ecosystems along the North America Arctic bioclimate gradient. *Applied Vegetation Science* 14, 440–463. Doi: 10.1111/j.1654-109X.2011.01149.x

Walker et al, 2011. 2010 Expedition to Krenkel Station, Hayes Island, Franz Josef Land, Russia, Data Report, Alaska Geobotany Center, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK. 63 pp.

4) I do not agree that LAI is a valid dataset from remote sensing data which is useful for process model evaluation (and if you like to use it please show in the fig ORCH13-GLASS and ORCH16-ORCH13 in order to understand the previous model bias and improvement).

Possible maps for a landscape-scale model evaluation: fAPAR (JRC), GPP (Jung et al., 2011 or Beer et al., 2010), evapotranspiration (Jung et al., 2010), biomass (Thurner et al., 2014), and inventory-based NPP and biomass data (IIASA; Beer et al., 2006; Quegan et al., 2011). This is important as the fraction of tiles of all PFTs has been modified. In general, it would also really good to evaluate catchment runoff with freely available data of large Arctic rivers.

As mentioned above, the primary objective of the paper is not to provide a complete and comprehensive evaluation of the model with all potential large-scale datasets, but to provide a complete description of the new PFTs (equations and parameters) including only a first step evaluation.

Additionally, the validation of the results by world-scale data is not straightforward and potentially critical. The main problem in proposed global products is that they do not include PFTs (or vegetation) distinctions. Moreover, the biomass, NPP and evapotranspiration are more driven by trees or fire distribution than by the influence of the new PFTs. Comparing these maps with the new vegetation cover could add potentially other sources of bias and thus only little additional information. Moreover, the majority of these data is also derived from satellite observations, with comparable biases to those associated to LAI. The fAPAR product, although less sensitive to saturation issues, also comes with its own issues when comparing to current model outputs. The evapotranspiration product from Jung et al. (2010) may suffer from the small set of eddy-covariance measurements available in the boreal zones.

For the catchment runoff, we have done a summary of the river discharge on the ten main Arctic watersheds (<http://www.r-arcticnet.sr.unh.edu/v4.0/main.html>) to compare with the runoff + drainage simulated on the same area and the same period, p.21 l.17-21: “Compared to observations (main Arctic watershed available at <http://www.r-arcticnet.sr.unh.edu/v4.0/main.html>), the river discharge simulated indicates a general underestimation in the northern high latitudes, linked to an overestimation of evaporation and sublimation (Gouttevin et al., 2012). Thus, this underestimation with ORC16 is smaller than with ORC13.”

Although not ideal, we thus kept the LAI as a first step evaluation. Following the suggestion of the reviewer, we added a map (and a transect) of ORC16-ORC13 in Fig. 11 (the map ODR13-GLASS was already showed. That shows a significant difference between ORC16 and ORC13, and so the improvement with ORC16: p19. L.7-8: “This improvement with ORC16 is directly due to significant lower LAI values in these regions (north of 55°N) compared to ORC13.”

5) The reduction in tree cover results in a reduction of transpiration in your grid cell averages. However, interception loss and evaporation should increase with a layer of mosses and lichens. If the water and energy balance is a topic in your paper, then please show results for all components, not only transpiration in Fig 12.

As explained above, the main focus of this article is to describe the implementation of boreal vegetation and only few key impacts, without a thorough analysis of the water, carbon and energy balances. However, we included additional diagnostics in the supplementary material, Fig. S5., with the main components of the water budget: evaporation (including interception), transpiration, runoff and drainage.

6) In this model version, two modifications affect soil temperature: snow depth and moss&lichen cover. First of all, the model version should be evaluated in terms of snow depth and soil temperature. For soil temperature, you can use GTN-P borehole data from Romanovsky et al. (2010) and Christiansen et al. (2010) available at PANGAEA, and maps of soil temperature and ALT even from your study region from Beer et al. (2013) at PANGAEA. I expect a cooling effect from mosses (Porada et al. 2016) due to higher insulation in summer, and a warming effect due to higher snow depth in areas of high shrub cover (still unclear to me at landscape scale as shrubs accumulate snow from lateral wind transport, so it is just relocated within the grid cell?). In Fig 13 both effects are combined. Is there a way to separate them? In Fig 13 it seems the model overestimates ALT and that is even higher in ORC16? In Fig 13b it seems all three grid cells show higher ALT (red) while in 13c one profile shows warmer temp (red) and the others show cooler temp? I generally suggest concentrating on soil temperature because ALT estimation from modelled temperature is not reliable.

We clearly understand the interest and your questions about soil temperature and water balance, key in the Arctic to understand physical processes, e.g. the temporal dynamics of ALT and the evolution of permafrost. The Fig. 13 was made to illustrate small perspectives as a sample of the panel of potential impacts, but not as a comprehensive analysis. Given the current length of the paper, it was not possible to investigate these crucial questions in depth.

Additionally, to be exhaustive and perform proper evaluations of this insulating aspect, a factorial analysis would be needed, which was beyond the scope of this article. A dedicated study, with a different version of the ORCHIDEE model, ORCHIDEE-MICT, (including a description of the permafrost properties) has been conducted (Guimberteau et al. GMP,

submitted). In this context, we have chosen to illustrate only that the combined effect (summer and winter) is often more complex than expected with simplified formulations (although they remain important for understanding complex responses at global scales).

To represent the specific snow accumulation due to lateral wind transport and due to the lower snow compaction (itself due to branch support), the changes introduced (Section 2.3.2) are, as you suggest, just relocated within a grid cell. This is only applied in the case of the snow height used for the snow protection of shrubs (Equation 15).

7) Parameter estimation: Please show a priori and a posteriori parameter distributions in the appendix.

We added the corresponding supplementary: Table S2.

8) Please include a discussion section in which you interpret the results using literature in order to learn something. Parts of your summary section can be used if enhanced by literature. The conclusions and outlook section should be much reduced.

We acknowledge that the long “summary and conclusion” section (section 4) was maybe not the best choice to highlight the results of the study and replace them in the context of recent findings with similar models. We have chosen to follow the reviewer’s advice and to split section 4 into a “discussion” section and a “conclusion” section (from p.22 l.4). The discussion now provides few interpretation of the results; however given the above-mentioned main objective of the paper (a model description), we do not provide a comprehensive interpretation of all carbon, water and energy related results. The conclusion has thus been reduced to the main key points of the paper, with an outlook of the next steps.

9) Several new methods are described but their importance, evaluation, and application is unclear: * Section 2.2.6: anoxic conditions are not simulated, soil organic matter dynamics are no topic of the paper. Please remove. Or was the intension to evaluate GPP and NEE at eddy covariance sites? * Why is shrub allometry important and why not only assume smaller trees? * Shrub-snow interactions are not evaluated or analyzed. What do we learn from these additional functions? * Effects on albedo: Has been albedo improved when comparing to satellite products?

We agree that there is probably a lack of evaluation of the new implementations described in the paper. The main reason comes from the need to keep the paper at a reasonable size and that a full evaluation including also a wider range of scientific applications has been left for a subsequent study. On the contrary we tried to represent the ecological complexity of vegetation, because biogeochemical and biophysical processes are interwoven.

Although we did not intend to evaluate the NEE at eddy covariance sites in this paper, we chose to include the modification linked to soil organic matter dynamics in order to provide a comprehensive model (for gross and net carbon fluxes), including the major processes that needed to be improved for subsequent biogeochemical applications.

Specifically for lowlands/peatlands, the maximum decomposition rate simulated with a maximum water content (i.e. in anoxic conditions) is not physically coherent and thus needed revision.

For shrubs, change in allometry (compared to trees) is the key process implemented for their representation: i) the initial tree allometry equation did not allow trees smaller than 10 meters, ii) this allometry impacts directly the mean and maximum values of biomass, which can be accumulated, iii) the height of the vegetation (and particularly the shrubs) is very important to take into account the snow temperature and protection (to maintain biomass in winter). The shrub-snow interaction is not precisely evaluated or analyzed as we believe the first priority is to evaluate whether the shrub biomass (i.e. including height, number of individuals,..) is realistically simulated.

The same concerns apply for the albedo, knowing that only the processes controlling the albedo of the snow were updated, and that the albedo of each new PFT has been kept to that of the original PFT (as a first approximation). Additional work is needed to fully characterize the albedo of the new PFTs and for NVPs its dependence to moisture conditions. This work is beyond the scope of the paper and we thus decided not to focus on a global evaluation of the albedo with existing satellite products.

In conclusion, it would have been orthogonal to the main objective of the paper to neglect key processes controlling the biogeochemical and biophysical functioning of the new boreal PFTs. But the evaluation and application of all of these aspects is impossible in one (already too long) article.

Minor issues:

Fig 10: not used in results but only in summary and that there also the fig does not support the sentence.

The Fig. 10 was use and directly mentioned in the result (Section 3.2., in the first submitted version from p.19 l.20 to p.19 l.34). However, to be more clear and concise we have decided to move this figure, as well as the figures 8 and 9, to the supplementary (Fig. S4).

CO₂ conductance in non-vascular plants depends strongly on its moisture and not on stomatal conductance. If that concept is not used here, then please discuss this limitation and related potential biases in detail.

We agree and it is for this reason that we have modified the constant values (g_0 and b_1) of the variable g_s named "stomatal conductance" (Section 2.2.1., Eq. 1 and 2.) to reduce its dependence to active stomata and increase its dependence to moisture.

Page 16, line 35: I do not understand.

This was a description of the list of optimized parameters. As you suggested, it is now more explicit with the appendix (Table S2). In addition, these lines have now been moved at the end of Section 2.6.2.

Response to Referee #3

We thank R3 for this helpful review. Enclosed please find a detailed explanation of the revisions we made based on R3's comments. For your convenience, comments are in bold and our response is in italic. Revisions we made in the manuscript are presented in italic with grey background.

This manuscript describes a revision to the ORCHIDEE land surface model to improve the way in which tundra and subarctic vegetation are simulated by the model. The authors achieve this update by implementing three new plant functional types (PFTs) - these are a boreal shrub type, an arctic graminoid type, and a non-vascular plant type - into the model framework. Implementing new PFTs in ORCHIDEE has two steps, 1) changing process representations where necessary, and 2) defining the set of parameters that characterizes each PFT. The new shrub and grass PFTs needed few changes to process representation to implement, while on the other hand, simulating the non-vascular plant PFT required a different way of dealing with plant water uptake, gross productivity, and mortality. Parameter sets for each of the new PFTs were estimated using a Bayesian estimation process. The authors use the result of the new PFTs, updated process representations, and parameter sets and run the new version of the (ORC16), and compare the result to field-based observations, to satellite remote sensing products, and to the previous version of the model (ORC13) to highlight the effects of the update.

In general, this manuscript is valuable and should be published. It describes a valuable update to ORCHIDEE, which will undoubtedly be used in a number of forthcoming and future studies. The changes to the model lead to improvements in the comparison with observations, and thus represent progress over ORC13. However, the manuscript presentation is not particularly good: the text requires a thorough copyediting to clarify grammar and usage style, some of the figures are too small, and there are a few small issues concerning the presentation of units and values which are elaborated below. Aside from these presentation issues, my major concern of this study was the choice of data used to inform the parameter optimization, and the appropriateness of comparing site-level measurements with model simulations performed on a 2-degree grid.

The entire manuscript was re-read by a native English speaker. Possible further improvements may be done upon request, for a next stage of revision or upon acceptance. However the grammar and usage style changes are not reported in this response. Furthermore, the size of all figures has been increased. Concerning your other comments, please find some answers below.

The largest concern I have with the current study is the authors' apparent inability to assemble a larger, more representative dataset of high-latitude plant characteristics with which to parameterize the model. Their Bayesian optimization relies exclusively on the Peregon et al., 2008 biomass and NPP dataset. These data were specifically collected on *wetland* vegetation, while ORCHIDEE, in this paper, is intended to simulate *upland* vegetation. This mismatch between what the data represent and what the model is trying to simulate is a very serious limitation and calls into question the appropriateness and quality of the model parameterization. Use of such a limited and specialized dataset to parameterize a global model might be acceptable in regions of the world for which there are very few ecological and ecophysiological data, e.g., in parts of the tropics, but for the Arctic, it is practically inexcusable because of enormous amount of field research that has been performed over the last 50 years. Data from iconic arctic research sites such as Toolik Lake in North America, Abisko in Europe, and Zackenberg in Greenland were ignored in development of the testing dataset. Large amounts of data on key characteristics such as aboveground biomass were collected in the entire circumarctic region as part of, e.g., the ITEX experiment. Data from all of these locations outside of west Siberia, while perhaps more difficult to assemble, could have provided valuable information on the status of upland tundra and subarctic vegetation that would have been more appropriate for performing the model parameterization. If the authors prefer to not improve their parameterization using more widespread and representative field data, at very least they should explain and justify their choice for using the wetland dataset of limited spatial extent more clearly in the manuscript.

We are aware of your concern about the spatial representativeness of the dataset used for the Bayesian optimisation. However part of our choice is justified by specific needs for the calibration and by the accessibility to the data. We needed total living biomass and productivity at different sites, with multi-annual observations, and for the three new PFTs. The published and unpublished data provided by Peregon et al. satisfied these criteria, while we did not find easily other data sets satisfying all criteria. We agree that there is

a large amount of recent campaigns in the Arctic with numerous in situ measurements especially at specific highly instrumented sites; however these data are not assembled into a freely available and comprehensive database. Note also that the western Siberian data are acquired mainly on lowlands but not exclusively on very humid sites. As you suggested, in this case it is important to clarify our approach and we have thus added in the text: p.14 l.22-24: “Note finally that using a single dataset in Western Siberia (mainly lowlands) for the model calibration may introduce some biases, which will have to be evaluated”.

However, to account for your very relevant suggestion, we have searched for additional data for the model evaluation, especially from the sites you recommended. We did not find any complete data set, in the mass of published literature, which could be used easily for the optimization step along with the Siberian data. Nevertheless, we now use two North-South Arctic transects (with biomass data in lowlands and uplands): one in Eurasia (Walker et al, 2011a) and one in North America (Walker et al, 2011b; and previous reports since 2007). While these data are not sufficient for the optimisation (the productivity is missing), we propose to use them to evaluate the model. We do not claim that a larger set of data could not have been gathered but given the focus of the paper, i.e. on the new process description, we believe the two sets of data that are now used (from Western Russian and from two transects) are sufficient. We added a new figure (Fig. 9) for the model evaluation with associated comments reported below.

P.16 l.35-39 and p.17 l.1: “We further compare the simulated biomasses with two other Arctic transects. The first one is the North America Arctic Transect (NAAT). It is situated in a continental area, and includes eight field locations (70°N 149°W to 79°N 100°W) sampled from 2002 to 2006 (Walker et al., 2011b) chosen as representative of zonal conditions. The second, located in a marine-influenced area, is the Eurasian Arctic Transect (EAT). It includes six field locations (58 to 73°N, between 67 to 81°E) sampled from 2007 to 2010 (Walker et al., 2008, 2009a, 2009b, 2011a).”

P.18 l.23-35: “Carbon stock with two Arctic transect

To evaluate the modelled biomass in other Arctic sites (not used in the calibration step), including uplands and lowlands, Fig. 9 shows scatter plots of observed and simulated biomass along two transects: the NAAT (North America) and the EAT (Eurasia) Arctic Transect. The NVPs and shrub biomasses are relatively well reproduced by the model (i.e. within the error bars). For both PFTs, the standard deviation of the observations includes the 1:1 line, but the observed biomasses are on average higher than the simulated

biomasses. Simulated shrub biomasses are biased low for the NAAT transect but not for the EAT transect.

In contrast, the mean value of observed biomass for boreal C3 grasses (Fig. 9.c) is low compared to the simulated biomasses for both cases. For half of the sites the simulated low biomass is in accordance with the observations, but for the other half the values are much larger (> 300 gC.m² whereas the observation do not exceed 54 gC.m²). Despite the optimisation with observations from western Siberia (Fig. 7; leading to a decrease of biomass compared to temperate C3 grasses) there is likely an overestimation of the biomass for boreal C3 grasses, probably associated with an overestimated productivity.”

Walker et al, 2011a: Vegetation of zonal patterned-ground ecosystems along the North America Arctic bioclimate gradient. Applied Vegetation Science 14, 440–463. Doi: 10.1111/j.1654-109X.2011.01149.x

Walker et al, 2011. 2010 Expedition to Krenkel Station, Hayes Island, Franz Josef Land, Russia, Data Report, Alaska Geobotany Center, Institute of Arctic Biology, University of Alaska Fairbanks, Fairbanks, AK. 63 pp.

Specific comments

Page 2, line 3

The last glacial inception began around 126.5-120 ka; correct this error

Done.

Page 2 line 28

The model described is called BIOME4; please correct the model name

Done.

Page 8 line 16

Anoxic conditions affect the activity of all types of soil microorganisms, not only bacteria, e.g., fungi, archaea, and multi-celled microorganisms. Please be more inclusive instead of using the word “bacteria”

We thank the reviewer for this relevant comment. We changed “bacteria” for “soil microorganism” (p8. l.29).

Page 13 line 14-18

Why not make the root profile shape parameter a function of the mean active-layer thickness? The model simulates active layer thickness,

and presumably most plants would optimize their rooting profile to be compatible with this value

We agree that this is an important suggestion. Using a dynamical root profile could be appropriate to take into account the active layer thickness or the water table or the plant growth status. However, to keep model consistency, it should be applied to all PFTs of the model, and not only the PFTs developed in this study. Given the requested work especially for the calibration issues, we chose not to change the general equation of the current version of ORCHIDEE. Note that this is currently under investigation for all PFTs.

Page 13 lines 21-23

This sentence is confusing. Please revise for clarity by explaining how this version of ORCHIDEE uses prescribed vegetation cover and therefore survival and establishment limits are not relevant.

We changed the sentence to: “Note that we did not add any bioclimatic limits, such as i) survival or establishment temperature thresholds as proposed by Bonan et al., (2003) and Oleson et al. (2013) or ii) a cumulated degree-day threshold (above the zero degree criteria) for the plant growth (Miller and Smith, 2012). In this study we use ORCHIDEE without the dynamic vegetation module, but with a prescribed vegetation cover preventing vegetation development in unfavourable areas” (p.13 l.24-28).

Page 13 line 31

Explain why using observational data collected in “boreal wetlands” is appropriate for a parameterizing a global model that simulates predominantly upland systems, indeed, there is no representation of wetlands at all in this version of ORCHIDEE (as far as I could understand).

We have already partially answered this comment above. The first reason is that it was the most appropriate dataset that was available to us, even though it concerns mainly lowlands. Secondly, although it is considered as lowland on average, such data set comprises some sites that are not so-called wetlands. Finally, although we have kept this data set for the model calibration, in order to evaluate results at a global scale, we now use an additional set of observations for the model evaluation. These new data include both upland and wetland observations (Fig. 9 and associated comment, p.16 l.35-39, p.17 l.1 and p.18 l.23-35).

Page 14 line 14-16

If the model was run on a 2-degree grid, why were the site-level data aggregated only to half-degree? Wouldn't it have made more sense to aggregate the data at the same spatial scale as the model simulations? Also, the choice of dataset (from wetlands) clearly limits the amount of data coming from non-vascular plants, shrubs, and grasses; wouldn't an effort to assemble a more spatially global and upland-representative dataset have helped here?

For the first part of your comment, indeed this point was not clear enough. In fact, the optimization is also done at 0.5° resolution. We have now added a new sentence to clarify this in the Section about the optimization (2.6.1): “The simulation for the optimisation was done with CRU-NCEP meteorological forcing (Wei et al., 2014; Viovy, 2015), at 0.5° resolution” (p. 16, l.20-22).

The second part of your comment was already answered above.

Page 15 line 4-5

The phrase starting “. . .in CAVM Mapping Team. . .” is awkward and hard to understand. Rephrase.

We rephrased as follows: “In the map from Loveland et al. (2000), we noticed that the tundra biome corresponds to the “sparse vegetation” or to the “lichens and mosses” LCCs distribution. In CAVM Team (2003), the tundra biome is described as containing ~30 to 60% NVPs” (p.15, l.11-13).

Page 16 line 20-21

As we know multi-annual and decadal climate cycles exist, e.g., ENSO, and that there was a clear trend on climate during the 1st half of the 20th Century, is it appropriate to select individual years randomly over this period for the model spinup? I realize that many other vegetation modeling protocols prescribe the same thing, but that doesn't mean that it is correct. Using a detrended climate timeseries would be a minimum first step towards improving the quality of the model spinup.

Thank you for this remark. Indeed this is probably a better solution. However, for this study, this would lead to re-running all simulations, which was not possible at this stage. Moreover, the impact on above-ground boreal vegetation after a century of stable climate would probably be minor.

Page 17 line 24

If the 2-degree resolution used to run the model presents problems in terms of comparison with observations, why wasn't the model run at finer resolution, or in an "individual point" model with local forcing. This version of ORCHIDEE does not simulate any 2D spatial processes that would be impossible to implement in a point mode.

The aim of this study was to improve boreal representation on a global scale. However, at such scale, fine-resolution (e.g. 0.5°, used for the optimization) simulations would be too computationally demanding. Moreover, local (point) meteorological forcing data, including precipitation, temperature, downward longwave and shortwave radiation, relative humidity and wind, were not available. This is why we chose to run the model at 2° resolution with a global climate forcing based on a merge of climate reanalysis and in situ observations. Else we agree that if the local forcing data would have been available, we should have used them.

Page 17 line 32-34

Making an effort to assemble a larger calibration-evaluation dataset would have helped here. If these data really do not exist, this has to be clearly explained in the manuscript.

This comment was already answered above. Data we found for other sites are not complete enough to be used for the calibration. However, they were used to improve the evaluation of our results (Fig. 9 and associated comment, p.16 l.35-39, p.17 l.1 and p.18 l.23-35).

Page 18 line 1-2

Again, having more, and more widespread observations might have helped here.

Same as above.

Page 18 line 24-26

I would be very helpful for the reader if the meteorological variables were provided in terms of more ecologically relevant units. For example, provide precipitation in terms of annual totals, and temperature in terms of summertime (JJA) or growing season means (instead of annual? – it's not clear what is provided here).

We have changed most units to more ecologically relevant ones (in "mm.y⁻¹.m⁻²" in p.21 l.2,11-12,15, p.58 l.12-13, Figs. 12 and S5). Moreover, we have now indicated more clearly on which period temperature is considered ("growing

season (AMJ) mean air temperature” p.58 l.13) and we have updated the values (p.58 l.16).

Page 19 line 16-17

Again, what are these temperature anomalies referring to – seasonal, annual, individual months? A +10 anomaly in winter temperature in an place where the mean winter temperature is -40 C may not really be ecological relevant.

It was annual temperature anomalies, but which are present all along the year (winter, growing season or summer). In order to be clearer and consistent with precedent changes, we changed by the growing season: p.59 l.11-12: “growing season temperatures” and “+6°C and + 10°C compared to America and Asia respectively”.

Page 20 line 3-4

The phrase with “...too low LAI...” is awkward. Revise.

We rephrased as follows: “However, the model underestimates LAI in the central-west of Siberia” (p.19 l.2).

Page 21 line 1-2

Again, provide ecologically relevant units, e.g., total transpiration per month.

Page 21 line 11-14

Again, adjust units of evapotranspiration, runoff, etc. to monthly, seasonal, or annual sums. Annual is probably best here.

We change all values by day (in $\text{mm.d}^{-1}.\text{m}^{-2}$) by values in “ $\text{mm.y}^{-1}.\text{m}^{-2}$ ” (p.21 l.2,11-12,15, p.58 l.12-13), including the Fig. 12 and S5.

Page 22 line 35

In the boreal regions and Arctic, the shrub vegetation is composed of both evergreen and deciduous (summergreen) broadleaved plants (angiosperms), and evergreen needleleaf plants (gymnosperms). Thus, there are at least three types of shrubs.

Indeed, we forgot one type here. This sentence was changed to: Boreal shrubs have been reduced in this first step to broadleaf deciduous phenology, although in reality there is a mix of deciduous and evergreen broadleaf shrubs and evergreen needleleaf shrubs” (p. 23, l. 26-27).

Figure 5

The maps should be reproduced in a larger size

Figure 6

The plots should be reproduced in larger size, or at least the points should be plotted a bit larger. It is hard to see some of the points, especially the cyan colored dots

Figure 11

The maps should be reproduced in a larger size

Figure 12

The maps should be reproduced in a larger size

All of the designed figures have been enlarged. In particular, the figure 6 has been improved to be more readable.

Towards a more detailed representation of high-latitude vegetation in the global land surface model ORCHIDEE (ORC-HL-VEGv1.0)

Arsène Druel^{1,2}, Philippe Peylin¹, Gerhard Krinner², Philippe Ciais¹, Nicolas Viovy¹, Anna Peregon^{1,3}, Vladislav Bastrikov¹, Natalya Kosykh³ and Nina Mironycheva-Tokareva³

¹Laboratoire des Sciences du Climat et de l'Environnement, CEA-CNRS-UVSQ CE Orme des Merisiers, 91 190 Gif sur Yvette, France

²CNRS, Univ. Grenoble Alpes, Institut des Géosciences de l'Environnement (IGE), F-38000 Grenoble, France

³Institute of Soil Science and Agrochemistry, Siberian Branch Russian Academy of Sciences (SB RAS), Novosibirsk, 630090, Ak. Lavrentieva ave., 8/2, Russia

Correspondence to: Arsène Druel (arsene.drue@gmail.com)

Journal: Geoscientific Model Development

Abstract. ~~Simulation To improve the simulation~~ of vegetation-climate feedbacks in ~~the~~ high-latitude ~~in the~~ ORCHIDEE land surface model was improved by addition of three new circumpolar Plant Functional Types (PFTs) ~~were added in the ORCHIDEE land surface model~~, namely non-vascular plants (NVPs) representing bryophytes and lichens, arctic shrubs, and arctic C3 grasses. Non-vascular plants are assigned no stomatal conductance, very shallow roots, and can desiccate during dry episodes and become active again during wet periods, which gives them a larger phenological plasticity (*i.e. adaptability and resilience to severe climatic constraints*) compared to grasses and shrubs. Shrubs have a specific carbon allocation scheme, and differ from trees by their larger survival rates in winter, due to protection by snow. Arctic C3 grasses have the same equations than in the original ORCHIDEE version, but different parameter values, ~~optimised~~ *optimized* from in-situ observations of biomass and NPP in Siberia. *In situ* observations of living biomass and productivity from Siberia were used to calibrate the parameters of the new PFTs using a Bayesian ~~optimisation~~ *optimization* procedure. With the new PFTs, we obtain a lower Net Primary Productivity (NPP) by 31% (from 55°N), as well as a lower roughness length (-41%), transpiration (~~-~~ *+33%*) and a higher winter albedo (by *+3.6%*) due to ~~increased a larger~~ snow cover. A simulation of the water balance and runoff and drainage in the high northern latitudes using the new PFTs results in an increase of fresh water discharge in the Arctic ocean by 11% (*+140 km³ km⁻² y⁻¹*), owing to less evapotranspiration. Future developments should focus on the competition between these three PFTs and boreal trees PFTs, in order to simulate their area changes in response to climate change, and the effect of carbon-nitrogen interactions.

1 Introduction

~~Global To understand the role of vegetation feedbacks in climate change, global~~ land surface models ~~are an essential component of included in~~ Earth System Models (ESM). ~~These land surface models~~ describe the carbon, water and energy exchanges between the ~~land surface~~ *vegetation* and the atmosphere at large *spatial* scales ~~and a broad range of temporal scales.~~ To this end, Surface-Vegetation-Atmosphere transfer schemes (SVATs, e.g. Henderson-Sellers et al., 1996) were developed and coupled with General Circulation Models

(GCMs) that provide the meteorological forcing used as input to SVATs. Several studies show that the terrestrial biosphere plays an important role in controlling the spatial and temporal distribution of carbon, water and energy fluxes, and thus, indirectly, in modulating regional- to continental-scale climate. In particular ~~Specifically~~, it appears that high-latitude ecosystems have a significant impact on the climate (Bonan, 1995; Christensen et al., 1999; Chapin et al., 2000). For example, circumpolar vegetation changes ~~have~~ played an important role in the last glacial inception, i.e. ~~12626.5 ka to 12020 ka~~ (Clark et al., 2009). Reduced tree cover led to an increase in albedo and snow cover, a reduction in temperature and precipitation and ultimately changes in atmospheric circulation and cooling ~~atof the~~ high-latitudes (de Noblet et al., 1996; Gallimore and Kutzbach, 1996; Meissner et al., 2003; Vavrus et al., 2008; Colleoni et al., 2009). More recently, Lorantý et al. (2014) and Thackeray et al. (2014) re-assessed the vegetation control on the snow-albedo feedback at high latitudes, highlighting the important effect of tree and shrub cover on large-scale snow albedo and its often unsatisfying representation in current-generation global climate models. Other- ~~In the circumpolar regions,~~ critical ~~physical~~ processes linked to circumpolar vegetation changes are the dynamics of permafrost (Lawrence and Slater, 2005; Koven et al., 2011), ~~snow deposition and cover and its effect on surface albedo, soil thermal dynamics~~ and the impact of vegetation ~~cover~~ roughness length on momentum and flux exchanges with the atmosphere (Vautard et al., 2010). While the Net Primary Productivity (NPP) and living plant biomass is low at high-latitudes because of ~~severe~~ harsh climatic conditions and a short growing season, carbon stocks in high-latitude soils, ~~and~~ in particular in permafrost, are very large (e.g. Tarnocai et al., 2009; Hugelius et al., 2011, 2014; Olefeldt et al., 2016) ~~Tarnocai et al., 2009; Hugelius et al., 2011~~ because of reduced decomposition of soil organic matter in soil decomposition and the burial of frozen carbon below the active layer over long period of time ~~seales~~. Changing soil properties and temperature in response to future warming could therefore release CO₂ and CH₄ from thawed permafrost, with a potential carbon release on the order of 92 ± 17 PgC by 2100 under a strong emission scenario ~~the current warming trajectory~~ (RCP8.5) (Schuur et al., 2015). Altogether, high-latitude vegetation significantly affects regional and global climates and overall leads to positive climate feedbacks (e.g., Pearson et al., 2013). High-latitude vegetation must therefore be correctly represented in ESMs, in particular in the light of projected strong Arctic and sub-Arctic climate warming and related biogeographic shifts. With the current warming trajectory, the colonisation of shrubs could be significant (e.g., Pearson et al., 2013; Frost and Epstein, 2014) ~~(Frost and Epstein, 2014)~~, and as observed by Blok et al. (2011b); it could lead to an Arctic greening (Blok et al., 2011b; Bonfils et al., 2012) with increased leaf area, decreased surface albedo in winter, and potential increase of temperatures at local and regional scales. For example, based on statistical modelling, Pearson et al. (2013) show that more than half of the vegetated areas of the Arctic are likely shift to a different physiognomic class by 2050, with a >50% increase in woody cover. However, Myers-Smith et al. (2015) have shown that the climate sensitivity of shrub growth is not uniform across the Arctic, indicating a need for detailed physically- and physiologically-based modelling of high-latitude vegetation changes. Further examples of observations of on-going changes in high-latitude vegetation concern its seasonality, which has been shown to have diminished over the past decades (Xu et al., 2013), and its relationship to interannual climate variability, which has been shown to have weakened (Piao et al., 2014).

In spite of these strong effects of vegetation of the high-latitude climate and the large expected, and in parts already observed, changes of vegetation cover and activity,

5 ~~Until recently~~ the description of circumpolar vegetation in land surface models ~~has been~~ relatively simple ~~until recently, and continues to be so in many models, with~~ ~~and discretized on~~ few Plant Functional Types (PFTs) that share similar equations and differ only by ~~parameter~~ ~~parameters~~ values (except for phenology which is usually PFT-specific). ~~In a recent review, Wullschleger et al. (2014) re-endorse the concept of PFTs~~ ~~for the description of high-latitude vegetation, but also note that surprisingly few DGVM represent~~ ~~fundamental high-latitude PFTs such as lichen and mosses.~~ In most land surface models (for instance those used in CMIP5 Earth System Models) all vegetation types were classified as either trees or grasses ~~PFTs~~. Taiga and tundra, where non-vascular plants and shrubs dominate the landscapes ~~in the reality~~, cover about 15% of global land surfaces (Beringer et al., 2001). In the ~~BIOME4BIOME~~ ecosystem model (used specifically to study past and future vegetation transition) the tundra diversity was taken into account ~~in the early 2000s~~ (Kaplan et al., 2003) ~~and~~ Chadburn et al. (2015) recently included mosses in the JULES model (Best et al., 2011). Similarly, a first description of lichen and bryophytes was implemented in the JSBACH model (Porada et al., 2013), ~~improve recently with a process-based implementation (Porada et al., 2016).~~ Biogeochemical and biophysical characteristics of shrubs are already implemented in some models, such as in the Community Land Model (Oleson et al., 2013), JULES (Clark et al., 2011) and JSBACH (Baudena et al., 2015). In this study we further develop the ORCHIDEE model (Krinner et al., 2005), the land surface component of the Institute Pierre Simon Laplace (IPSL) ESM, to represent non-vascular plants, arctic shrubs and tundra grasses. This study focuses on the parameterizations of these three new PFTs, their interactions ~~as~~ part of the Dynamic Global Vegetation Model (DGVM) of ORCHIDEE being treated in a ~~subsequent~~ ~~following~~ study.

20 To date, the ORCHIDEE model contains 8 different types of trees (tropical ~~broadleaf~~ ~~broad-leaved~~ evergreen and ~~deciduous~~ (raingreen), temperate needleleaf evergreen, ~~broadleaf~~ ~~broad-leaved~~ evergreen and ~~deciduous~~ (summergreen), boreal ~~broadleaf deciduous~~ (~~broad-leaved~~ summergreen), needleleaf evergreen and ~~deciduous~~ (summergreen)), 4 types of grasses (C3 and C4 grassland as well as C3 and C4 generic crops) and bare soil (Krinner et al., 2005), ~~using the PFT concept. While in ORCHIDEE high-latitude vegetation was represented by a single PFT for C3 grasses and several PFTs for boreal trees, namely boreal broadleaf deciduous, needleleaf deciduous and evergreen conifers (Krinner et al., 2005), in reality it contains graminoid tundra, shrubs and wetlands including mosses and sedges (see CAVM Team, 2003). In view of the diversity of circumpolar vegetation, the current discretization of the vegetation in ORCHIDEE does not allow accurate modelling of the regional dynamics of water, carbon and energy fluxes.~~ ~~using the PFT concept. In the reality, high latitude vegetation contains graminoid tundra, shrubs and wetlands including mosses and sedges (see CAVM, for Circumpolar Arctic Vegetation Map, Mapping Team et al., 2003) while in ORCHIDEE it was represented by a single PFT for C3 grasses and several PFTs for boreal trees, namely boreal broadleaved deciduous, needleleaved deciduous and evergreen conifers (Krinner et al., 2005). In view of the diversity of circumpolar vegetation, the current discretization of the vegetation in ORCHIDEE does not allow to properly model the regional dynamics of water, carbon and energy fluxes.~~

35 Key plant functional types missing in the model for the high-latitudes are mosses, ~~lichens~~ and ~~lichens and~~ shrubs. Mosses and lichens are non-vascular plants; their uptake of nutrients is not supported by xylem sap flow and their gas exchange of water and CO₂ is not regulated by stomata. Moreover, mosses and lichens have different environmental needs than grasses (i.e., more resistant ~~to~~ ~~for~~ hydric and thermal stress or ~~to~~ ~~for~~ nitrogen

limitation). Shrubs are smaller than trees and have a different morphology, inducing a larger snow accumulation in winter, and tolerance to wind ~~and~~ cold temperature, and ~~therefore have~~ a different potential for colonisation (shrubs being endemic in many tundra ecosystems can grow rapidly in response to warming, whereas trees need to establish).

The aim of ~~the work~~~~this study~~ is to improve the description of circumpolar vegetation in ORCHIDEE ~~in order to allow for a better projection of future climate changes in high latitudes, notably via a more certain quantification of vegetation feedbacks to high-latitude climate change, and a more trustworthy projection of global effects of high-latitude vegetation changes via their impact on the carbon cycle. We added~~by adding mosses and shrubs and ~~adjusted~~adjusting parameters related to C3 grasses, ~~advancing the representation of~~~~in order to improve~~ the spatial and temporal dynamics of biogeochemical and biophysical processes in the soil-plant-atmosphere continuum. The implementation of the new plant functional types is described in Sect. 2. Results obtained both for site scale and large-scale simulations are described in Sect. 0. Sect. 4 presents a summary of the key findings together with some perspectives.

2 Methods

2.1 ORCHIDEE: overall model description

ORCHIDEE describes the exchange of energy, water and carbon between the atmosphere and the biosphere. The model includes the representation of carbon and water exchange at leaf-scale ~~sealed~~ up to canopy-scale, the allocation of carbon within plant compartments (leaves, roots, heartwood and sapwood), autotrophic respiration, litter production, plant mortality and decomposition of soil organic matter (after Parton et al., 1988). ~~Leaf-scale photosynthesis follows the formulation~~Leaf-scale photosynthesis follows the formulation of ~~Farquhar et al. (1980)~~ Farquhar et al. (1980) for C3 plants ~~by Farquhar et al. (1980)~~ and ~~Ball and Berry~~ Ball and Berry for stomatal conductance ~~by Ball and Berry~~ (Ball et al., 1987) implemented according to Yin and Struik (2009) and Kattge and Knorr (2007), i.e. with a seasonal acclimation of ~~maximum~~ photosynthetic rates to temperature.

The soil hydrology model includes an 11-layer diffusion model following the van Genuchten (1980) equations for texture-dependent hydraulic saturation capacity and vertical diffusivity (de Rosnay et al., 2002). The model runs at half-hourly time ~~steps~~step but describes slow processes such as carbon allocation, respiration, phenology or litter decomposition at ~~a~~-time ~~steps~~step of one day. ORCHIDEE uses the concept of Plant Functional Types (PFTs) to describe the heterogeneity of land surface ecosystems. Thirteen PFTs (including bare soil) are already present with 8 types of trees and 2 natural and 2 agricultural herbaceous (C3 and C4) types (Krinner et al., 2005), as summarized in Table 1.

The high-latitude version of ORCHIDEE (ORC-HL from ORCHIDEE rev1322) used in this study includes a soil-freezing scheme (Gouttevin et al., 2012) and a 3-layer explicit snow model (described initially in Wang et al., 2013). In this new ORCHIDEE version (ORC-HL-VEGv1.0), 3 new PFTs are added to the 13 original ones (Table 1), i.e. non-vascular plants (~~NVPs~~NVP) including bryophytes (mosses, liverworts and hornworts) and lichens, boreal shrubs, and boreal C3 grasses. ~~Note that tropical trees are not present in high latitudes.~~

2.2 Non-Vascular Plants (NVPs): Bryophytes & Lichens

Bryophytes and lichens (NVPs) ~~have are very specific plant vegetation types, with~~ a rather small amount of living biomass, around 200 g.m⁻² (Bond-Lamberty and Gower, 2007; Gornall et al., 2007), but with significant dead organic matter beneath. In contrast, in boreal and tundra ecosystem where mosses compose a small fraction of total ecosystem biomass, their net primary productivity (NPP) can be up to 50% of total annual NPP (Viereck et al., 1986; Beringer et al., 2001) and corresponds to approximately 1–6% of the global terrestrial net primary productivity (NPP) (Ito, 2011; Porada et al., 2013). In addition, NVPs have no sap (i.e. no water circulation), no roots (only rhizoids to hold on to the ground) and no active stomata to ~~optimise~~ optimize the uptake of CO₂ in order to minimize water loss.

To represent NVPs

~~We modified~~ the equations of C3 grasses ~~was modified plants in order to describe NVPs~~ as follows. First, we consider ~~that~~ NVP biomass ~~to be is mainly~~ represented ~~mainly~~ by leaf carbon (i.e., no wood, reserves and root). Their leaves are assumed to access water in the top-soil without roots (i.e. no carbon allocated to a root compartment). ~~In addition, we~~ ~~We also~~ modified the equations ~~for of~~ photosynthesis and stomatal conductance, carbon allocation, and energy balance ([see below](#)). ~~In the following we detail how the few key processes of ORCHIDEE have been adapted as well as the new processes were implemented to represent NVP specificities.~~ For all other processes and associated parameters not described below, we used the C3 grasses equations (as reported by Krinner et al., 2005).

NVPs:

2.2.1 Photosynthesis and stomatal conductance

Photosynthesis of C3 plants in ORCHIDEE is based on Farquhar and Sharkey (1982), with the stomatal conductance (g_s) implemented according to Yin and Struik (2009):

$$g_s = g_o + \frac{A + R_d}{C_i + C_{i*}} \times f_{VPD} \quad (1)$$

With g_o the stomatal conductance when irradiance is null, A the rate of CO₂ assimilation, R_d the dark respiration rate, C_i the intercellular CO₂ partial pressure and C_{i*} the C_i-based CO₂ compensation point in the absence of dark respiration. f_{VPD} is a function describing the effect of leaf-to-air vapour pressure difference (VPD), described empirically following Yin and Struik (2009):

$$f_{VPD} = \frac{1}{[1/(a_1 - b_1 \cdot VPD) - 1]} \quad (2)$$

With a_1 & b_1 empirical constants. This function limits the stomatal conductance under dry air conditions.

Vascular plants have stomata (Kirkham, 2005; Ruzsala et al., 2011) to regulate gas fluxes (i.e. CO₂, transpiration). For NVPs, the situation is more complex and diverse (Williams and Flanagan, 1996; Chater et al., 2013): some species have “non active” stomata (Ruzsala et al., 2011) like *Oedipodium*, others have only “pseudo-stomata” like *Sphagnum*, and some have no stomata like *Andreaeobryum* (Haig, 2013). For the sake of simplicity and given the lack of a well-established photosynthesis model for each ~~NVP~~ NVPs type, we considered ~~that~~ all NVPs ~~to~~ have “pseudo-stomata”. ~~Thus we~~ ~~We thus~~ kept Eq. (1) for g_s (Yin and Struik, 2009) but with a conductance that only weakly depends on the VPD. Observation of ~~NVP~~ NVPs transpiration

suggests that their conductance has a small dependence to humidity and atmospheric CO₂ concentration, but a large mean value. We thus defined the coefficients a_1 and $b_1 \neq 2$ (see Table 2) so that the VPD dependency of leaf stomatal conductance f_{vpd} in Eq. (2) is almost independent of VPD and chose a large value for g_0 to simulate a high stomatal conductance. This solution is close to that used by Dimitrov et al. (2011), i.e. a constant conductance.

2.2.2 NVPs: Plant carbon allocation

ORCHIDEE has five biomass carbon reservoirs for C3 grasses: leaves, root, reserve, reproductive organs (fruits), and sapwood below and above ground. We choose to keep only the leaf reservoir to represent the NVP biomass and the fruits pool for reproduction (see Table 2). Furthermore, C3 grasses are deciduous summergreen vegetation with only reserve pools during wintertime. Using the leaf pool to represent NVPs biomass implies to consider NVPs as an evergreen PFT (see Table 2) with leaves present all year long. The main challenge is then to adapt the leaf biomass turnover in order to represent the observed temporal dynamic of lichens and bryophytes biomass.

2.2.3 NVPs: Biomass carbon turnover

We first modified the original leaf senescence parameter from 120 days (for grasslands) to 470 days for NVPs (Table 2). We then ~~Then we~~ defined an energy cost (i.e. an extra turnover of biomass) for NVP survival in cold winter conditions and limited photosynthesis due to the thickness of the NVPs reducing light penetration. These two processes are described hereafter.

Bryophytes and lichens have a very good resistance to extreme conditions introduced by lower leaf senescence and no leaf fall. ~~However, this~~ ~~This~~ adaptation has ~~however~~ an energy and thus a biomass cost, modelled through an additional carbon loss (t_{nppo} in gC.m⁻².d⁻¹) based on the cumulative number of day (d_{cum}) when the Net Primary productivity (NPP) is negative or null, as given by Eq. (3).

$$t_{nppo} = b \times k_l$$

$$k_l = \begin{cases} 0 & , d_{cum} < d_0 \\ k_{lmax} \times \frac{(d_{cum} - d_0)}{(d_m - d_0)} & , d_0 < d_{cum} < d_m \\ k_{lmax} \times \frac{(d_{cum} - d_f)}{(d_m - d_f)} & , d_m < d_{cum} < d_f \end{cases} \quad (3)$$

Where b the (leaf) biomass of NVPs (gC.m⁻²) and k_l the additional fraction of biomass lost during extreme conditions (or turnover rate in d⁻¹) with a maximum value of k_{lmax} (in d⁻¹), d_0 a threshold delay time (in days) before increasing the turnover, d_f (days) the maximum number of days for applying the extra turnover, and d_m (days) the day number when k_l reaches its maximum value after d_0 . The values of all parameters are summarised in Table 2. Figure 1 illustrates the increasing biomass turnover linked to extreme conditions with k_l as a function of time in the season with negative or zero NPP. After a maximum, the turnover decreases in order to represent the induced resistance and thus survival to extreme conditions, i.e. under snow cover in winter or under dryness.

Using NPP to determine the period of the year with extreme conditions allows us to combine different stress factors such as cold temperature and very low moisture. Hence the combination of short-term stress episodes (periods when $d_0 > 0$) such as a short drought followed by a snowfall (blocking of light and cold

temperature stress) on the NVPs could result in a long-term impact (increase in turnover) on vegetation.

The second turnover is related to favourable conditions with a large growth of biomass during the growing season (such as in peatlands). Given their large NPP under favourable conditions, NVPs can accumulate biomass over several tens of centimetres. In this case, sunlight cannot reach the lower portion of the canopy due to light penetration decreasing, although this biomass is still considered as leaf material (see 2.2.1). The underneath biomass usually dies from a lack of light and possibly a lack of oxygen in wet conditions. Given that oxygen concentration is not simulated in this model, the effect of anoxic conditions and severe light limitation are simply parameterized by increasing the overall leaf biomass turnover rate during the growing season. We chose the Leaf Area Index (LAI) to define this additional turnover: when the maximum LAI (LAI_{lim}) is reached, the underlying layers will not receive any sunlight, resulting in an increase of their turnover (t_{missL}) represented by Eq. (4).

$$t_{missL} = b \times (e^{l_{coef} \times (LAI - LAI_{lim})} - 1), \text{ if } LAI > LAI_{lim} \quad (4)$$

Where b is the daily leaf biomass of NVPs ($gC.m^{-2}$), l_{coef} a coefficient (d^{-1}) and LAI_{lim} a threshold leaf area index defined from Bond Lamberty and Gower (2007). These two parameters are optimized in Sect. 2.6.1 and their values reported in Table 2.

2.2.4 NVPs: Water access for NVPs

Plant water uptake

In ORCHIDEE, all vegetation types have access to soil water through a root system. The ability of roots to extract water depends on soil moisture in the different soil layers (11 currently, see 2.1) and the root density profile (R) (de Rosnay, 1999):

$$R(z) = e^{-r_p \times z} \quad (5)$$

With z the soil depth (m) and r_p a PFT dependent parameter to control the shape of the root profile.

NVPs do not have roots to absorb water (or nutrients from the underlying substrate). Some of them, such as *Sphagnum*, can have threadlike rhizoids but only to anchor to the soil. So they can only access the surrounding surface water. However, ORCHIDEE does not include a surface liquid water reservoir; thus for simplicity we have assumed that NVPs have access to water stored in the first top-soil layers. This assumption allows keeping an internal coherence between PFTs and facilitates the treatment of the competition for water between PFTs. The value of the r_p parameter (Table 2) for NVPs was defined through the optimization (see Sect. 2.6.1). With 50% water uptake (without roots) at 2.5cm and 95% at 11cm, we obtained water access values closed to those proposed by Dimitrov et al. (2011) and by Chadburn et al. (2015). Figure 2 illustrates the soil water uptake profile for NVPs, and the root profiles for C3 grasses and boreal trees (used in ORCHIDEE).

Impact of drought on the desiccation of NVPs

During and after a water stress period, the water content of NVPs decreases significantly (desiccation) which reduces the plant photosynthetic capacity (Williams and Flanagan, 1996; Wania et al., 2009; Dimitrov et al.,

2011). As for the other PFTs in ORCHIDEE, the instantaneous effect of soil water limitation will reduce photosynthesis through a soil water stress function imposed on the maximum photosynthetic capacity (Farquhar et al, (1980) photosynthesis model). Additionally, for NVPs, plant desiccation occurs and the time needed before recovery to optimum photosynthetic capacity must be taken into account.

5

To account for this effect, Wania et al. (2009) reduced gross primary production as a function of the annual mean water table position. In ORC-HL-VEGv1.0 we chose to use a monthly running mean hydric stress factor (w_s) computed from the relative water content in each soil layer weighted by the specific water uptake profile of NVPs defined in Fig. 2. We defined a desiccation function, d_{ess} , as a linear function of w_s (Eq. (6) and Fig. 3) varying between 1 (no impact) and a minimum value d_{off} , when w_s decreases to zero under maximum water stress. The function $d_{ess}(w_s)$ illustrated in Fig. 3 scales the maximum rate of carboxylation ($V_{c_{max}}$) as well as the maintenance respiration. The maximum rate of electron transport ($V_{j_{max}}$) is scaled through $V_{c_{max}}$. Indeed, leaves maintenance respiration defined in ORCHIDEE being a function of the leaf carbon content (biomass) and LAI, should then be reduced when NVPs get desiccated. With this formulation, we can take into account the impact of a drought on a monthly time scale.

15

$$d_{ess} = \begin{cases} d_{off} + \frac{1-d_{off}}{w_s min} \times w_s, & w_s < w_s min \\ 1 & , w_s \geq w_s min \end{cases} \quad (6)$$

With $w_s min$ being the minimum threshold hydric stress for desiccation (a constant defined in Table 2).

2.2.5 NVPs: Heat transfers

Non-vascular plants, and more precisely bryophytes, form an insulating layer above the soil, with thus a strong control on the heat exchange between the atmosphere and the soil (Dyrness, 1982; Beringer et al., 2001; Blok et al., 2011a). In its standard version, ORCHIDEE does not account for the thermal insulation properties of vegetation in the calculation of the surface energy budget. For the sake of simplicity and following the same approach as in Chadburn et al. (2015), we modified in ORC-HL-VEG the upper soil layer characteristics to describe the effects of NVPs on the heat transfers to the soil over a depth that is equivalent to the NVP thickness and for the fraction of each grid cell ~~box~~ covered by NVPs.

20

25

First we estimate the thickness of NVPs (h) assuming a fixed biomass density:

$$h = \frac{b}{\rho} \quad (7)$$

With b the total NVPs biomass ($g.m^{-2}$) and ρ its density ($gC.m^{-3}$; see Table 2)

30

The thermal capacity / conductivity (Eqs. (8) & (9)) of the upper soil layers (equivalent to the depth of the NVPs layer) are modified based on the soil volumetric moisture content (as in the standard ORCHIDEE version) and the heat conductivity and capacity of NVPs, following Soudzilovskaia et al. (2013). The heat thermal capacity of the top-soil thickness h occupied by NVPs, C , follows from:

$$C = C_{dry} + m_{vol} \times (C_{wet} - C_{dry}) \quad (8)$$

35

Where m_{vol} is the volumetric relative moisture content over a thickness h , C_{dry} the dry thermal capacity of dry NVPs and C_{wet} the wet heat capacity of wet NVPs (from Soudzilovskaia et al., 2013; see Table 2). Note that in the standard case without NVPs, C_{wet} and C_{dry} are defined from the soil texture (see Wang et al., 2016). In the

case of frozen soil we use an ice capacity (C_{ice}) for NVPs, deduced relatively to C_{ice} of soil. When the soil is partly frozen a weighting average between the two thermal capacities is calculated (using, x , the unfrozen soil fraction). The overall thermal conductivity, λ , follows from:

$$\begin{aligned}\lambda &= \lambda_{dry} + m_{vol} \times (\lambda_{sat} - \lambda_{dry}) \\ \lambda_{sat} &= \lambda_{sat,wet}^x \times \lambda_{sat,ice}^{1-x}\end{aligned}\quad (9)$$

5 | With λ_{dry} being the dry soil thermal conductivity, $\lambda_{sat,wet}$ the unfrozen wet thermal conductivity (from Soudzilovskaia et al., 2013) and $\lambda_{sat,ice}$ the frozen thermal conductivity of NVPs (derived relatively to $\lambda_{sat,ice}$ of soil.) See Table 2 for values and units. Note that the current version of ORCHIDEE only calculates one energy budget being the average of all vegetation types present in a grid cell; the overall thermal soil characteristics thus correspond to a weighted average of the soil characteristics according to the fraction of NVPs covering a
10 | grid cell.

2.2.6 NVPs: Soil organic matter decomposition

In the standard version of ORCHIDEE, two important factors, temperature and moisture, exert a control over litter and soil organic matter decomposition (following the CENTURY model, Parton et al., 1988). These factors are computed from weighted mean soil temperature and soil moisture profiles, assuming an
15 | exponential profile of soil organic matter content and associated decomposition processes between 0 and 2 m depth. For the moisture control of decomposition, the original function (Parton et al., 1988; Krinner et al., 2005) is increasing with soil moisture content (maximum at saturation), which is not adapted for water-saturated soils, where anoxic conditions reduce soil microorganism condition reduces bacterial activity (such as in peatlands). As these conditions may prevail for NVPs covers, we modified the original scheme.

20 | First, we introduced a vertical discretisation of below ground litter carbon pools, assuming it follows the same distribution as the root profile for vascular plants or soil water uptake profile for NVPs (exponential decay as Eq. (5), in de Rosnay, 1999), as in Frohking et al. (2001). Moreover, Thus, the below ground litter is considered to be linked to vegetation source (i.e. roots for vascular plants). Moreover we consider that there is no above-ground litter for NVPs, so that leaf litter is treated like below ground litter,
25 | as in Frohking et al. (2001) and Chadburn et al. (2015). With this new vertical discretisation, we chose to use the temperature and soil moisture of each layer to define the control litter decomposition.

To account for anoxic conditions often prevailing in water saturated NVP ecosystems causing slow decomposition rates (Frohking et al., 2001), we changed the moisture decomposition function (R_{SR}) applied for
30 | each layer as in Moyano et al. (2012), using a look-up table approach. Equation (10) and Fig. 4 describes the new function and the reduced decomposition with soil moisture content (applied for the litter from issue of all PFTs).

$$\begin{aligned}PR_{SL}(m_{vol}) &= m_{c(3)} \times m_{vol}^3 + m_{c(2)} \times m_{vol}^2 + m_{c(1)} \times m_{vol} + m_{c(0)} \\ SR(m_{vol}) &= \prod_{k=0}^{m_{vol}} PR_{SL}(k) \\ R_{SR}(m_{vol}) &= \frac{SR(m_{vol})}{\max_{0 < k < 1}(SR(k))}\end{aligned}\quad (10)$$

With SR being the soil respiration (coefficient), PR_{SR} the proportional response of SR to soil moisture, R_{SR} the relative respiration, m_{vol} the soil volumetric moisture content (unit less), $m_{c(1-3)}$ three parameters taken from

Moyano et al. (2012). SR is equal to the product of all PR_{SL} values (denoted by Π symbol) at each 0.01 moisture interval (k), from zero to the computed SR moisture. To obtain R_{SR} , SR is divided by the maximum of SR for all k intervals (0 to 1). See Table 2 for constant values. Note that the temperature function decomposition is not modified.

2.2.7 ~~NVPs:~~ Summary and other parameters

Other parameters and processes used for NVPs are set equal to those of C3 grasses, such as albedo and roughness as described by Krinner et al. (2005). We have ~~optimised~~ ~~optimized~~ specific parameters of NVPs (listed with asterisk in Table 2) against observation (see Sect. 2.5.1), following a Bayesian ~~optimisation~~ ~~optimization~~ framework (see Sect. 2.6.1). The values of the main parameters for the NVPs including the ~~optimised~~ ~~optimized~~ ones are reported in Table 2.

~~The implementation of the NVP PFT is performed in such a way that if we need to separate in different sub-PFTs (i.e. study bryophytes and lichens separately), this would be easy to do, with new associated parameters.~~

2.3 Boreal deciduous shrubs

Shrubs share ~~similar~~ biogeochemical and biophysical processes ~~withas~~ trees. Therefore, the introduction of a new shrub PFT is based on the equations ~~forof the~~ boreal deciduous ~~broadleaf~~ ~~broadleaved~~ tree PFT. The main difference between trees and shrubs concerns the size, and thus the allometry resulting from carbon allocation. ~~Furthermore~~ ~~Further~~, shrubs grow faster and therefore ~~colonise~~ ~~colonize~~ landscapes before trees do. For high-latitudes, the ~~cold~~ protection of shrubs ~~against cold~~ by snow is an important process that needs to be taken into account, since snow depth and shrub height are positively correlated (McFadden et al., 2001; Sturm et al., 2001). Snow cover tends to be thicker when shrubs are present (McFadden et al., 2001), and a thicker snow cover better protects shrubs from frost damage.

~~In the following, we describe these particularities including the new allometry, the snow—shrubs interactions as well as the impact of shrubs on surface roughness and albedo.~~ Note that all modifications ~~made here~~ are generic so that we can easily create additional ~~shrubs~~ ~~shrubs~~ types, such as needleleaf or evergreen phenotype, with only few parameter changes.

2.3.1 ~~Shrubs:~~ Allometry ~~Shrub~~ allometry

Tree allometry in ORCHIDEE is based on a pipe tune model (Smith et al., 2001). It represents the relation between height and diameter as a power (or log-linear) function, with no height limit. Shrub development is more horizontal than vertical (Bentley et al., 1970; Sitch et al., 2003; Lufafa et al., 2009), which requires modification of the tree allometry. We implemented the allometry rules described by Aiba and Kohyama (1996) with specific values for shrubs from Martínez and López-Portillo (2003). Equation (11) gives the allometry relation between individual height (H , m), diameter (D , m), volume (V , m^3), the number of individuals (n_i), the total crown area (C_a , m^2), the total stem basal areal (T , m^2), the total woody biomass (m_w , $gC.m^{-2}$) and wood density (ρ_w , between 0 and 1). The height of a shrub ~~resemble tois a~~ logarithmic function of its diameter (Eq. (11.a)) and its volume is represented by a cylinder (Eq. (11.b)). The shrub vegetation cover is defined as a function of the total stem basal area (Eq. (11.c)). With simple geometric relations (Eq. (11.d)) and

assuming a fixed crown area (C_a become a constant) the system can be solved and all key variables expressed as a function of shrub woody biomass (m_w). ~~The (the height is given by Eq. (11.e) and the number of individuals is adapted in order to keep the crown area fixed (Eq. (11.c. & d.)).~~ If the crown area is not fixed (e.g. with ~~dynamice~~dynamical vegetation), there is no analytical solution to obtain the height.

$$\begin{aligned}
 \text{a) } 1/H &= 1/(A \times D^\gamma) + 1/H_{max} \\
 \text{b) } V &= \pi/4 \times \frac{H_{max} \times A \times D^{2+\gamma}}{H_{max} + A \times D^\gamma} \frac{H_{max} \times A \times D^{2+\gamma}}{H_{max} + A \times D^\gamma} \\
 \text{c) } C_a &= \beta \times T^\alpha = \beta \times (n_i \times \pi/4 \times D^2)^\alpha \\
 \text{d) } m_w &= n_i \times V \times \rho_w \quad \text{and} \quad H = \frac{n_i \times V}{T} \\
 \text{e) } H &= \frac{m_w}{\rho_w \times (C_a/\beta)^{1/\alpha}}
 \end{aligned} \tag{11}$$

Were A , β , γ , α and H_{max} are parameters adapted from Martínez and López-Portillo (2003) (see Table 4). Here, the parameter H_{max} defining the maximal height (m) was ~~optimised~~optimized (see Sect. 2.6.1). ~~In To be~~ accordance with imposed vegetation coverage, a minimum woody vegetation height (H_{min} , m) was prescribed; based on the maximum height, according to:

$$H_{min} = H_{max}/h_c \tag{12}$$

Where h_c is a factor defined in Table 4. Based on the new shrub allometry ~~description~~equations (Eq. (11)), new parameters can be derived for shrubs with the pipe tune model (Table 4).

2.3.2 ~~Shrubs: Impact of shrubs on snow~~

Shrub vegetation affects snow cover through snow compaction and spatial heterogeneity of snow deposition ~~(due to lateral wind transport)~~. Shrub (and tree) branches support part of the snow cover. As a result, the snow weight on lower snow layers is smaller and the compaction of snow crystals is reduced. Moreover, wind is reduced by the presence of a shrub (and tree) canopy, which further reduces snow compaction compared to short vegetation cover. We kept the original snow compaction equation in ORCHIDEE (Wang et al. (2013), their Eqs. (11), (12) and table A1) but chose new values for the parameters controlling compaction depending upon low or high vegetation (Table 3) in order to model a different depth and density over the fraction of a grid cell covered with shrubs (and tree).

Currently there is no sub-grid simulation of snow cover and energy balance in ORCHIDEE, so there is no distinction according to the fraction of different PFTs present in a grid cell. To account for differences between PFTs we compute snow compaction separately for short vegetation (bare soil, ~~grasses~~grass and ~~NVPs~~NVP), shrubs and trees. The resulting average snow depth and density over a grid cell is obtained by weighting each vegetation-dependent compaction by its fraction. The deposition of snow is assumed to be ~~identical~~the same among the different PFTs. A PFT-dependent snow depth is needed to compute the protection of vegetation by snow (Sect. 2.3.3). To compensate for the lack of an explicit PFT-dependent snow depth, an empirical correction is applied to account for the effect of vegetation type on snow compaction and deposition on shrubs:

$$d_{s,v} = d_{s,f} \times d_s$$

$$d_{s,f} = \begin{cases} 1 + f_v, & f_v \leq 0.5 \\ 2 - f_v, & f_v > 0.5 \end{cases} \quad (13)$$

With $d_{s,v}$ being the snow depth of high vegetation (shrubs and trees, m), d_s the average snow depth (m) over the grid-cell, and $d_{s,f}$ a function of f_v , the fraction of high vegetation. [Note that this equation is a heuristic formulation discussed in section 4.](#)

2.3.3 Shrubs: mortality ~~reduction~~ ~~reduced~~ by snow protection

ORCHIDEE, ~~when used to compute dynamically the vegetation distribution~~ includes a tree mortality during extremely cold days, calculated as the percentage of biomass lost at the end of each day, ~~when used to compute the vegetation distribution dynamically~~ (see Zhu et al., 2015). ~~This mortality depends on a minimum temperature, as defined in Eq. (14). We used the same equation but assigned a critical minimum survival temperature to all boreal (including needleleaf) trees. This mortality depends on a minimum temperature, as defined in Eq. (14). We used the same equation than in Zhu et al. (2015) but boreal needleleaf trees are also assigned a critical minimum survival temperature.~~

$$\text{If } T_{\min} < T_{\min,crit}, M_{ce} = k_{ce} \times (T_{\min,crit} - T_{\min}) \quad (14)$$

With M_{ce} being the mortality rate due to cold extremes, $T_{\min,crit}$ the minimum critical survival temperature (defined for each PFT), T_{\min} the daily minimum air temperature and k_{ce} a mortality coefficient. The values of these parameters are given in Table 4.

For shrubs we ~~used~~ a similar approach to control the loss of biomass due to extreme cold ~~temperature~~. A mortality rate similar to Eq. (14) is applied to the highest parts of shrubs that are not covered by snow. For the part of shrubs situated inside snow layers (see 2.3.2, Eq. (13) for the shrubs snow depth calculation), snowpack temperature is used in Eq. (15). We defined a daily vertical profile of minimum temperature $T_{\min}(z)$ function of shrub height above ground (z), by linear interpolation between soil, snow layers and air temperatures above the shrub height emerging from the snow pack. To simulate the mortality of shrub parts being exposed to extreme cold, the following mortality equation is applied from the top part of shrubs.

$$M_{ce} = \int_{H_{\min}}^H \frac{k_{ce} \cdot f_n(T)}{H} \int_{H_{\min}}^H k_{ce} \cdot f_n(T) dz$$

$$f_n(z) = \begin{cases} 0 & , T_{\min} \geq T_{\min,crit} \\ T_{\min,crit} - T_{\min}(z), & T_{\min} < T_{\min,crit} \end{cases} \quad (15)$$

With M_{ce} being the extreme cold mortality, $T_{\min,crit}$ a minimum critical temperature (defined by PFT), k_{ce} a coefficient, H is the shrub height and H_{\min} its minimum height (Eq. (12)). The values of the parameters of Eq. (15) for shrubs are given in Table 4. This equation is the integral of Eq. (14) applied to the height of shrubs.

2.3.4 Shrubs: Modification of roughness and albedo

In ORCHIDEE, the surface roughness length is directly computed from the height of the vegetation. Similarly, surface albedo depends on the vegetation type. Because shrubs can be partially or entirely covered by snow, the computation of surface roughness and albedo in the presence of shrubs needs to take into account snow height. The calculation of surface roughness length has thus been modified. First vegetation height is computed separately for shrubs (using Eq. (11)) and for trees (using the original pipe tune model equation of Smith et al.,

2001). The height of the snow cover over shrubs is then subtracted from the vegetation height in order to estimate the height of the vegetation above the snow surface (i.e. the relative height), which determines the surface roughness. The relative difference between the relative height and the total height is not substantial for trees (height > 5m), but it can be important for shrubs (> 30cm) which can be totally covered by snow. To represent the spatial heterogeneity of snow cover, when the snow thickness is close to the height of vegetation, a linear function is applied to estimate the height above snow:

$$H_{PFT_{as}} = \begin{cases} H_{PFT} - d_s & , H_{PFT} > d_s \cdot (1 + \Delta_{z_0}) \\ 0 & , H_{PFT} < d_s \cdot (1 - \Delta_{z_0}) \\ (H_{PFT} - d_s(1 - \Delta_{z_0}))/2, & otherwise \end{cases}$$

$$(16) \quad H_{PFT_{as}} = \begin{cases} H_{PFT} - d_s & , H_{PFT} > d_s \cdot (1 + \Delta_{z_0}) \\ 0 & , H_{PFT} < d_s \cdot (1 - \Delta_{z_0}) \\ (H_{PFT} - d_s(1 - \Delta_{z_0}))/2, & else \end{cases} \quad (16)$$

Where H_{PFT} is the height of the PFT, $H_{PFT_{as}}$ is the height of the PFT above the snow, d_s depth of snow, and Δ_{z_0} the width of the transition zone due to spatial heterogeneity of snow cover (see Table 4).

The fraction of vegetation (f_v) is used to

compute the roughness length z_0 . For trees and shrubs the maximum fraction of vegetation $f_v = f_{v,max}$ (prescribed if the vegetation cover is static, or calculated when the vegetation cover is dynamic, and independent of LAI) is used to take into account the influence of trunks and branches even if there are no leaves. For grasses and NVPs, to take into account the variation of leaf cover (for example absent for grasses in winter) only the projected surface of the foliage in the canopy $f_v = f_{v,max}(1 - e^{-LAI/2})$ is used because there are no woody elements. The rest of surface is considered as bare soil with a constant roughness length value.

Finally the roughness length of a given PFT is calculated as its height above snow multiplied by a roughness parameter $z_{0,c}$, as initially in ORCHIDEE. If this value is lower than the bare soil roughness ($z_{0,bs}$ fixed), then the latter value is used. The grid cell mean roughness length is computed (from Vihma and Savijärvi, 1991) as a function of each PFT roughness weighted by the vegetation cover, f_v :

$$\log(z_0) = \sum_{PFT} (f_v \times \log(\max(\frac{H_{PFT_{as}}}{z_{0,c}}, z_{0,bs}))) \quad (17)$$

Where z_0 is the grid-cell averaged roughness (m), $z_{0,bs}$ the roughness of the bare soil (m), f_v the fraction of each PFT and $z_{0,c}$ a constant roughness parameter. The values of the parameters of Eq. (17) are given in Table 4.

The mean albedo of a grid cell depends on the vegetation, bare soil and snow albedo and their fractional coverage. While snow albedo is a function of snow age (computed for each vegetation type), bare soil and vegetation albedo are constant in time. A critical parameter to weigh the different terms is the fraction of the grid cell covered by snow, snw_{frac} , on bare soil and vegetation. In ORCHIDEE this fraction only depends on the snow mass, as defined in Chalita and Le Treut (1994). We chose to modify this approach in order to account for the effect of the vegetation structure as in Douville et al. (1995) and Boone (2002), using the roughness length calculated from Eq. (17) which is given by:

$$snw_{frac} = \frac{snw_{dz}}{snw_{dz} + \xi z_0} \quad (18)$$

With snw_{frac} being the fraction of the grid covered by snow, snw_{dz} the snow thickness, z_0 the roughness length and ξ a parameter (defined in Table 4).

2.3.5 ~~Shrubs: Parameters~~ ~~Shrub parameters~~

Table 4 ~~summarises~~ ~~summarizes~~ the main parameter values used in the ~~equation~~ ~~equation~~ described previously as well as ~~a~~ few other parameters modified for the shrub PFT (compared to the initial tree PFT).

2.4 Cold ~~climate~~ ~~climates~~ C3-Grasses

~~In order to better account for biogeochemical differences between arctic, temperate and tropical grasses (only one PFT in ORCHIDEE), we~~ ~~We~~ re-parameterised ~~parameterized~~ the grassland PFT for circumpolar regions, following the generic equations of C3 grasses. Few parameters have been calibrated (see list in Table 5) to modify primarily the photosynthetic activity, the root distribution in the soil and the leaf development.

The rate of carboxylation, limited by Rubisco (V_c) and ~~by~~ electron transport (V_j), ~~is~~ ~~are~~ dependent on specific parameters (following Yin and Struik (2009) and presented in Eq. (19)), themselves ~~functions~~ ~~function~~ of monthly mean temperature (t_m , K) (Eq. (20)).

$$F(T) = k_{25} \times e^{\frac{E_a(T-T_{25})}{T_{25}R T}} \times \frac{1 + e^{\frac{T_{25} \Delta S - E_d}{T_{25} R}}}{1 + e^{\frac{T \Delta S - E_d}{T R}}} \quad (19)$$

With $F(T)$ ~~being~~ the rate function V_c or V_j , k_{25} the maximum of each rate (V_{c_max} or V_{j_max}) at a reference temperature T_{25} (25°C or 298 K; note that V_{c_max} and V_{j_max} are linked by a linear function being temperature dependent), T the current temperature (K), E_a the activation energy, E_d the deactivation energy, ΔS the entropy factor and R the ideal gas constant (Table 5).

The entropy factor ΔS for V_{c_max} or V_{j_max} is calculated as follows:

$$\Delta S = a + b \times t_m \quad (20)$$

With a and b two constants (Table 5). This formulation from Kattge and Knorr (2007) include an adaptation of seasonal growth temperature (derived from ~~the~~ spatial relation between V_{c_max} and J_{max} in TRY database and extrapolated for temporal equations). Observations by Miller and Smith (2012) of the optimal temperature for photosynthesis for graminoids and forb tundra (10 to 20°C) were used to define new parameter values, which were then ~~optimised~~ ~~optimized~~ (list of ~~variables~~ ~~variable~~ in Table 5). The ~~optimisation~~ ~~optimization~~ procedure is described in Sect. 2.6.1.

~~According to Bonan et al. (2003) or Iversen et al. (2015) the~~

~~The~~ depth over which 95% of the root is located corresponds roughly to 0.5 ~~mmeter~~ for boreal C3 grasses and to 1 ~~mmeter~~ for temperate C3 grasses, ~~according to Bonan et al. (2003) or Iversen et al. (2015)~~. Using this estimate we changed the a priori value of the root profile shape parameter (r_p parameter; see Eq. (5) and de Rosnay, 1999) for cold grasses and after ~~optimisation~~ ~~optimization~~ (see Table 5) we obtained that 95% of the roots are within the first 40 cm of the soil.

The specific leaf area (SLA) was also ~~optimised~~ ~~optimized~~ for cold climate grasses, using as a priori the initial values from C3 temperate grasses. Note that ~~for simplicity and because of their weak impact on simulation when the vegetation is fixed,~~ we did not add ~~any bioclimatic limits, such as i)~~ survival or establishment ~~temperature thresholds~~ ~~limits~~ as ~~proposed by~~ ~~in~~ Bonan et al., (2003) and Oleson et al. (2013) or ~~ii)~~ a cumulated degree-day threshold (above ~~the zero~~ ~~degree~~ criteria) for the ~~plant growth~~ ~~development~~ (Miller and Smith,

2012). [In this study we use ORCHIDEE without the dynamic vegetation module, but with a prescribed vegetation cover preventing vegetation development in unfavourable areas.](#)

2.5 Observations and vegetation distribution

2.5.1 Field survey data

5 The calibration of the parameters [enteredentering](#) in the equations of ~~NVPs~~[NVP](#), shrubs and cold climate grasses is based on observations for the period 1993-2001 gathered in Peregon et al. (2008) and extended up to 2013 for this study. The data set contains georeferenced point-scale observations of the total summertime living biomass ($\text{g}\cdot\text{m}^{-2}$) and annual net primary productivity NPP ($\text{g}\cdot\text{m}^{-2}\cdot\text{yr}^{-1}$) for non-vascular plants (mosses and lichens) and vascular plants (grasses and shrubs) in boreal wetlands. Test sites for field observations [are](#)
10 located in Western Siberia (Latitude 55° to 71° N, Longitude 63 to 91° E), which is suited for spatial analysis of NPP and biomass due to its flat topography along a wide latitudinal gradient and large variety of natural ecosystems, with minor anthropogenic influence.

At each test site, detailed geobotanical descriptions were recorded and biomass sampling was conducted. Sampling was repeated two or three times during the growing season at the same test sites for several
15 consecutive years to obtain information on interannual variability. Field studies were conducted between June and October at more than 99% of the test sites, and between July and September for 90% of them. General descriptions of in-field and laboratory methods used to estimate NPP and biomass ~~in wetlands~~ are described in Peregon et al. (2008, 2016).

The data set takes into account all components of NPP and living biomass: above-, land-surface and
20 belowground fractions measured *in-situ* at different topographical features (such as hummocks, hollows, ridges). In order to avoid the “bound” effect and use of values at the border between two vegetation classes, we chose to [exclusively](#) take into account ~~observationonly-observation~~ where the studied vegetation represented at least 10% of the surface. Spatial differences in these microsite characteristics (i.e. hydrologic and thermal regimes, nutrient availability) strongly determine vegetation characteristics, as well as NPP and biomass, and
25 small-scale heterogeneity induced by these microsite characteristics can be as large as the large-scale variability due to climatic gradients across the area covered by the dataset. Because the small-scale variability cannot be represented in a large-scale model like ORCHIDEE, and small-scale information on microsite hydrological and topographical characteristics were not available, no perfect model-data fit can be expected and we should rather seek for a broad model-data agreement.

30 The data have therefore been grouped into supersites at 0.5° spatial resolution, giving 36 supersites. The 36 sites have data on mosses (comprising in total 1209 individual observations), but only 16 supersites presenting non-vascular plants, shrubs and grasses (comprising in total 660 individual observations) (Fig. [5](#)). [Note finally that using a single dataset in Western Siberia \(mainly lowlands\) for the model calibration may introduce some biases, which will have to be evaluated.](#)~~4~~

35 2.5.2 Vegetation distribution

For this study we prescribe the spatial distribution of the vegetation, while a follow-up study will focus on the dynamics of [the](#) vegetation. We thus had to update the vegetation map used by the standard version of ORCHIDEE in order to include the spatial distribution of the new PFTs. The land cover product used to define

PFT distribution in ORCHIDEE is derived from the land cover product of the European Space Agency (ESA) Climate Change Initiative (CCI) (available at <http://www.esa-landcover-cci.org/>). The product is based on medium-resolution satellite observation and provides information on the vegetation distribution using land cover classes (LCC) defined by the United Nations Land Cover Classification System (UNLCCS). In order to match the satellite land cover classes with the PFTs coverage in ORCHIDEE, we use a conversion table established by Poulter et al. (2015). Note that the climate classification system of Köppen (Peel et al., 2007) is also used to further partition some vegetation types into tropical, temperate and boreal zones (see also Poulter et al., 2015). The new vegetation map is thus obtained from this Land Cover dataset (version 1.6.1) transformed with ~~aby~~ conversion table ~~from Poulter et al. (2015)~~ (tool available from <http://maps.elie.ucl.ac.be/CCI/viewer/>), from ~~300 m~~^{300m} LCC data. From the standard conversion table used in ORCHIDEE, the three new PFTs were included using the following modifications (Table S1):

- i. The C3 grasses (initially defined globally) that were located in class 5 of Köppen classification (polar and alpine climates) were assigned to the new cold climate C3 grasses PFT.
- ii. In the original version of the conversion table, LCCs were first separated between trees and shrubs (Table S1), then aggregated into ~~tree~~^{trees} PFTs. Here we kept the shrubs and trees separated to define the shrub PFT coverage.
- iii. “Lichens and mosses” LCC were classified by Poulter et al. (2015) into C3 grasses and bare soil PFTs, and now are used to define a separate NVP PFT (Table S1). However the NVP coverage that corresponds to the lichens and mosses LCC is clearly underestimated with the CCI product over Eurasia compared to North America and to other pan-arctic land cover maps (*i.e.* in ~~Circumpolar Arctic Vegetation Map, CAVM Team, 2003~~)(*i.e.* in ~~Cirumpolar Arctic Vegetation Map: CAVM Mapping Team et al., 2003~~), in which ~~NVP~~^{NVPs} cover is much larger. In ~~the Loveland et al. (2000)~~ map ~~from Loveland et al. (2000)~~, we noticed that the tundra biome corresponds to the “sparse vegetation” or to the “lichens and mosses” LCCs distribution. ~~In CAVM Team (2003), in CAVM Mapping Team et al. (2003)~~ the tundra biome is described as ~~containing a composite of ~30 to 60% of~~ NVPs. Combining these two maps with the ESA CCI LCC map, we modified the conversion of “sparse vegetation” LCC in the ESA CCI map, initially to 35% bare soil and 40% grass PFTs, into 20% of bare soil, 10% cold climate grass PFT and 45% of the NVP PFT (Table S1). The remaining fraction of sparse vegetation (25%) has not been modified and is considered as a mix of trees and shrubs.

The resulting spatial distribution ~~north of 60°N~~ of is consistent with CAVM and Loveland et al, with 2.9, 2.2 and 2.8 ~~million~~^{millions} km² of NVPs, shrubs and cold climate grasses, respectively, ~~north of 60°N~~.

The distribution of the different circumboreal PFTs is presented in Fig. ~~65~~. NVPs are mainly present in northern latitudes where climate conditions for the other PFTs are too extreme. Shrubs are present everywhere in northern latitudes but sparsely, with the tree PFTs always dominating. This is due to the approach we chose, because shrubs are diagnosed from the same LCCs as trees, with a smaller fractional coverage (Table S1). The cold climate C3 grasses come mainly from boreal forest LCCs in northern latitudes and from meadows further south (Table S1). They are dominant only in the latter.

2.6 ~~Optimisation~~ Optimization strategy and evaluation protocol

2.6.1 Parameter ~~optimisation~~ optimization strategy

We used a Bayesian ~~optimisation~~ optimization procedure to ~~improve the value of~~ optimize selected parameters of the new NVPs, shrubs and boreal C3 grass PFTs. ~~Prior, where prior~~ information on the parameter is combined with the information that can be extracted from an ensemble of observations (see Sect. 2.5.1). Assuming that the errors associated with the parameters, the observations and the model follow Gaussian distributions, the optimal parameter set corresponds to the minimum of a cost function, $J(\mathbf{x})$, that measures the mismatch between i) the observations (\mathbf{y}) and the corresponding model outputs, $H(\mathbf{x})$, (where H is the model operator), and ii) the a priori (\mathbf{x}_b) and ~~optimised~~ optimized parameters (\mathbf{x}), weighted by their error covariance matrices (Tarantola, 1987; Eq. (21)):

$$J(\mathbf{x}) = \frac{1}{2} [(\mathbf{H}(\mathbf{x}) - \mathbf{y})^T \mathbf{R}^{-1} (\mathbf{H}(\mathbf{x}) - \mathbf{y}) + (\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b)] \quad (21)$$

\mathbf{R} represents the error variance/covariance matrix associated with the observations and \mathbf{B} the parameter prior error variance/covariance matrix. Note that \mathbf{R} includes the errors on the measurements, model structure and the meteorological forcing. Model errors are rather difficult to assess and may be much larger than the measurement error itself. Therefore, we chose to focus on the structural error and defined the variances in \mathbf{R} as the mean squared difference between the prior model and the observations (as in (Kuppel et al., 2013)). For simplicity we assumed that the observation error covariances were independent between the different observations and therefore we kept \mathbf{R} diagonal (off-diagonal terms set to zero).

The determination of the optimal parameter vector that ~~minimises~~ minimizes $J(\mathbf{x})$ is performed using a Monte Carlo approach based on a Genetic Algorithm (GA) following the implementation of Santaren et al. (2014). The algorithm works iteratively, starting with a pool of vectors of parameters (i.e. the chromosomes) defined from randomly perturbed parameters. At each iteration, it randomly perturbs or exchanges parameters of the chromosomes and ranks them based on the cost function values, so that the best chromosomes (parameter combinations corresponding to the lower cost function values) produce more descendants (following the principle of natural selection). For details of the implementation see Santaren et al. (2014). Note that this algorithm is more efficient to find the minimum of J than a gradient-based method as discussed in Bastrikov et al. (in preparation).

For each ~~optimised~~ optimized parameter (Table S2), the initial values were taken from the literature or from the values used for the ORCHIDEE boreal deciduous tree PFT for shrubs and from the C3 grasses PFT for NVPs and cold climate C3 grasses. We defined the observation errors (\mathbf{R} diagonal) as 50 gC.m^{-2} (1-sigma standard deviation) for the biomass and for NPP, based on field ~~measurement~~ measurements errors (Peregon et al., 2008) and a priori model data mismatch. The number of ~~iterations~~ iteration was set to 25 and the number of chromosomes to 15 for NVPs and 10 for C3 grasses and shrubs, after some initial check of the convergence of the algorithm. ~~The simulation for the optimisation was done with CRU-NCEP meteorological forcing (Wei et al., 2014; Viovy, 2015), at 0.5° resolution. In~~ Note that in order to spin up the model with respect to the living biomass, each simulation starts 10 years before the observation period for NVPs and grasses, and 19 years for shrubs.

2.6.2 Evaluation Protocol

To illustrate the impact of new boreal vegetation compared to standard PFTs we show the results of two different simulations: one with the standard 13 PFTs of ORCHIDEE (ORC13) and the second with the new circumboreal PFTs (13 standards + 3 new PFTs: ORC16). Both simulations use the CRU-NCEP meteorological forcing (Wei et al., 2014; Viovy, 2015)(Wei et al., 2014; Viovy, 2015) based on gridded monthly observations from the Climatic Research Unit (CRU) at 0.5° and the climate re-analysis from the National Center for Environmental Prediction (NCEP) model (reduced to 2° resolution), available from 1901 to 2013. We spin up the model carbon pools (above and below ground) with a 5,000 years simulation recycling the forcing files from 1901 to 1950 randomly). We then used a transient simulation from 1901 to 2004 with linked CO₂ concentration. The spatial domain is also limited to the latitudes above 40° North.

First, the total biomass and NPP are evaluated against observations ~~using with~~ extended data from Peregón et al. (2008). ~~We further compare the simulated biomasses with two We then analyse other key variables (such as LAI, albedo, soil temperature, total evaporation, etc.) to provide further insight on the impacts on carbon, energy and water fluxes. The analysis is carried out on multiple spatial and temporal scales. Arctic transects. The first one is the North America Arctic Transect (NAAT). It is situated in a continental area, and includes eight field locations (70°N 149°W to 79°N 100°W) sampled from 2002 to 2006 (Walker et al., 2011b) chosen as representative of zonal conditions. The second, located in a marine-influenced area, is the Eurasian Arctic Transect (EAT). It includes six field locations (58 to 73°N, between 67 to 81°E) sampled from 2007 to 2010 (Walker et al., 2008, 2009a, 2009b, 2011a). In order~~ Then, to evaluate the simulated LAI, we use the GLASS (Global Land Surface Satellite) LAI product (Liang et al., 2013; Xiao et al., 2014). This product has a temporal resolution of 8 days and is available from 1982 to 2012. Data used in this study cover the period from 2004 to 2013 and were derived from MODIS (moderate resolution imaging spectroradiometer) land surface reflectance (MOD09A1), at a resolution of 1 km. In order to compare this GLASS product with our 2° resolution simulations, an extrapolated map of the 1 km resolution to the 2° resolution was built and a mask was applied to remove 2° resolution grid cells with a land fraction below 0.7. ~~Finally we analyse key variables (such as NPP, albedo, soil temperature, total evaporation, etc.) to provide further insight on the impacts on carbon, energy and water fluxes. The analysis is carried out on multiple spatial and temporal scales. Following the optimisation protocol described in Sect. 2.6.1, we calibrated 12, 6 and 7 parameters for the NVPs, shrubs and cold climate grasses respectively (see list in Tables 2, 4, 5 and S2). The optimisation relied on observations of living biomass and Net Primary Productivity observations presented in Sect. 2.5.1.~~

3 Results

3.1 Model calibration and fit to the observations

~~Following the optimization protocol described in Sect. 2.6.1, we calibrated 12, 6 and 7 parameters for the NVPs, shrubs and cold climate grasses respectively (see list in Table 2, Table 4 and Table 5). The optimization relies on observations of living biomass and Net Primary Productivity observations presented in Sect. 2.5.1. First we should notice that the~~ selected observations are ~~characterised~~ characterized by a very large standard deviation (SD). For cold climate grasses the SDs of the observed total biomass and NPP are close to their mean values (total biomass = $558 \pm 427 \text{ gC.m}^{-2}.\text{y}^{-1}$; NPP = $321 \pm 222 \text{ gC.m}^{-2}$). For boreal shrubs the SDs are also

very large (total biomass = $768 \pm 432 \text{ gC.m}^{-2}.\text{y}^{-1}$; NPP = $321 \pm 104 \text{ gC.m}^{-2}$), while for non-vascular plants they reach only half of the mean values (total biomass = $217 \pm 105 \text{ gC.m}^{-2}.\text{y}^{-1}$; NPP = $117 \pm 61 \text{ gC.m}^{-2}$). The cost function ($J(\mathbf{x})$ in Eq. (21)) was reduced ~~compared to, through the optimization and from~~ prior ~~valueparameter values,~~ by 31% for NVPs, 64% for shrubs and 54% for boreal C3 grasses ~~through the optimisation (see values in Tables 2, 4, 5 and S2). and the parameters were optimized within their physical range of variation (see values in Table 2, Table 4 and Table 5).~~ All results that are discussed below were obtained with the ~~set of optimisedoptimized~~ parameters ~~set~~.

~~ScatterFigure 6 shows scatter~~ plots of modelled versus observed living biomass and NPP for the new PFTs ~~and~~. ~~The observations are~~ grouped by bioclimatic zones ~~are displayed in Fig. 7., including forest steppe in the south, different taiga ecosystems (south, middle and north), forest tundra and tundra in the far north.~~ For NVPs the model mean across all sites for biomass and NPP is close to the observed mean, ~~(see values in Fig. 6),~~ but the cross-site spread is not well captured. In particular the model spread is too small, especially for the forest-steppe ecosystem, indicating that the current model structure cannot simulate the spatial variability that is observed between sites. Note also that for the forest-steppe region ~~the mean~~ NPP and living biomass of NVPs are largely ~~underestimatedunder-estimated,~~ by more than 50 and 100 gC.m^{-2} , respectively. For cold climate C3 grasses the model spread is much smaller than the observation spread (for both NPP and biomass), although the model mean across all sites is relatively close to the observed value. In particular the model fails to represent the large NPP and biomass for the southern ecosystem (the forest-steppe), while for the other ecosystems it overestimates the NPP and ~~slightly~~ the biomass. For shrubs, the results are ~~relatively~~ similar with ~~also~~ a too low model productivity for the forest-steppe ecosystem. Overall the model captures ~~for each new PFT~~ the mean across all observations ~~for each new PFT~~ but ~~shows~~with a large bias for the southern bioclimatic region, where the low simulated values are probably due to a too large water stress in the model (possibly induced by the forcing file at 2° resolution ~~in a mountainous region,~~ unable to reproduce local conditions).

~~Latitudinal transects of simulated~~We now compare the latitudinal gradient of NPP and biomass over the Central Siberian region ~~are comparedshown in Fig. 4. Figure 7 displays model transects from 50°N to 74°N , with mean values calculated over the 78°E to 82°E longitudinal band and over the period 2004-2013, together with the observations (sites shown in Fig. 5) in Fig. 8. aggregated by site (averaged for all year) for each new PFT.~~

The simulated NPP shows broadly a maximum between 57°N and 65°N for the three PFTs, with a decrease south of 57°N (by more than a factor two from 57°N to 55°N) and a more progressive decrease north of 65°N . For the NVPs the northern NPP decrease occurs only after 69°N . The observed values are broadly consistent within their uncertainties with the simulated latitudinal gradients for the selected region, although in absence of any observations north of 66°N for shrubs and boreal C3 grasses it is not possible to evaluate the slope of the northern decrease of the simulated productivity. For boreal C3 grasses, if we exclude two sites at 55°N and 67°N having much larger NPP, the other sites reveal a latitudinal pattern similar to the ~~modelledmodel~~ one, although with smaller values. The simulated total living biomass follows similar latitudinal patterns for the three PFTs, with ~~nevertheless~~ higher biomass for shrubs between 57°N and 65°N due to wood accumulation. The biomass observations for NVPs display the same pattern ~~as in~~the model. For cold climate C3 grasses, ~~even~~ without considering the two sites with very large NPP, the observed living biomass is higher than the ~~modelledmodel~~ ones despite the observed lower NPP (Fig. 87-left). ~~This~~it is probably due to ~~the~~ large fraction

of below-ground biomass of grasses. For shrubs, the model displays a maximum ~~of~~ biomass around 60°N for this region with large decrease at lower or higher latitudes, ~~which that~~ is not directly supported by the set of available observations.

Overall, if the decrease of biomass productivity in the north can be explained by a decline of photosynthesis (due to more extreme conditions), the low value simulated south of 55°N can be attributed to water limitations (snowfall and rainfall are reduced by 30% in the region 50°N - 55°N compared to 60°N - 65°N), due to change of geographical (or bio-climatic) conditions. Note that two grassland sites that are very ~~close~~ (65.8°N, 75.4°E and 65.9°N, 75.0°E) have very different NPP (750 gC.m⁻² and 187 gC.m⁻²) and living biomass values (962 gC.m⁻² and 260 gC.m⁻²), which illustrate the small-scale variability reported above that cannot be captured by the model.

3.2 Evaluation of the simulated biomass and LAI

Carbon stock with two Arctic transect

To evaluate the modelled biomass in other Arctic sites (not used in the calibration step), including uplands and lowlands, Fig. 9 shows scatter plots of observed and simulated biomass along two transects: the NAAT (North America) and the EAT (Eurasia) Arctic Transect. The NVPs and shrub biomasses are relatively well reproduced by the model (i.e. within the error bars). For both PFTs, the standard deviation of the observations includes the 1:1 line, but the observed biomasses are on average higher than the simulated biomasses. Simulated shrub biomasses are biased low for the NAAT transect but not for the EAT transect.

In contrast, the mean value of observed biomass for boreal C3 grasses (Fig. 9.c) is low compared to the simulated biomasses for both cases. For half of the sites the simulated low biomass is in accordance with the observations, but for the other half the values are much larger (> 300 gC.m² whereas the observation do not exceed 54 gC.m²). Despite the optimisation with observations from western Siberia (Fig. 7; leading to a decrease of biomass compared to temperate C3 grasses) there is likely an overestimation of the biomass for boreal C3 grasses, probably associated with an overestimated productivity.

Leaf Area Index with GLASS LAI product

Overall the main spatial patterns of Leaf Area Index (LAI) simulated with ORC16 match the patterns of the GLASS product well (Fig. 10) with i) a latitudinal band with higher LAI around 60°N in Eurasia and below 60°N in Northern America and ii) lower LAI at low latitudes in central Siberia and in above 65°N in Siberia and North America. However, the model underestimates LAI in the central-west of Siberia. Comparison between GLASS product and the two model simulations (ORC16 and ORC13) indicates an overall improvement of the simulated LAI with the inclusion of the new boreal PFTs. A substantial decrease of LAI in Northern Europe (from 55°N), Northern-Western Siberia (from 55°N and until 135°E) and Northern America (from 50°N) is simulated in ORC16 compare to ORC13, which is in better accordance with GLASS product. This improvement with ORC16 is directly due to significant lower LAI values in these regions (north of 55°N) compared to ORC13. North of 65°N in Asia and America, these lower values in ORC16 are attributed to the introduction of NVPs in replacement of C3 grasses (Sect. 2.5.2) with lower LAI (see Sect. 3.2). In addition, the introduction of cold climate C3 grasses and shrubs with lower maximum LAI (e.g. 2.5 for shrubs against around 4 for tree PFTs) also contributes. Elsewhere, ORC16 and ORC13 simulations present on average

similar LAI anomalies compare to GLASS (mainly located in the south), except for Alaska and Eastern Siberia where ORC16 – GLASS anomalies are slightly more negative than with ORC13.

3.23.3 Carbon fluxes and stocks of the new PFTs: spatiotemporal variations

We now analyse the carbon fluxes (the NPP) and the carbon stocks (July, August and September mean living biomass) obtained with a simulation over the whole boreal zone with the new PFTs (16 PFTs, referred as ORC16; see Fig. 5). The results are averaged over North America (180°E to 60°E, without Greenland), Europe (20°E to 40°E) and North Asia (40°E to 180°E) (in Figs. 8–10 and Fig. S1) and we only show the new PFTs (i.e., boreal C3 grasses, NVPs and shrubs) and the boreal broad leaf summergreen trees (from which shrubs are derived) results (expressed by square meter of each PFT).

Latitudinal gradients:

Figure 8 displays latitudinal transects of NPP and living biomass between 45°N and 82°N for each region (see Fig. S1 for the biomass of boreal broadleaved trees). On average we obtain a similar latitudinal gradient in terms of productivity and biomass for all PFTs is obtained (Fig. 11.a), with roughly a maximum of biomass and productivity in North America around 60°N. Further north and until 80°N, an important 52°N (with above a continuous decrease of NPP and biomass can be observed, with an even steeper slope for shrubs until 72°N) and in Asia around 58°N (with a decrease until 78°N) and with a plateau in Europe between 50°N and 70°N (follow by an abrupt decrease). The shape of these latitudinal gradients is primarily controlled by the climate (Fig. S1), in particular for, especially the precipitation and temperature gradients and with a strong influence of the topography. For example in Asia the precipitation gradient increases from 45°N (less than 1 mm.d⁻¹) to a maximum around 55°N–60°N (1.5 mm.d⁻¹) and then decreases again northward, while the mean air temperature (at 2m) decreases gradually from 45°N (around +7°C) to 75°N (-13°C). For this region the decrease of precipitation from 60°N to 45°N explains the decrease of NPP and biomass. In Europe the climatic conditions are on average more favourable (e.g. +5°C at 45°N to +10°C à 70°N) which explains the higher productivity and biomasses at high latitude (i.e. around 70°N).

On average boreal Boreal C3 grasses have on average comparable living biomass but lower NPP than temperate C3 grasses in the southern latitudes where both PFTs are present. NVPs on the other hand NVPs always have a much lower productivity and living biomass than grasses (more than $\leq 50\%$ lower). Despite the NVP fact that the NVPs implementation being is based on C3 grasses, we also notice that the latitudinal gradients of both productivity and living biomass differ between these two PFTs with smoother latitudinal variations for the NVPs than the ones for boreal C3 grasses, illustrating also the importance of the added processes for the NVPs (resistances to extreme conditions, see Sect. 2.2.3 and 2.2.4). Similarly, shrubs systematically display a lower NPP (by a factor of two) and much lower biomass (factor 20, see Fig. S3S4) than the corresponding boreal deciduous summergreen trees although with similar latitudinal patterns. The reduced biomass accumulation for shrubs is controlled by the new allometry relations described in Sect. 2.3.1, a lower residence time (i.e. higher mortality) and a higher fraction of GPP lost as growth respiration (Sect. 2.3.5).

These lower biomass and NPP of the new boreal PFTs compared to the PFT from which they are derived imply a globally lower value in simulation ORC16 than in ORC13 (without the new PFT). For example, the NPP is lower by 31% north of 55°N.

Temporal evolution:

On average, Figure 9 shows the simulated yearly time series from 1901 to present day for both NPP and living biomass, averaged north of 55°N, to illustrate the response of the vegetation to climate change. The simulated productivity increases on average for the three regions (Figs. 11.b right, S2) from 1950 to 2013 (Fig. 9.a) by around 272.5% for boreal C3 grasses, 210.49% for NVPs and 80% for boreal shrubs (versus 35% for trees, Fig. S3) from 1950 to 2013. The simulated biomass increases (Figs. 11.b left, S2; Fig. 9.b or Fig. S1 with boreal trees) by the same proportion than the NPP for cold climate grasses and NVPs (+23% and +200%, respectively), +25% and +200%, while for shrubs the increase is stronger (+85%). It is 140%. Note also of interest that the biomass increase for shrubs is much larger than for boreal broadleaf broad-leaved trees (+20%, S3).

Globally, the increase of both NPP and biomass over the last 60 years is substantial for all PFTs, but largest for non-vascular plants and shrubs (see number above), which are more sensitive to climate change and CO₂ increase in the model. For shrubs, climate change at high northern latitudes has a direct impact on mortality in winter (Sect. 2.3.3); an increase of the minimum temperature implies a lower mortality. Importantly, we expect that the impact of climate change in the transient simulation would be small before 1950. The combination of lower mortality and higher photosynthesis (due to temperature) in Europe, where the temperatures are substantially larger (up to +10°C compared to the other regions), explains the higher increase in simulated biomass and NPP. Note that because the model spin-up was done with climate forcing randomly taken from the period 1901 - 1950 (Sect. 2.6.2) we expect that the impact of climate change in the transient simulation would be small before 1950.

The Figure 10 displays the mean seasonal cycle of NPP for the three continental regions (mean over 2004-2013 and above 55°N). As expected, the growing season starts late spring with a sharp increase of the NPP up to July and then a slower decrease up to November, for all PFTs. The seasonality is slightly different for NVPs (Fig. S4), for which the NPP starts earlier in spring, followed by maximum reaches reached earlier (in June). Considering that the impact of the global increase in temperature is large in spring and autumn, the NVPs can take better advantage of it. During these two periods, more than 20% of the annual increase in NPP for NVPs occurs (Fig. 11), while there is almost no increase for other PFTs. The, with a small NPP decrease over the summer (Fig. S4) with sometimes locally a summer minimum in August) before the large decrease from September on. Such difference is due to the impact of desiccation during summer time (due to an increase of the water stress, see Sect. 2.2.4) that decreases the maximum potential photosynthesis rate. Finally only small differences in the timing of NPP occur between the three regions, with an earlier start in Europe (1 month), probably due to higher temperatures.

Note also that NPP starts slightly earlier in spring for NVPs than for the other boreal PFTs, especially in Europe (Fig. 10). Moreover, the impact of the global increase in temperature is large in spring and autumn, causing a lengthening of the boreal growing season. The vegetation that could make the best use of these temperature increases may thus get a larger benefit of climate change. This is the case for NVPs, which display an earlier start of the growing season in spring (from March in Europe or April elsewhere) and a later end of season in autumn (after October) (not shown). During these two periods, more than 20% of the annual increase in NPP (Fig. 9) for NVPs occurs, while there is almost no increase for other PFTs.

3.3 Evaluation of the simulated Leaf Area Index

Figure 11 displays the mean (over 2004–2013) boreal distributions of Leaf Area Index (LAI) in summer (July, August and September) simulated by ORCHIDEE with the new PFTs (ORC16) and from the GLASS LAI product (see Sect. 2.6.2). It also displays the differences between the simulated LAI (either with the new PFTs description, ORC16, or the old standard description, ORC13) and the GLASS product. Overall the main spatial patterns simulated with ORC16 match relatively well the patterns of the GLASS product with i) a latitudinal band with higher LAI around 60°N in Eurasia and below 60°N in northern America and ii) lower LAI at low latitudes in central Siberia and in above 65°N in Siberia and North America. However, too low LAI seems to be simulated in western Siberia. Comparison between GLASS product and the two model simulations (ORC16 and ORC13) indicates an overall improvement of the simulated LAI with the inclusion of the new boreal PFTs. A substantial decrease of LAI in Northern Europe (from 55°N), Northern Western Siberia (from 55°N and until 135°E) and Northern America (from 50°N) is simulated in ORC16 compare to ORC13, which is in better accordance with GLASS product. These lower values in ORC16 are attributed, north of 65°N in Asia and America, to the introduction of NVPs in replacement of C3 grasses (Sect. 2.5.2) with lower LAI (see Sect. 3.2). In addition, the introduction of cold climate C3 grasses and shrubs with lower maximum LAI (e.g. 2.5 for shrubs against around 4 for tree PFTs) also contributes. Elsewhere, ORC16 and ORC13 simulations present on average similar LAI anomalies (mainly located in the south), except for Alaska and Eastern Siberia where ORC16–GLASS anomalies are slightly more negative than with ORC13.

3.4 Biophysical impacts of the new boreal vegetation description

The annual albedo We now investigate the impacts of the new vegetation types on a few key variables related to the energy and water budgets (Fig. 12). The annual albedo shows a significant increase (up to 0.1) with the new boreal PFTs (ORC16) compared to the standard version (ORC13). The higher albedo occurs primarily in winter and early spring (see January and April in Fig. 12) in northern high-latitudes (+3.6% North of 55°N), whereas there is nearly no change during summertime and early autumn. If we consider the contribution from vegetation only (i.e. the mean albedo of the fraction of the grid covered by vegetation without the effect of snow cover and without bare soil) there is a small decrease with the new PFTs in most regions can be observed, with the exception, except in northern-central Siberia. These changes are due to the LAI of the different PFTs that control the fraction of the grid effectively covered by the vegetation foliage. The higher vegetation albedo in ORC13 can be attributed to the larger values of the LAI for trees compared to shrubs and for temperate C3 grasses compared to cold climate C3 grasses. In the Siberian region, the lower vegetation albedo in ORC13 occurs in early spring, while higher values are present all year-round, due to changes in LAI with NVPs. Note that changing from a C3 deciduous grassland to an evergreen PFTs (i.e. the NVPs) impacts the albedo even in winter time if the snow cover is not complete. Overall, the small changes of vegetation albedo and its dissymmetry with the changes in total albedo indicate that the substantial increase in the total albedo is linked to changes in the snow albedo and/or snow cover. The snow cover is controlled by the snow depth, the vegetation type and its roughness (see Sect. 2.3.4).

Roughness length is stable throughout the year and clearly decreases with the new vegetation types (up to -0.5 m (Fig. 12), which represents at least a decrease of 41% from 55°N to 25°N, Fig. 12), due to height

differences between trees and shrubs, the height being used to compute the roughness length (Eq. (17)). ~~Conversely~~~~Contrariwise~~, the snow depth and albedo are not impacted by vegetation changes, because there is no difference between trees and shrubs concerning the snow compaction (described in Sect. 2.3.2). Given that roughness and snow depth contribute to the albedo through the fraction of snow on the vegetation (Eq. (18)), the modification of winter albedo is due mostly to roughness length changes.

~~Transpiration~~~~As expected~~, ~~transpiration~~ is ~~mainly~~ affected (~~-33% from 55°N~~), ~~as expected mainly~~ during the summer period with much lower values (up to ~~-150 0.5~~ $\text{mm.y}^{-1}.\text{m}^{-2}$) in July around 60°N in West Eurasia and below 60°N in North America in the ORC16 simulation versus the ORC13 simulation. ~~Combining~~~~Crossing~~ this information with the vegetation map, this ~~effect~~ is probably due to the replacement of trees by shrubs; shrubs have a lower leaf biomass, a lower photosynthesis rate (Figs. ~~S1 to S48-10,12~~), and a lower roughness (Fig. 12, inducing less turbulent flow) leading to a lower transpiration. On the other hand, the introduction of NVPs, which have a higher stomatal conductance that could lead to an increase in transpiration, does not seem to have a major impact. However, if we focus on land surfaces North of 65°N (representing 11.2 millions km^2), the inclusion of the new PFTs slightly changes the components of the water budget. The inputs are identical between both simulations and the snowfall represents 53% of the total annual precipitation. The outputs represent ~~respectively~~ for ORC16 and ORC13 ~~80.70-22~~ and ~~77.5 0.21~~ $\text{mm.y}^{-1}.\text{m}^{-2}$ ~~respectively~~ for the runoff, ~~38.50-11~~ and ~~30.4 0.08~~ $\text{mm.y}^{-1}.\text{m}^{-2}$ for the drainage, ~~198.30-54~~ and ~~211.2 0.58~~ $\text{mm.y}^{-1}.\text{m}^{-2}$ for the evaporation, and ~~60.70-17~~ and ~~68.0 -19~~ $\text{mm.y}^{-1}.\text{m}^{-2}$ for the sublimation. There is thus a slight decrease of evaporation (-6%) and sublimation (-11%) with the new boreal vegetation description, compensated for by an increase of the runoff (+4%) and drainage (+27%) (Fig. ~~S5~~ %). The lower transpiration in summer simulated by ORC16 (up to ~~-150 mm.y⁻¹.m⁻²~~, see Fig. 12) is less substantial during other seasons, and it could be partly compensated by bare soil evapotranspiration. Finally, the global water balance leads to an increase of runoff and drainage to $135 \text{ km}^3.\text{y}^{-1}$ (+10%) north of 65°N (~~+11% with 140 km³.y⁻¹ North of 55°N~~). ~~Compared to observations (main Artic watershed available at <http://www.r-arcticnet.sr.unh.edu/v4.0/main.html>), the river discharge simulated indicates a general underestimation in the northern high latitudes, linked to an overestimation of evaporation and sublimation (Gouttevin et al., 2012). Thus, this underestimation with ORC16 is smaller than with ORC13.~~

~~We finally investigate the impact of the new PFT description on the soil energy budget and more specifically the potential impact on the future reduction of the permafrost areas. Figure 13.a represents the thickness of the active layer, which corresponds to the maximum depth of the 0°C isotherm. The model represents the permanentlypermanen# frozen soil considered as permafrost limit North of 50°N in North America and East Asia and North of 60°N elsewhere (Fig. 13.a). Figure 13.b displays the change in active layer thickness with the new PFTs (ORC16). At its southern limit, the active layer thickness seems to increase on average and by up to 1 m in ORC16 compared to ORC13 (Fig. 13.b). To determine the role of each vegetation type, differences in the profiles of the annual soil temperature (mean over 2004-2013) are displayed in Fig. 13.c for three locations with different vegetation coverage. The profile at 169°E 63°N (Fig. 13.c); selected for its high NVP coverage (40%), shows colder soil temperatures in the ORC16 simulation (-0,15 °C on average from the surface to 16 m), with warmest surface (0 to 1 m) temperature in winter (up to +0,25°C) and coldest surface temperature in summer (up to -0.7°C). This result indicates a lower surface conductivity, due to the insulation of the first centimeters of soil by NVPs (see Sect. 2.2.5). The 45°E 63°N profile (Fig. 13.b) was selected~~

because of large differences between the ORC16 and ORC13 active layer thicknesses. It shows a higher soil temperature in the ORC16 simulation (+0.18 °C on average, with low seasonal variation) and corresponds to a low coverage by NVPs (3%). This higher temperature can be explained by a large fraction of the new shrubs and ~~C3~~-cold climate C3 grasses (> 50%) inducing a lower transpiration (Fig. 12). The reduction of transpiration in ORC16 leads in turn to a higher soil humidity and thus a higher thermal conductivity (see C_{wet} and C_{dry} values in Table 2). Finally, the 65°E 61°N (Fig. 13.b) profile was selected in ~~asome~~ point where no active layer differences ~~could be observed, was noted~~. It includes 75% of new boreal PFTs from which 14% of NVPs and displays colder soil temperature in ORC16 up to 5 meters (although varying with depth), but similar temperature between ORC16 and OCR13 deeper into the soil (differences below 0.05°C on average).

Overall, the impact of the thermal insulation by NVPs seems to be compensated by an increase of soil humidity brought by the boreal PFTs. The active layer becomes deeper with the new boreal vascular plants (boreal C3 grasses and shrubs) due to higher soil conductivity, while the presence of NVPs decreases the active layer thickness with higher soil insulation. The coverage differences between NVPs and new vascular plant explains the global positive difference values in Fig 13.b.

4 DiscussionSummary and conclusions

4.1 Challenges associated to the description of new boreal vegetation

The implementation of a new PFT to describe non-vascular plants was challenging, as we had to introduce new or modify the standard equations and parameters to represent physiological properties of mosses and lichens. A shallow root profile was chosen to represent the access to surface water and a large leaf water and CO₂ conductance was introduced to represent the lack of stomata. A specific plant resistance to water stress (through resistance to negative NPP (Sect. 2.2.3) and desiccation (Sect. 2.2.4)), the impact of NVPs on soil thermal properties and a modification of litter decomposition were also implemented (Sect. 2.2). After a Bayesian parameter calibration, the simulated living biomass and productivity (Figs. 7-9) represent the observed large-scale mean gradients (i.e. between climatic zones and for transects). Furthermore, the total living biomass simulated in the 2000s (around 100 gC.m⁻² in Fig. 11) is in accordance with the estimates given by Bond-Lamberty and Gower (2007) and Gornall et al. (2007). For the introduction of boreal shrubs, a new allometry had to be defined (compared to trees) in order to simulate a realistic vegetation height, which is further used to describe the interactions of shrubs with snow, and in particular increased snow accumulation and density decrease near shrubs (Sect. 2.3). As for the NVPs, the simulated biomass and productivity, after the parameter optimisation, are in good agreement with the observations (Figs. 7-9). However, the snow-shrub interactions may be underestimated; Eq. (13), with a maximum snow depth obtained for a grid-cell fraction of high vegetation of 0.5, may underestimate the impact of shrubs on snow in the case of low shrub cover. Having only few shrubs still leads to significant snow accumulation (McFadden et al., 2001; Sturm et al., 2001). Further investigation of the sub-grid scale parameterization of snow-shrub interaction is necessary, possibly using similar equations but optimising the shrub cover fraction for which the snow depth is maximum (currently 0.5 but possibly significantly smaller).

Finally, the implementation of boreal C3 grasses is limited to parameter changes (see Table 5). However, even after calibration, the adequacy of the simulated biomass with respect to the observation remains low: in the

three transects, the model largely overestimates the biomass at more than half of the sites (Figs. 7-9). Moreover, the parameter that controls the so-called entropy factor for photosynthesis rates (b in eq. (20)) was optimised to zero (Tables 5 and S2), involving de facto the removal of seasonal temperature dependence of photosynthesis. This results highlight a potential limit of the Yin and Struik (2009) expression for carboxylation rate and could be due to the fact that the air temperature never gets warm enough to induce seasonal acclimation. We therefore suggest that changing only few parameters for C3 grass is not sufficient to represent the carbon stocks and fluxes of boreal grasses, and additional processes have to be considered (also possibly linked to autotrophic respiration).

In this study we added non-vascular plants, boreal shrubs and boreal C3 grasses in the land surface scheme ORCHIDEE. While the implementation of boreal C3 grasses boils down to parameter changes (see Table 5), new key processes have been introduced for the other two PFTs:

- For shrubs, a new allometry was defined (compared to trees) in order to simulate a realistic vegetation height, which is further used to describe shrubs interactions with snow (Sect. 2.3).
- For NVPs, we opted for an “indirect” representation of their physiological functioning using the same process representation as for vascular plants but with specific modifications (parameters and equations). A shallow root profile was chosen to represent the access to surface water. A large leaf water and CO₂ conductance was introduced to represent the lack of stomata. Additionally, a specific plant resistance to water stress, the impact of NVPs on soil thermal properties and a modification of litter decomposition were implemented (Sect. 2.2).

In order to calibrate the main parameters of these new boreal PFTs, observations of net primary productivity and living biomass from Siberia were used (Sect. 2.5.1) with a standard Bayesian optimization procedure (see Sect. 2.6.1). Note finally that the large data spread (Figs. 6-7-9) due to large spatial variability at the scale of a few meters could not be represented by the model with a 2° climate forcing and no explicit representation of the underground vegetation (and competition) and edaphic conditions. Note that the better adequacy between the observations and the simulation for NVPs is partly due to more homogenous data.

Given the limitations discussed in the sections above, we suggest new developments to improve the realism of the simulated water, carbon and energy fluxes for the arctic region. First, it would be important to better represent the spatial heterogeneity of edaphic conditions, possibly with the use of topography information (i.e., to improve the water stress computation), and the vertical structure of the vegetation in coherence with light penetration and intra-canopy gradients of climate variables, as in Ryder et al. (2016). A more accurate vertical representation of the vegetation structure implies to introduce vegetation strata with the possibility to have under-storey vegetation, such as shrubs, grasses or NVPs under a tree canopy (e.g., in Frohking et al., 1996). Furthermore, it could be important to take into account the impact of other chemical components and processes, such as the availability of oxygen in the upper soil to represent anoxic conditions and of nitrogen to account for possible limitation on plant productivity (Epstein et al., 2000; Bond-Lamberty and Gower, 2007; Goll et al., 2012; Koven et al., 2013), especially for NVPs. Thereby, extreme conditions would be more realistically simulated (such as for peatlands) avoiding the use of proxies for key environmental drivers (such as soil humidity for anoxic conditions). Concerning shrubs, we selected a boreal broad-leaved summergreen phenology, although in reality there is a mix of summergreen and evergreen needled-leaved shrubs. Given that the main changes introduced for the shrub PFT are linked to the allometry and the interaction with snow (Sect.

2.3), it should be straightforward to split this PFT into different types, as already done for trees (Table 1), with only a few varying parameters (such as phenology type, minimal critical temperature or $V_{c_{max}(25)}$). For other climatic regions than the Arctic, new processes may need to be added, such as root development for shrubs in savannahs. In a similar way we can split NVPs between lichens and mosses. Furthermore, to improve the dynamic of shrubs snow interactions, it would be important to implement an energy balance and a snow mass balance for each PFT, separately. Thereby, the interactions between wind, snow deposition and compaction and vegetation structure could be integrated (McFadden et al., 2001). Finally, the implementation of other processes such as soil flooding (due to permafrost thawing for example) should be also considered as a crucial additional step.

4.2 Biogeochemical impacts of the new boreal vegetation

The overall biogeochemical behaviour of the new boreal PFTs is significantly different than that of the original PFTs. NVPs exhibit a lower productivity than the cold climate C3 grasses, which is lower than the temperate C3 grasses, because of their lower maximum rate of carboxylation ($V_{c_{max}(25)}$ respectively at 28, 40 and 70 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). However, as a counterpart, the NVPs present a better adaptation to the northern latitudes, with higher productivity in spring and at the end of autumn (Fig. S4) and a decline in summer due to a water stress. This behaviour corresponds to the observation that NVPs are, compared to vascular plants, most active during the shoulder seasons, due to less severe water stress and reduced competition for light (Williams and Flanagan, 1996; Campioli et al., 2009). It is thus important to include these adaptation strategies (linked to a resistance to desiccation or adapted turnover and differences in stomatal conductance and photosynthesis capacity) in global LSMs for a more accurate estimation of climate change impacts on boreal productivity. Shrubs also have a lower productivity and biomass than trees (Figs. S1-S4) because of their lower LAI, new plant allometry and adapted mortality and respiration. Of particular importance are also the differences in terms of snow protection and cold temperature induced mortality. These features will be crucial when dealing with dynamic vegetation rather prescribe land cover as in this study. Overall, the inclusion of new boreal vegetation types considerably decreases the productivity, the total living biomass, and thus the LAI, which becomes closer to satellite observations (considering GLASS product, Fig. 10, Liang et al., 2013; Xiao et al., 2014; or the GIMMS product, not shown, Zhu et al., 2013). As a direct consequence, previous simulations with ORCHIDEE (and in particular those for the last IPCC (2013) report) and possibly other models, that have not explicitly described boreal NVPs, shrubs and grasses, might have significantly overestimated biomass and productivity in northern latitudes.

The overall biogeochemical behaviour of the new boreal PFTs is significantly different than that of the original PFTs. Cold climate grasses exhibit a lower productivity than the original C3 grasses because of their lower maximum rate of carboxylation ($V_{c_{max}(25)}$, in Table 5), but a comparable biomass. NVPs globally have a lower productivity and biomass than temperate and boreal C3 grasses (Figs. 8-9), which is also explained by the low $V_{c_{max}(25)}$ (respectively 70, 40 and 28 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$). However, these lower mean values mask a better adaptation of NVPs to the northern latitudes, with higher productivity in spring and at the end of autumn (Fig. 10) and a decline in summer due to a water stress. Such adaptation arises from few specific processes implemented for the NVPs such as the resistance to desiccation or the adapted turnover, stomatal conductance and photosynthesis capacity. Shrubs also have a lower productivity and a much lower biomass than trees (Figs. 8-

9) because of their lower LAI, new plant allometry and adapted mortality and respiration. Shrubs have an increased mortality induced by cold temperatures, but they are on the same time protected by snow (thermal protection; Eq. (15)). On the other hand, trees do not have this increased mortality with extreme temperature and it could be beneficial to include this effect when the vegetation is fixed, using for instance Eq. (14) that is only applied in ORCHIDEE when the vegetation cover is dynamically calculated (Krinner et al., 2005; Zhu et al., 2015).

Spatially, the northern limit of shrubs is situated further south than the northern limit of NVPs and cold climate grasses, as described in CAVM Mapping Team et al. (2003) and Loveland et al. (2000). Moreover, there are differences between the three boreal regions (North America, North Asia and Europe) due to climatic conditions: productivity and total living biomass decrease rapidly with latitude in Northern America, more slowly in Asia, while in Europe they remain at a high level far north (Fig. 8). Overall for the arctic regions, the total carbon flux is dominated by the prescribed vegetation distribution and more specifically by the fractions of trees and temperate grasses (Fig. 5). The inclusion of new boreal vegetation types decreases considerably the productivity, the total living biomass, and thus the LAI, which becomes more closer to satellite observations (GLASS product, Fig. 11) (Liang et al., 2013; Xiao et al., 2014). This implies that in previous simulations (and in particular those for the last IPCC report), considering vegetation without boreal shrubs and grasses might have induced a significant overestimation of biomass and productivity in northern latitudes.

As expected, the simulated global increase of NPP, GPP and biomass over the last 60 years (Fig. 119) reveals the vegetation response to global warming and increased CO₂. This response is substantial, especially for NVPs and boreal shrubs and particularly for the accumulation of biomass. Thus, in boreal regions the new PFTs are more sensitive to climate change than the original ones, even if their overall contribution (productivity and biomass) remains lower, implying that the standard ORCHIDEE version under-estimates the potential changes of vegetation biomass and productivity. ~~In addition, shifts of vegetation are already observed (Frost and Epstein, 2014; Zhu et al., 2016) and must be taken into account in dynamical vegetation modelling.~~

Based on this study, we foresee several applications for the biogeochemical cycles. First, it is crucial to update the dynamic vegetation module of ORCHIDEE in order to account for and to calibrate the competition between all PFTs. This requires defining for instance the drivers of the competition between grasses and NVPs and between shrubs and trees. Such developments will open the road for new studies of boreal vegetation changes, in the future or in the past, in liaison with climate changes. Second, the simulation of more realistic NPP and biomass in boreal landscapes could help to better simulate the dynamic of past boreal vegetation cover and boreal carbon stocks. For example, for the Last Glacial Period, it would enable a better estimation of carbon accumulation in the soil and thus of carbon stocks present in today's permafrost.

4.3 Biophysical impacts of the new boreal vegetation

The albedo of As illustrated in the new results section (Figs. 12-13), multiple impacts on the energy and water balance of boreal vegetation is still considered the same as that of the ecosystem occur with implementation of new PFTs they are derived from, although the colours of these PFTs may vary substantially, with important impact on the albedo. In particular for NVPs (Porada et al., 2016) the colour may vary according to the relative humidity of the plant (Hamerlynck et al., 2000), an effect linked to the temporal dynamics of surface moisture that is difficult to capture with global models. In this study, the in the ORCHIDEE model.

The changes in vegetation albedo (Fig. 12) thus result directly from changes in vegetation cover. ~~in this study the vegetation map is prescribed and PFT-dependent albedo parameters are identical for cold climate grasses and NVPs / Shrubs and the corresponding standard PFTs (grasses / trees).~~ Therefore, with its lower LAI, the new boreal vegetation induces a lower soil and vegetation albedo (without taking into account the snow cover), except in winter for areas where newly introduced evergreen NVPs are present. In contrast, the overall albedo increase (Fig. 12) does not seem directly impacted by the vegetation distribution. This depends on a combination of the locally heat high vegetation albedo due to NVPs, and the decrease of roughness length, due to the substitution of a fraction of trees by shrubs (Sect. 2.5.2), which implies an increase of snow cover fraction (Eq. (18)).

The substitution of a fraction of trees by shrubs largely contributes to the summer transpiration decrease. The active layer thickness (Fig. 13) and permafrost extentextension are impacted by the NVPs through two competing effects. NVPs insulate the soil as modelled in previous studies (Porada et al., 2016) but also increase the soil thermal conductivity through an increase of soil humidity due to a global decrease of transpiration. Overall, we obtain a weak or negative impact of the new boreal vegetation implementation on the permafrost extent. This is at odds with results reported elsewhere (Jorgenson et al., 2010; Soudzilovskaia et al., 2013; Chadburn et al., 2015; Porada et al., 2016). ~~(Soudzilovskaia et al., 2013; Chadburn et al., 2015).~~ Further investigations are required to determine whether this is an artefact of our choice to replace the standard soil thermal capacity and conductivity by intermediate values between those from NVPs and mineral soil. A further improvement will ~~One option would be to~~ model explicitly the ~~treat the NVPs as a layer with its own~~ energy budget of the moss layer (and heat transfer). ~~and thermal characteristic above the soil.~~ Also note that, while the NVP heat conductivity and heat capacity used in this study are in accordance with other experiments (Soudzilovskaia et al., 2013; Chadburn et al., 2015), the average thickness of mosses in our simulation is lower than the one prescribedused in Chadburn et al. (2015), where it was fixed. Moreover, NVPs have an impact on the surface soil water dynamicsdynamic, not currently explicitly modelledwell represented in ORCHIDEE. For example, in JULES, Chadburn et al. (2015) chose to use a suction equation from Brooks and Corey (1964) to compute the plant water uptake and represent the “spongy” effect of NVPs. In ORCHIDEE, a first step is needed with the computation of a ~~In ORC-HL-VEGv1.0, three options were therefore considered: (1) increase the leaf interception and infiltrate part of this water into the soil, (2) limit the runoff in order to hold more water on the upper soil layers, or (3) increase the water retention by changing soil parameters controlling diffusion and drainage. However, given that in the current version of ORCHIDEE a unique~~ soil water budget for each PFT and not is performed for the entire herbaceous layer as currently done, before we can properly (no distinction between NVPs and grasses), it was not possible to represent this ~~the~~ suction effect. As a direct consequence, the ~~of NVPs more precisely.~~ The water content of surface layers mayis thus probably underestimated, which directly impacts ~~and can impact~~ the soil conductivity.

Overall, the total runoff and drainage above 65°N with the new vegetation increases substantiallyby 11% with respect to the 13-PFT case, and reach around 140km³.y⁻¹ (see Sect. 3.4). Future replacement of NVPs and grasses by shrubs and trees could therefore counteract the direct effect of atmospheric CO₂ increase (i.e. decrease of transpiration) on Arctic river runoff (e.g. Gedney et al., 2006).

5 Conclusions

To improve

5 ~~In this study we improved the simulation of the energy, water and carbon budgets of boreal ecosystems with ORCHIDEE, the introduction of new PFTs was a necessary and crucial step. We have introduced the main description of boreal biophysical and biochemical processes controlling NVPs and boreal shrubs functioning and applied Bayesian calibration of the most important parameters. The ability of the process-based model to simulate observed productivity and above-ground biomass has been improved by comparison to the original PFTs, likely improving the model skill to simulate carbon and water responses to climate changes. A next step will be to separate the NVPs into bryophytes and lichens, which differ with respect to their physical properties, such as water storage capacity or albedo, or their carbon fluxes (Schulze and Caldwell, 1994; Porada et al., 2016). Boreal shrubs have been reduced in this first step to broadleaf deciduous phenology, although in reality there is a mix of deciduous and evergreen broadleaf shrubs and evergreen needleleaf shrubs. It should be straightforward to split such PFT into different types, as already done for trees, with only a few varying key parameters (linked to minimum critical temperature, $V_{c_{max(25)}}$ or evergreen phenology type, which represents more than 48% of shrubs North of 55°N according to the CCI product and Table S1). In contrast, adapting a few selected C3 grass parameters in order to represent boreal grasses, without including new or modifying existing processes, appears insufficient to adequately simulate the observed biomass gradient on three north – south transects.~~

20 ~~Given the limitations discussed above, further developments are necessary to improve the model for the simulated water, carbon and energy fluxes for the Arctic region. It is important to better represent, but we did not consider the feedbacks between vegetation and climate. the vertical structure of the vegetation in coherence with light penetration and intra-canopy gradients of climate variables, as in Ryder et al. (2016). A more accurate vertical representation of the vegetation structure implies introducing vegetation strata with the possibility to have under-storey vegetation, such as shrubs, grasses or NVPs under a tree canopy (e.g., in Frolking et al., 1996). Furthermore, it could be important to take into account the impact of other chemical components and processes, such as the availability of oxygen in the upper soil to represent anoxic conditions and of nitrogen to account for possible limitation on plant productivity (Epstein et al., 2000; Bond-Lamberty and Gower, 2007; Goll et al., 2012; Koven et al., 2013). This is especially important for NVPs, which have an ecological advantage in these stressful conditions (such as poor nitrogen availability). To improve the dynamics of shrubs-snow interactions, it would be important to implement an energy balance and a snow mass balance for each PFT, separately. Thereby, the interactions between wind, snow deposition and compaction and vegetation structure could be integrated (McFadden et al., 2001). In addition, shifts of vegetation are already observed (Frost and Epstein, 2014; Zhu et al., 2016) and must be taken into account in dynamical vegetation modelling. Finally, the implementation of other processes such as soil flooding (due to permafrost thawing for example) should be also considered as a crucial additional step.~~

35 ~~The improvement of the ORCHIDEE vegetation dynamics (Krinner et al., 2005; Zhu et al., 2015) to include the new PFTs (i.e. competition between NVP, grasses, shrubs and trees) will allow the study of boreal vegetation changes, in the future and in the past, in conjunction with climate changes. The simulation of more realistic NPP and biomass in boreal landscapes could help to better simulate the dynamics of past boreal vegetation cover and boreal carbon stocks. For example, for the Last Glacial Period, it would enable a better~~

estimation of carbon accumulation in the soil and thus of carbon stocks present in today's permafrost. Moreover, it will be possible to assess potential feedbacks between vegetation and climate with an improved description of boreal vegetation in the IPSL-CM earth system model, of which ORCHIDEE is the surface component. For example, the simulated increase of albedo, with the new boreal PFTs and new albedo formulation (Sect. 2.3.4), could ~~reduce~~ locally reduce the surface air temperature and potentially impact the snow ~~dynamics~~. ~~dynamic for instance~~. Moreover, the decrease of surface roughness length, due to the replacement of trees by shrubs (Sect. 2.3.1), will impact the exchange of momentum between the surface and the atmosphere and thus likely impact regional to large scale circulation patterns (e.g., Vautard et al., 2010). ~~It is thus necessary to evaluate all potential feedbacks between vegetation and climate with such improved description of boreal vegetation in the IPSL-CM earth system model (ORCHIDEE being the surface component).~~

Code availability

The code and ~~the~~ run environment of ORCHIDEE are open source (<http://forge.ipsl.jussieu.fr/orchidee>). ~~Readers~~ ~~Nevertheless~~ ~~readers~~ interested in running the ORC-HL-VEGv1.0 version described in this paper can have access to the code (available at <https://github.com/ArseneD/ORC-HL-VEG> commit b74ae16) and are encouraged to contact the corresponding author for full details and practicality.

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Bare soil			
Trees	Tropical	Broadleaf	Evergreen
		Broadleaf	Deciduous Raingreen
	Temperate	Needleleaf	Evergreen
		Broadleaf	Evergreen
		Broadleaf	Deciduous Summergreen
	Boreal	Needleleaf	Evergreen
		Broadleaf	Deciduous Summergreen
		Needleleaf	Deciduous Summergreen
	*Shrubs	*Boreal	*Broadleaf
Grasses	Natural	C3	Global
			*Arctic
		C4	
	Crops	C3	
		C4	
*Non-Vascular (C3) plants			

Table 1: PFTs included in ORCHIDEE. New PFTs incorporated in this study are indicated with asterisks. [The deciduous are raingreen in tropical climate and summergreen in others.](#)

Parameters	Description	Original C3 grasses	Non-Vascular Plants
Phenotype		Deciduous Summergreen	Evergreen
Organs	Organs proportion	roots, reserves, leaves, fruits (10%)	Leaves (95%), fruits (5%)
g_0 ($\frac{\text{Cmol}}{\text{mol} \cdot \text{m}^2 \cdot \text{s}} \cdot \text{bar}^{-1}$)	Stomatal conductance when irradiance is null	0.00625	0.052 *
a_1 (-)	Empirical constants	0.85 (all PFT)	0.85
b_1 (-)	Empirical constants	0.14	0.41 *
Senescence (day)	Theoretical number of days before senescence	120	470 *
d_0 (day)	Delay before increasing the turnover (if $\text{NPP} \leq 0$)	-	20
d_m (day)	Number of days when the fraction of biomass loss is maximal (if $\text{NPP} \leq 0$)	-	60
d_f (day)	Maximum number of daysday for this extra turnover (if $\text{NPP} \leq 0$)	-	130
$k_{l \max}$ (daydays)	Maximal fraction of biomass loss (if $\text{NPP} \leq 0$)	-	0.05 *
LAI_{lim} (-)	Threshold leaf area index (for turnover)	-	2.4 *
l_{coef} (day^{-1}) (-)	Coefficient	-	0.014 *
r_p (-)	Parameter to control root profile	4	18 *
$w_s \min$ (-)	Minimum hydric stress before any desiccation effect	-	0.8
d_{off} (-)	Offset of desiccation effect	-	0.55 *
ρ ($\text{gC} \cdot \text{m}^{-3}$)	Density	-	$0.5 \cdot 10^4$
C_{dry} ($\text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$)	Dry soil thermal capacity	1.80	$0.29 \cdot 10^6$
C_{wet} ($\text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$)	Wet thermal capacity	3.03	$4.29 \cdot 10^6$
C_{ice} ($\text{J} \cdot \text{m}^{-3} \cdot \text{K}^{-1}$)	Ice thermal capacity	2.11	$3.26 \cdot 10^6$
λ_{dry} ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)	Dry soil thermal conductivity	0.4	0.092
λ_{sat_wet} ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)	Wet thermal conductivity	0.6	0.754
λ_{sat_ice} ($\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)	Ice thermal conductivity	2.2	0.715
$m_{c(0)}$ (-)	Constant		1.178
$m_{c(1)}$ (-)	Constant		-1.12
$m_{c(2)}$ (-)	Constant		2.22
$m_{c(3)}$ (-)	Constant		-1.40
LAI_{max} ($\text{m}^2 \cdot \text{m}^{-2}$)	Maximum Leaf Area Index	2	$3.06^{* \&***}$
$VC_{max(25)}$ ($\mu\text{mol} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$)	Maximum rate of carboxylation at 25°C	70	28 *
SLA ($\text{m}^2 \cdot \text{gC}^{-1}$)	Specific Leaf Area	$2.6 \cdot 10^{-2}$	$0.84 \cdot 10^{-2} *$
f_{m_resp} ($\text{gC} \cdot \text{gC}^{-1} \cdot \text{day}^{-1}$)	Maintenance respiration coefficient at 0°C	$2.62 \cdot 10^{-3}$	$2.57 \cdot 10^{-3} *$

Table 2: Non-Vascular Plant parameters.

* [Optimised](#)[Optimized](#) parameter (see Sect. 2.6.1)

** Estimated from Yoshikawa et al. (2002) and O'Donnell et al. (2009)

*** Estimated from Bond-Lamberty and Gower (2007)

Parameters	Description	Original values	Ground vegetation	High vegetation
			(Bare soil, Grasses and NVPs)	(Shrubs and Trees)
a_{sc}	Snow settling parameter (s^{-1})	2.8×10^{-6}	1.4×10^{-6}	4.2×10^{-6}
b_{sc}	Snow settling parameter (K^{-1})	0.04	0.02	0.06
c_{sc}	Snow settling parameter ($m^3.kg^{-1}$) ¹⁾	460	230	690
a_{η}	Snow Newtonian viscosity parameter (K^{-1})	0.081	0.0405	0.12
b_{η}	Snow Newtonian viscosity parameter ($m^3.kg^{-1}$)	0.018	0.009	0.027
η_0	Snow Newtonian viscosity parameter (Pa.s)	3.7×10^7	1.85×10^7	5.55×10^7

Table 3: Snow compaction parameters. Original values from Wang et al. (2013) and herbaceous and high vegetation values are chosen to stay in the range value proposed by Wang et al. (2013).

Allometry				
Parameters	Description	Trees		Shrubs
		Pipe tune	Pipe tune (like trees)	Aiba and Kohyama (1996)**
A	Allometry constant	-	-	0.75
β	Allometry constant	40.0	8.0	$\text{Log}(\beta) = 2.42$
γ	Allometry constant	0.5	0.55	1.15
α	Allometry constant	100.0	216.9	0.8
δ	Allometry constant	1.6	1.6	-
H_{max} (m)	Maximum height	15	3.5 *	3.5 *
H_{f_dia} (0-1)	Maximum height used to compute the diameter	-	-	0.90
h_c	Minimum height factor	10	10	10
Other Parameters				
Parameters	Description	Trees		Shrubs
k_{ce} (-)	Coefficient of mortality due to extreme coldness	0.04		0.04
$T_{min,crit}$ (°C)	Minimum critical temperature	-45		-45
z_{0_c} (m)	Roughness constant	16		16
z_{0_bs} (m)	Roughness of the bare soil	0.01		0.01
Δ_{zo} (-)	Width of the transition zone when d_s is around H_{PFT}	0.3		0.3
ξ (-)	Snow fraction constant	5		5
SLA (m ² .gC ⁻¹)	Specific Leaf Area	$2.6 \cdot 10^{-2}$		$2.7 \cdot 10^{-2}$ *
LAI_{max} (m ² .m ⁻²)	Maximum Leaf Area Index	4.5		2.5 *
$VC_{max(25)}$ ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$)	Maximum rate of carboxylation at 25°C	45		38 *
Residence Time (y)		80		32 *
f_{g_resp} (0-1)	Fraction of GPP which is lost as growth respiration	0.28		0.59 *

Table 4: Shrub parameters.

* ~~Optimised~~Optimized parameter (see Sect. 2.6.1)

** Adapted from Martínez and López-Portillo, 2003

Parameters	Description	Original C3 grass	Boreal C3 grass
$Vc_{max(25)}$ (mol.m ⁻² .s ⁻¹)	Maximum rate of carboxylation at 25°C	70	40 *
E_a (J.mol ⁻¹)	Activation energy	71 513	71 513
E_d (J.mol ⁻¹)	Deactivation energy	200 000	200 000 *
a (J.mol ⁻¹ .K ⁻¹)	Entropy constant	668.39	668.39
b (J.mol ⁻¹ .K ⁻¹ .°C ⁻¹)	Entropy constant	-1.07	0.0 *
$J_{max(25)}$	Maximum rate of electron transport at 25°C		
E_a (J.mol ⁻¹)	Activation energy	49 884	49 884
E_d (J.mol ⁻¹)	Deactivation energy	200 000	200 000 *
a (J.mol ⁻¹ .K ⁻¹)	Entropy constant	659.7	659.7
b (J.mol ⁻¹ .K ⁻¹ .°C ⁻¹)	Entropy constant	-0,75	0 *
r_p (-)	Parameter to control root profile	4	5.6 *
SLA (m ² .gC ⁻¹)	Specific Leaf Area	2.6 x 10 ⁻²	2.2 x 10 ⁻² *
R (J.mol ⁻¹ .K ⁻¹)	Ideal gas constant	8.314	8.314

Table 5: Boreal C3 grasses parameters.

* ~~Optimised~~Optimized parameter (see Sect. 2.6.1). Note that J_{max} and Vc_{max} parameters, namely E_d and b , were linked for the ~~optimisation~~optimization.

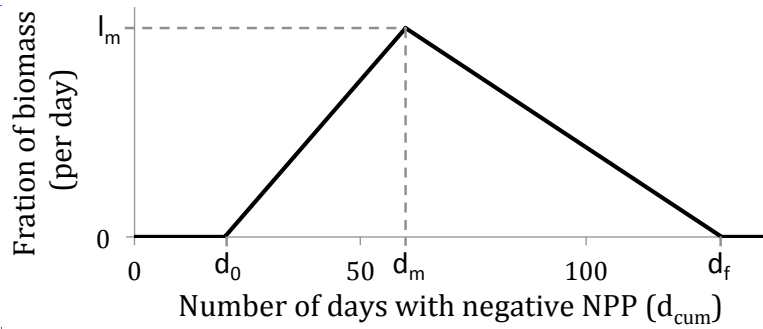
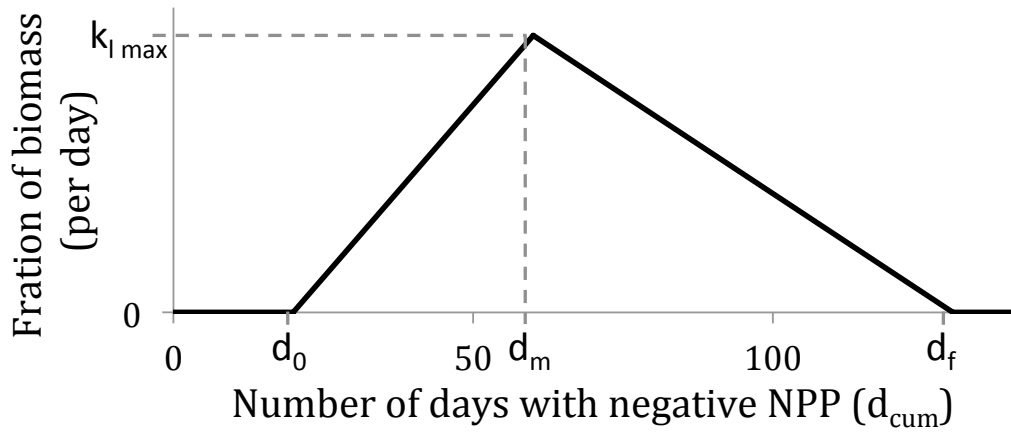


Figure 1: Additional non-vascular biomass loss turnover rate (k_l in d^{-1}) during the non-growing season period when NPP is lower or equal than zero, starting at 0 on the horizontal axis.

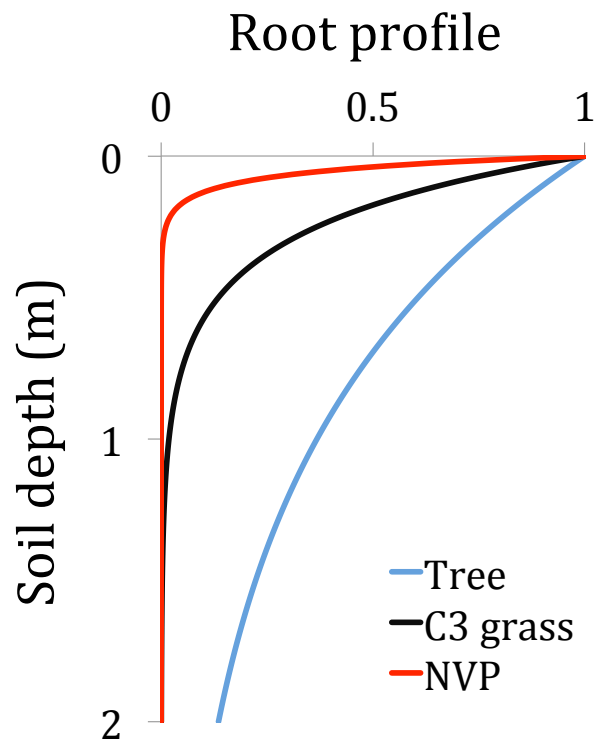


Figure 2: Root profile of boreal broadleaf trees, C3 grasses and soil water uptake profile for NVPs.

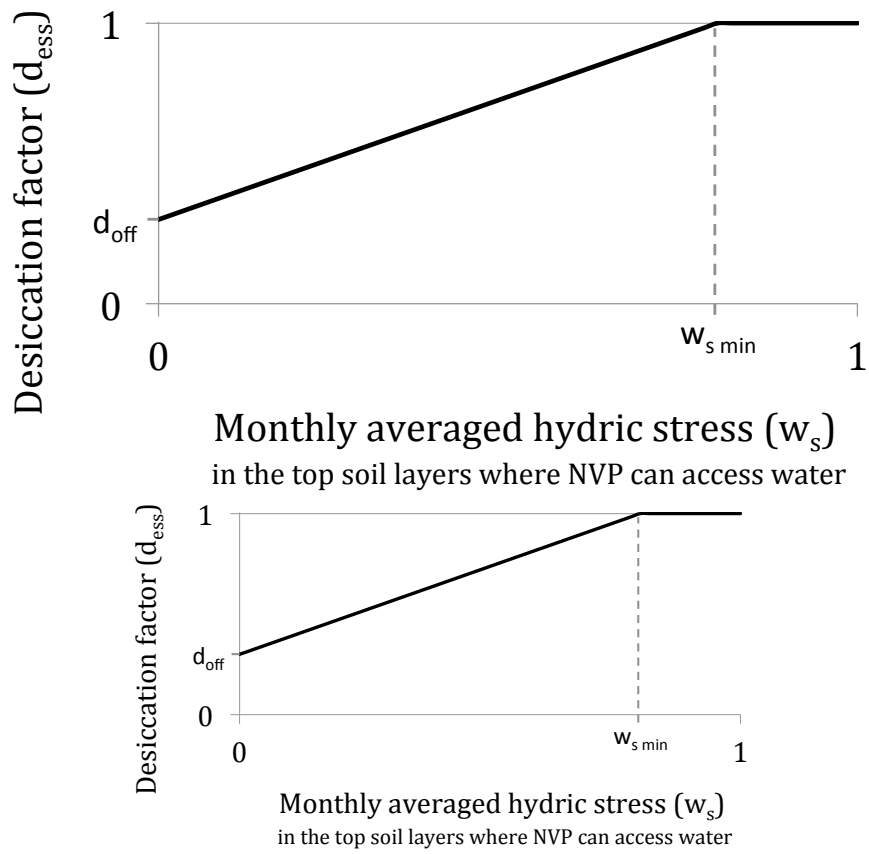
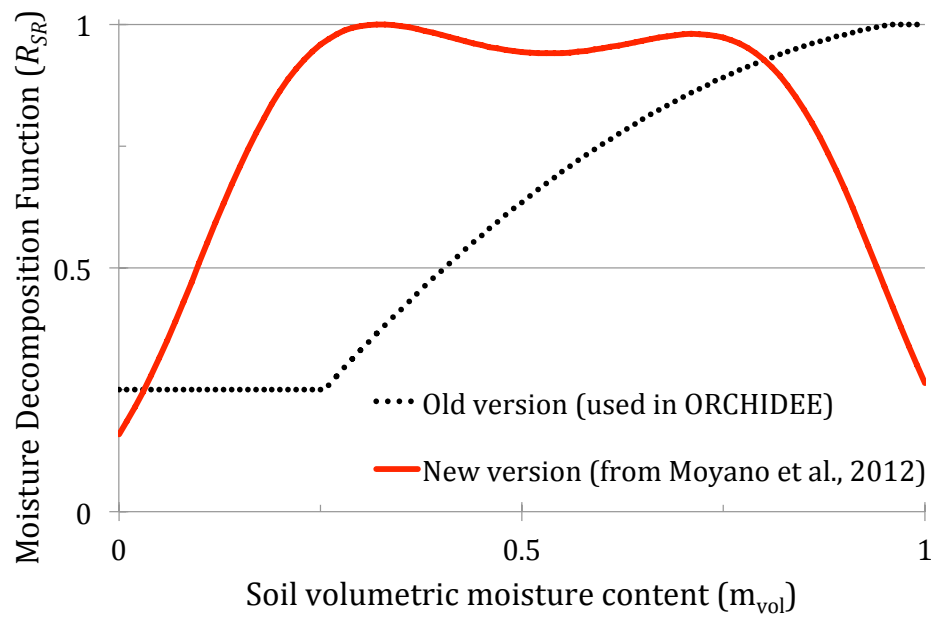
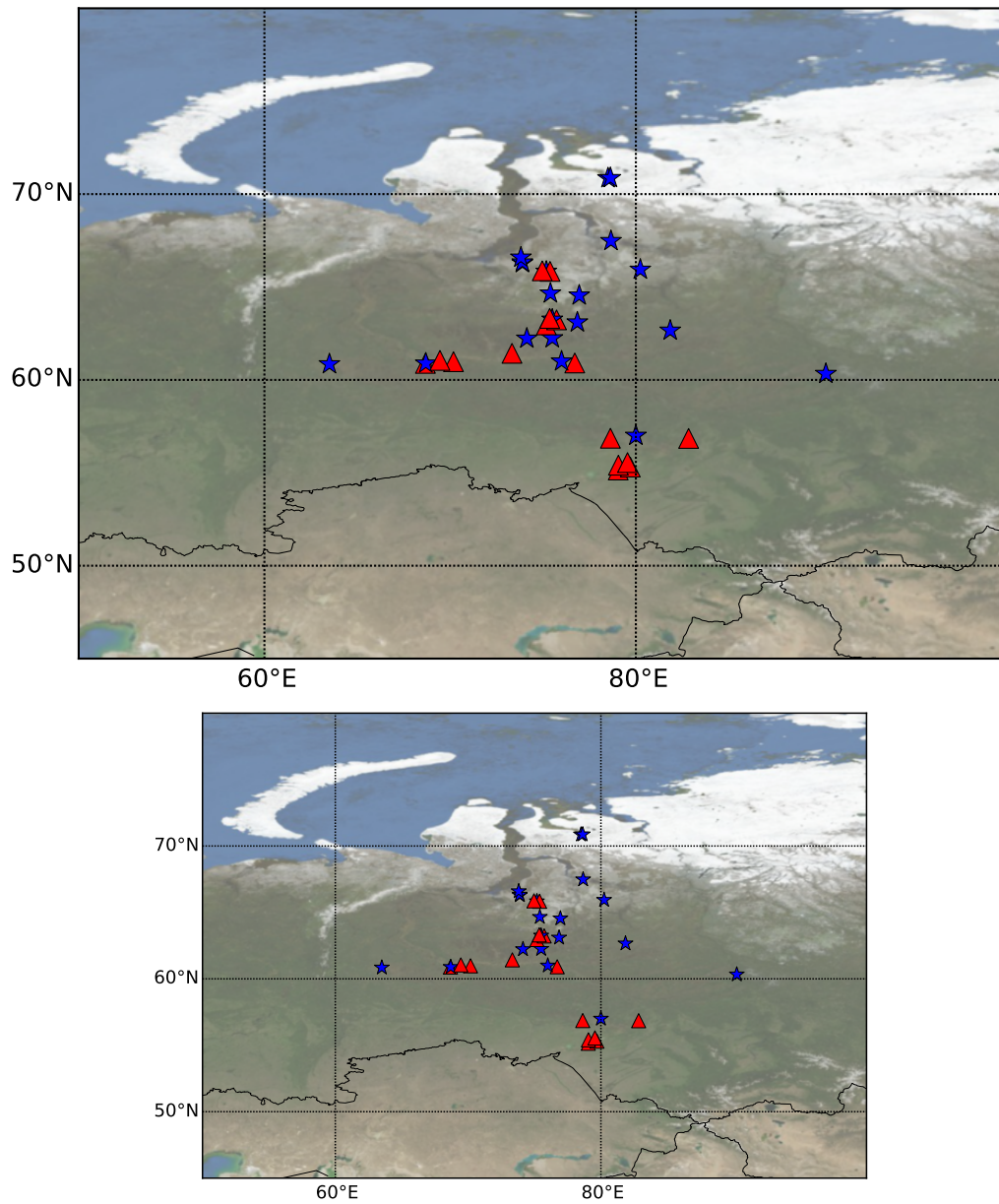


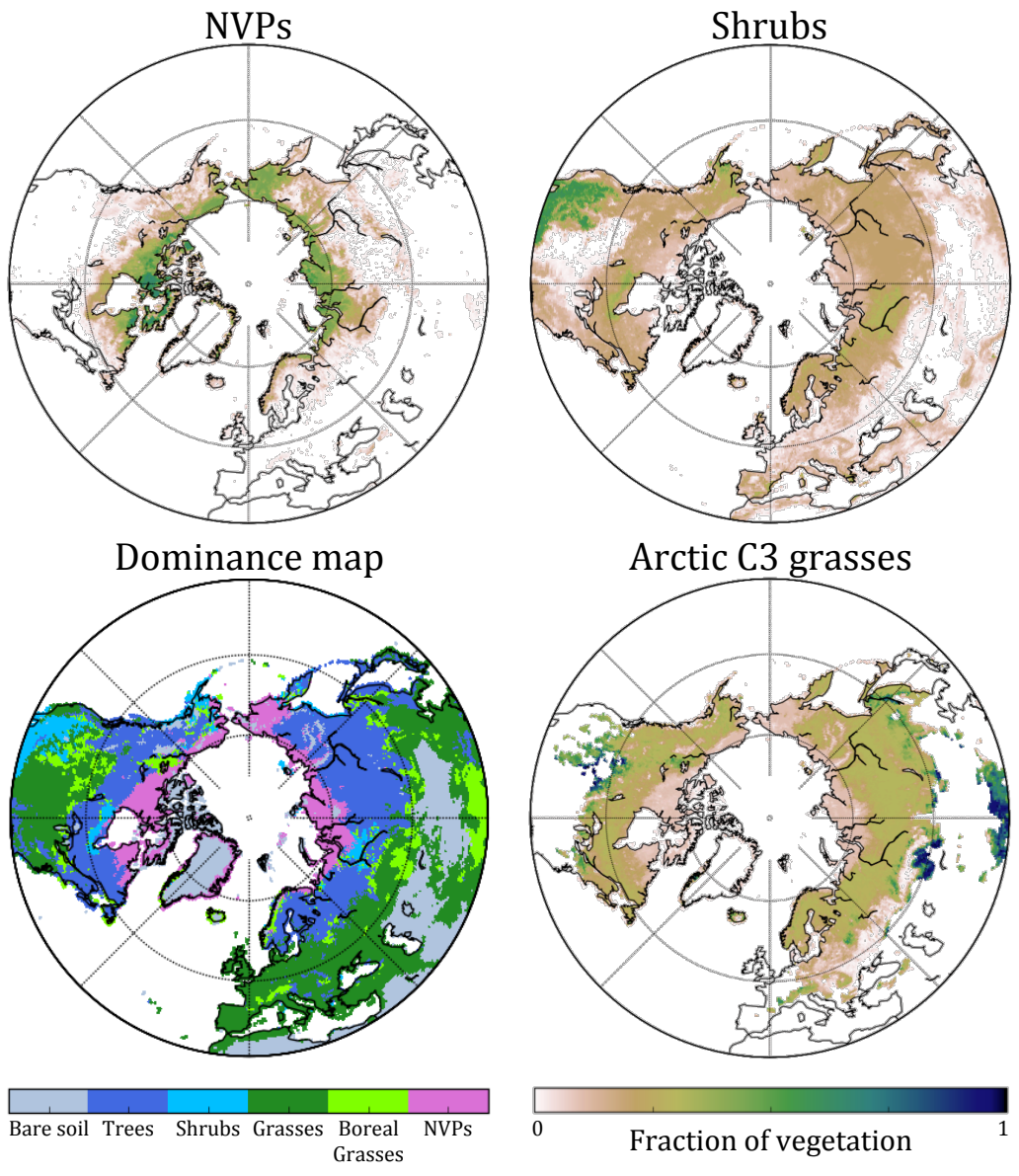
Figure 3: Desiccation function for Non-Vascular Plants~~non-vascular plants~~.



[Figure 4: Moisture decomposition function used in ORCHIDEE compare to the one suggest by Moyano et al. \(2012\).](#)



5 **Figure 5: 36 sites of vegetation green biomass and Net Primary productivity (NPP). Triangles in red: sites with NPPs, grasses and shrubs at the same location, stars in blue: sites with only NPPs.**



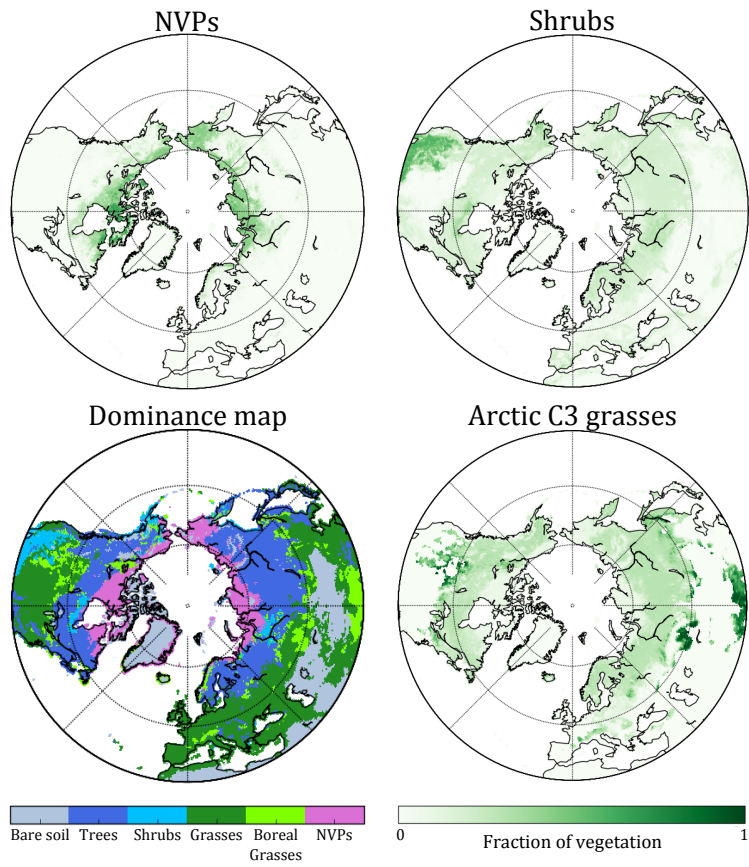
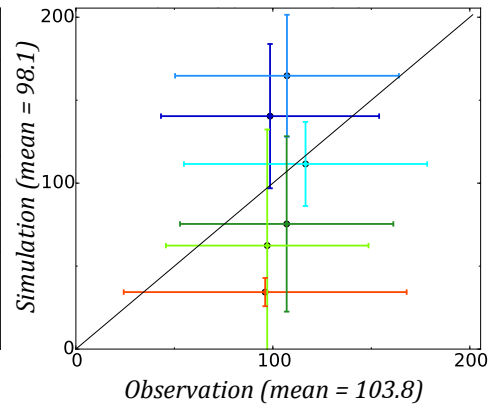
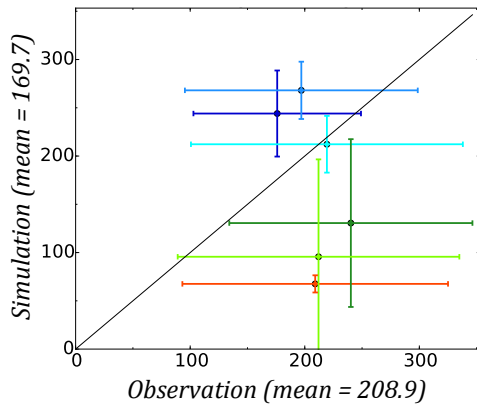


Figure 6: Map of new PFTs vegetation coverage and dominance.

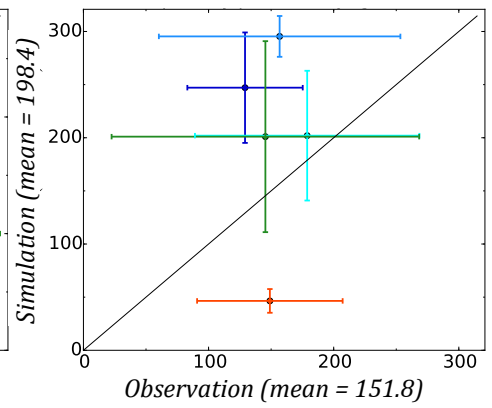
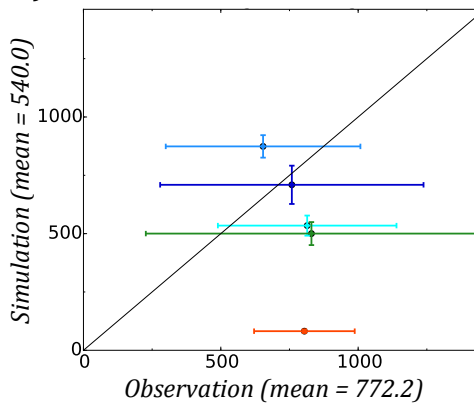
Living biomass (gC.m⁻²)

NPP (gC.m⁻²)

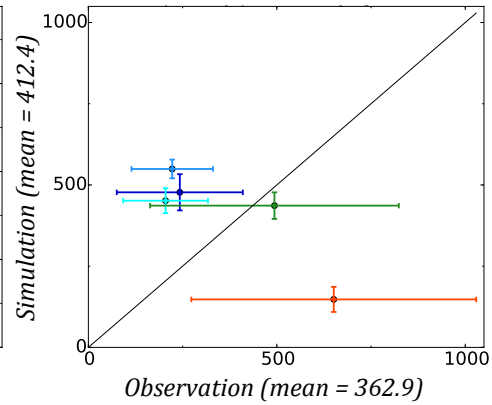
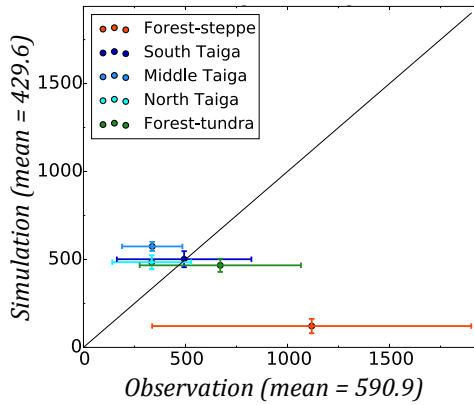
a) NVPs



b) Shrubs



c) Arctic C3 grasses



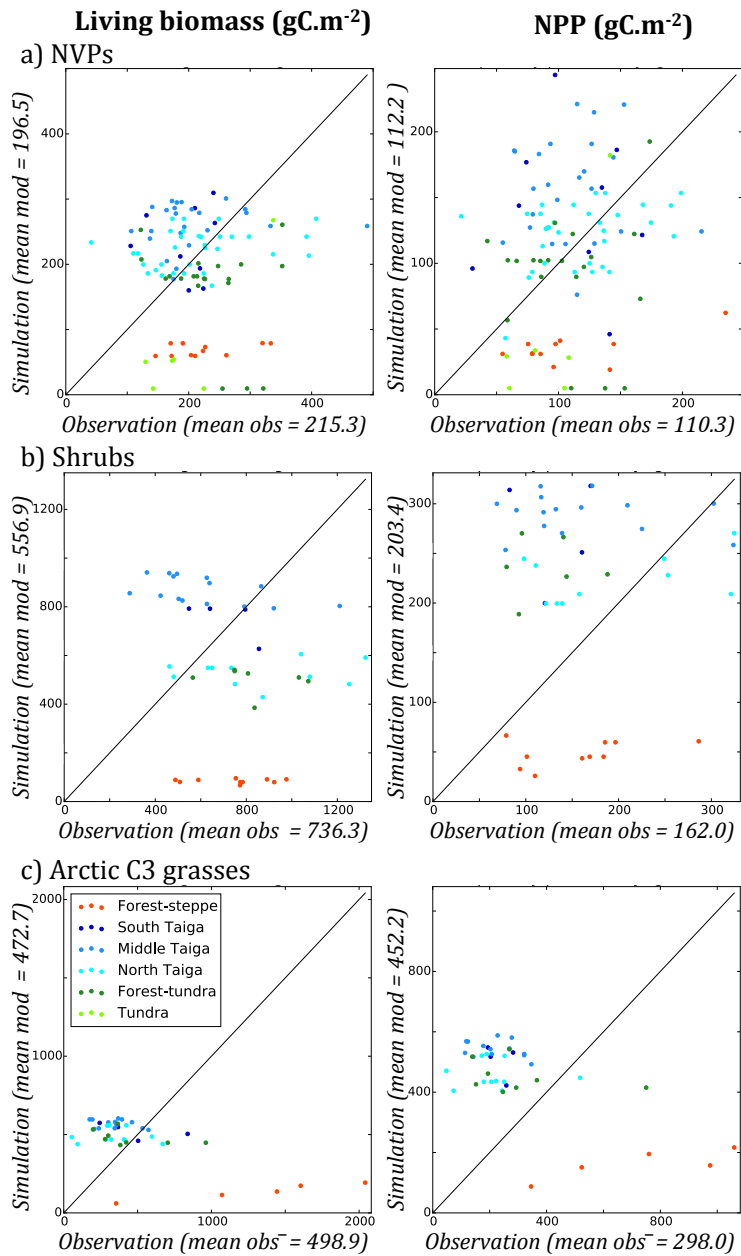


Figure 7: Model versus observed (from Peregon et al., 2008) values for the total living biomass (left column) and the NPP (right column), for NVPs (a), shrubs (b) and cold climate grasses (c). The mean values for each subzone (with different across all sites and all years) are displayed for the model and the observations. The colour indicates the associated bioclimatic zones: forest-steppe in the south, different taiga ecosystems (south, middle and north), forest-tundra and tundra in the far north. The error bars show the standard deviation due to the different sites and years considered by subzone, to which is added the standard deviation of measurements for observations.

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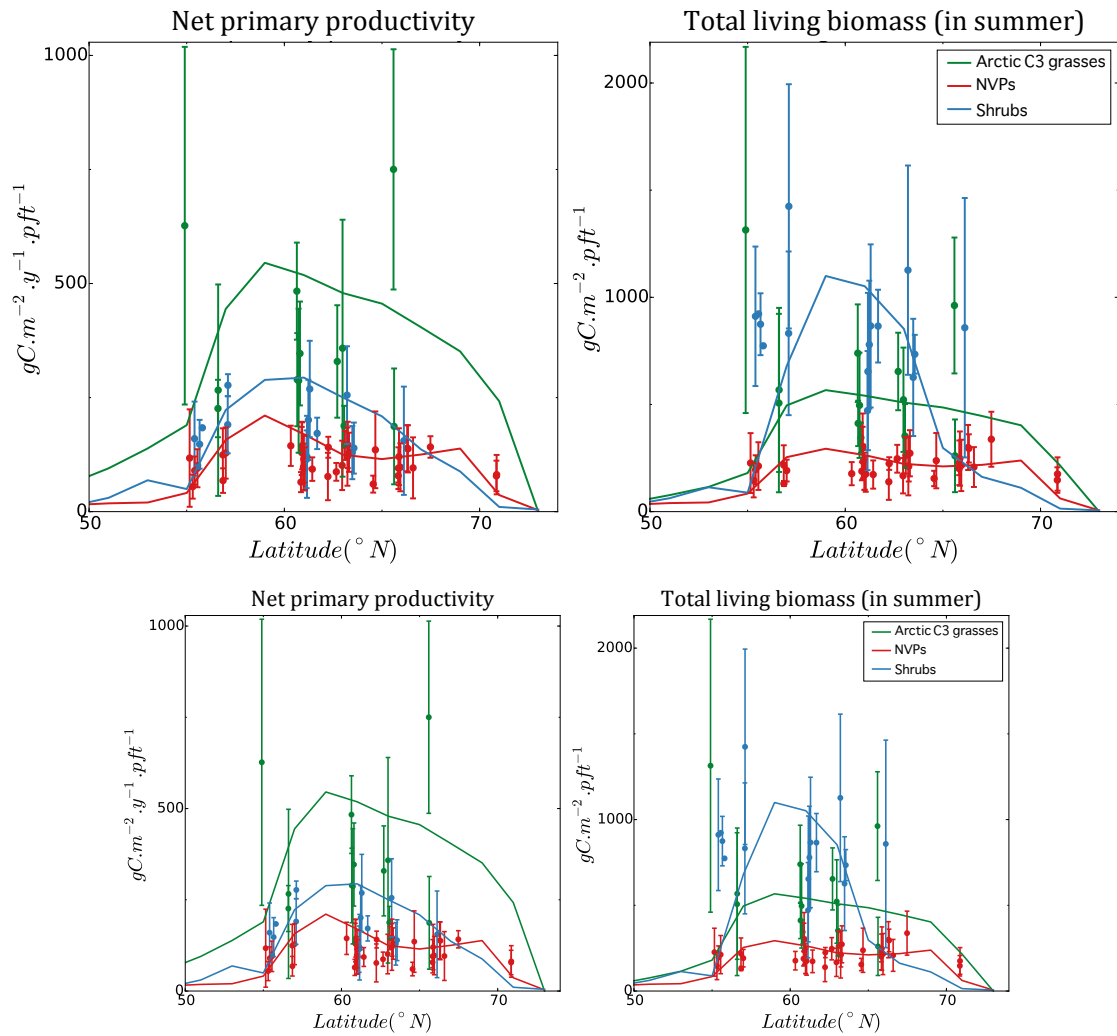
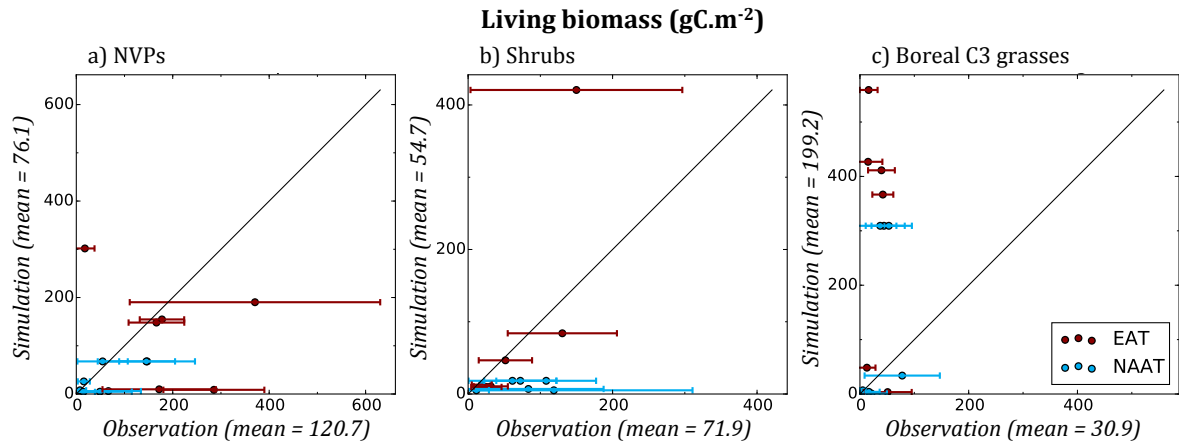
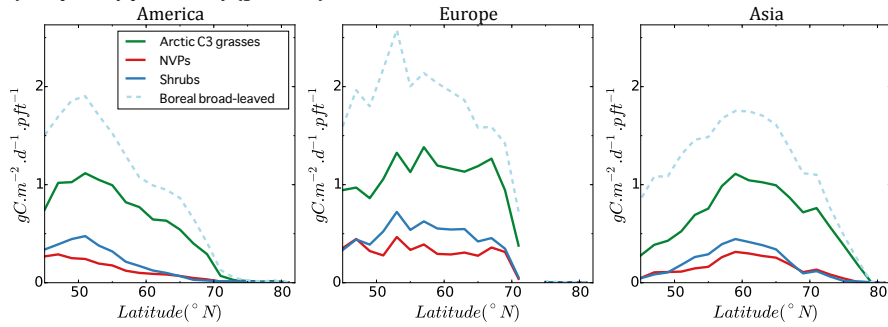


Figure 8: Latitudinal transects of the modelled and observed annual Net Primary Productivity and total living biomass in summer (July, August and September) over the period 2004-2013 for the new PFTs, namely boreal C3 grasses (in green), non-vascular plants (in red) and shrubs (in blue). The simulated values are averaged over the longitudinal band 78°E - 82°E, and per latitudinal bands of 2 degrees, from starting at 50°N to 74°N. The observations are aggregated by site (averaged for all years) for each new PFT.

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a) Net primary productivity ($\text{gC}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)



b) Total living biomass in summer ($\text{gC}\cdot\text{m}^{-2}$)

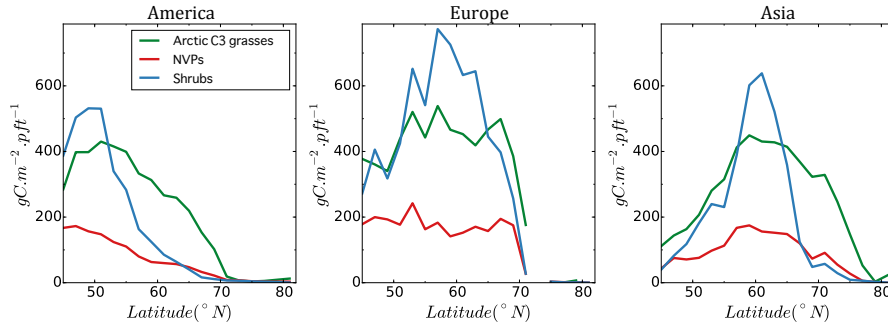


Figure 9: Model versus observed living biomass for NVPs (a), shrubs (b) and cold climate grasses (c), in two different transect: the North America Arctic Transect (in blue) and the Eurasian Arctic Transect (in red). The error bars represent the standard deviation of observation inside each site.

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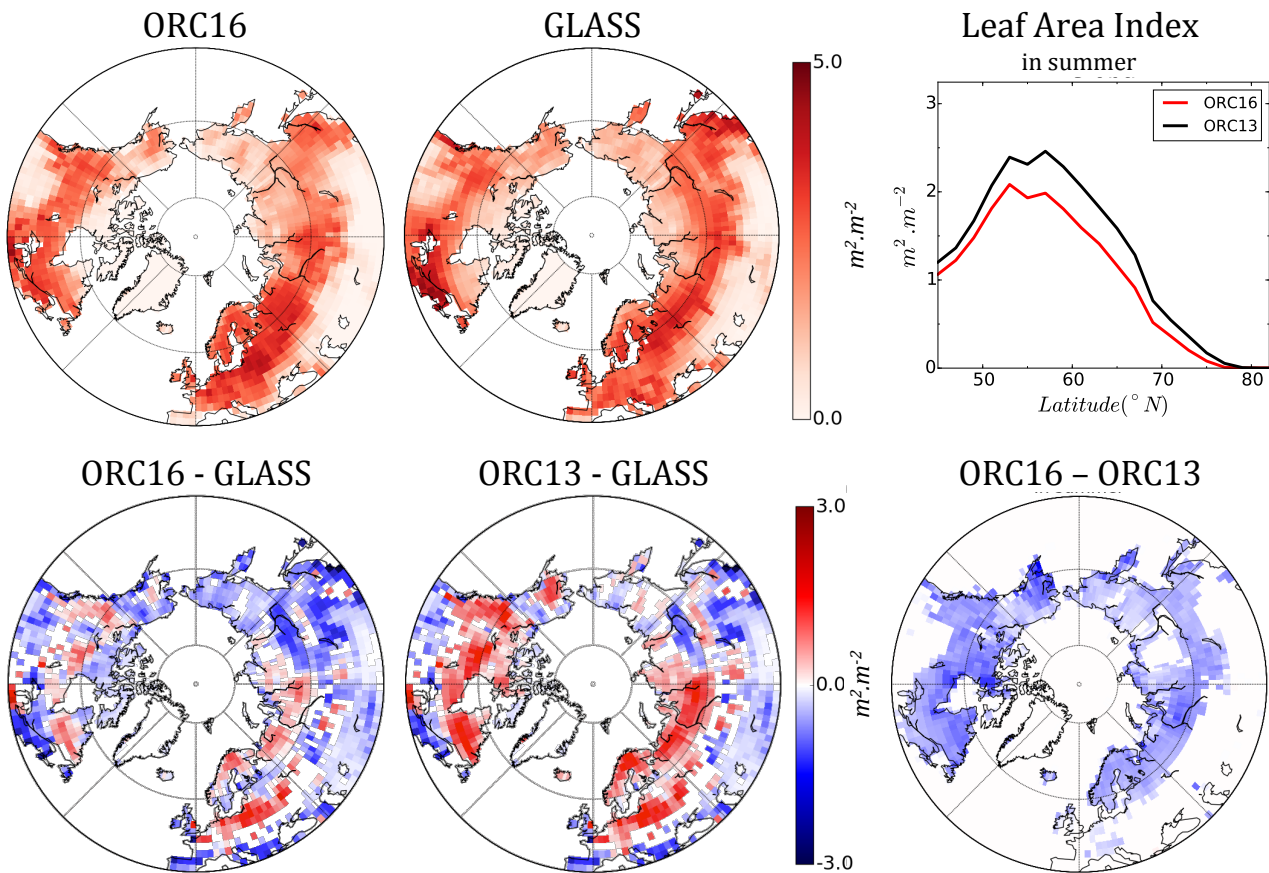


Figure 1: Latitudinal transects of the mean 2004–2013 net primary productivity (NPP) (a) and total living biomasses (b) of new PFTs (boreal C3 grasses, NVPs and boreal shrubs) and boreal broad-leaved tree (dashed, only in a), simulated in ORC16.

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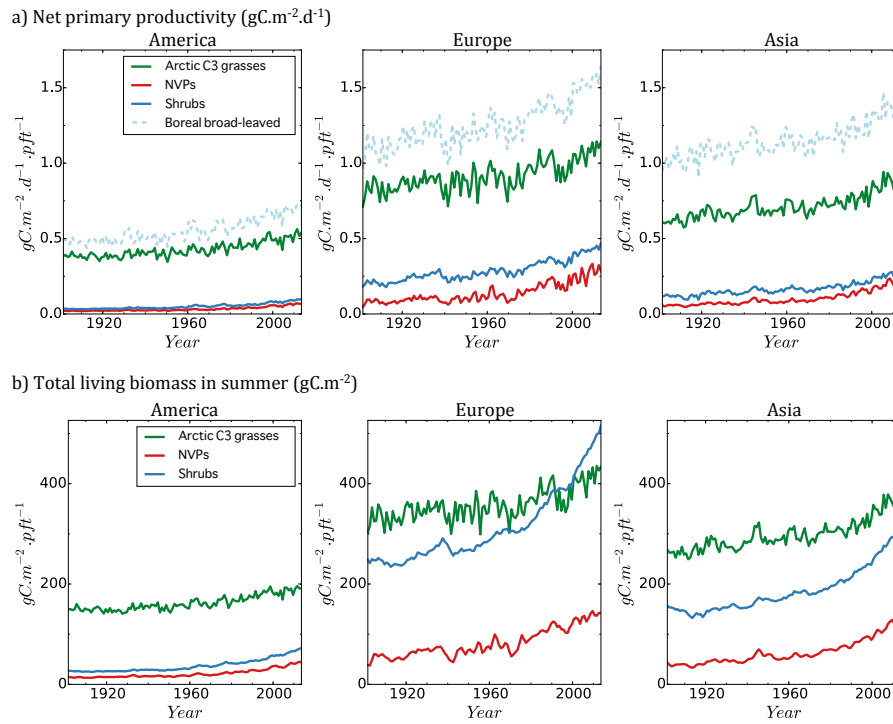


Figure 10: Time series from 1901 to 2013 and from 55°N of Net Primary Productivity (a) and total living biomass (b) of new PFTs (boreal C3 grasses, NVPs and boreal shrubs) and boreal broad-leaved tree (dashed, only in a).

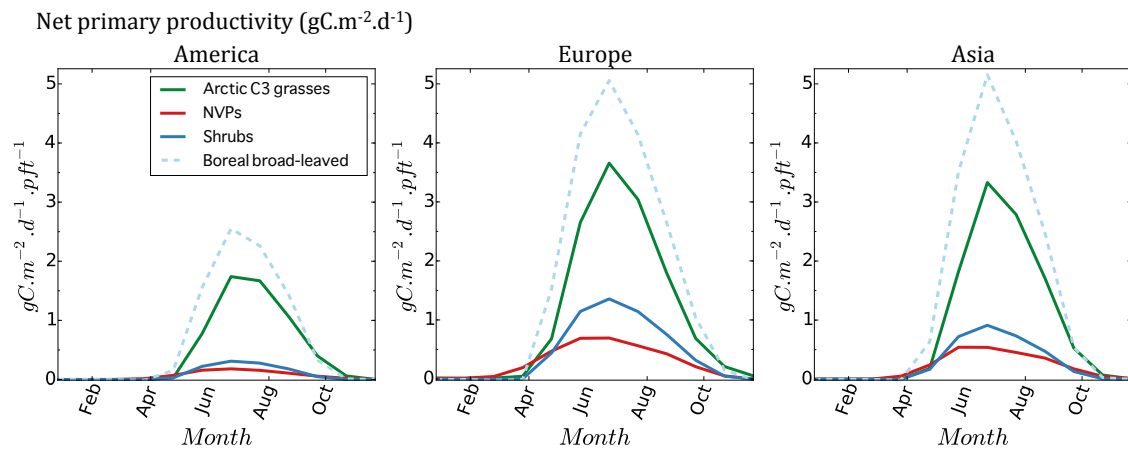
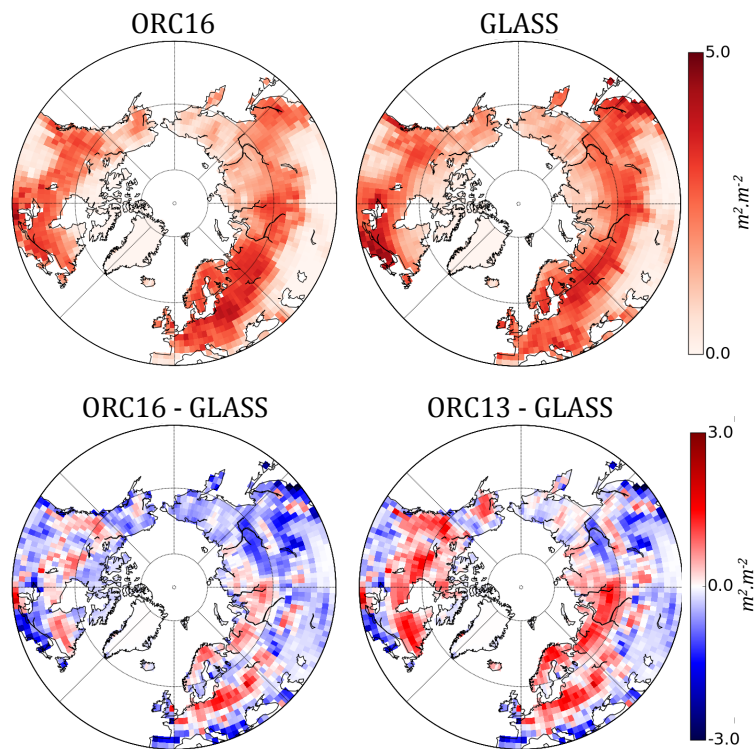


Figure 10: Inter-annual net primary productivity time series (mean 2004–2013) of new PFTs (boreal C3 grasses, NVPs and boreal shrubs) and boreal broad-leaved tree (dashed).



5 **Figure 11:** Global maps of leaf area index (LAI) in summer (mean of July, August and September between 2004 and 2013) simulated by ORCHIDEE with the new PFTs (ORC16) and derived from satellite observations (GLASS LAI product, see section 2.6.2), as well as the significant difference ($p_{\text{value}}=0.05$) between the simulation with the new PFTs and the old 13 PFTs (ORC16 and ORC13 respectively), and the respective differences with and the GLASS product.

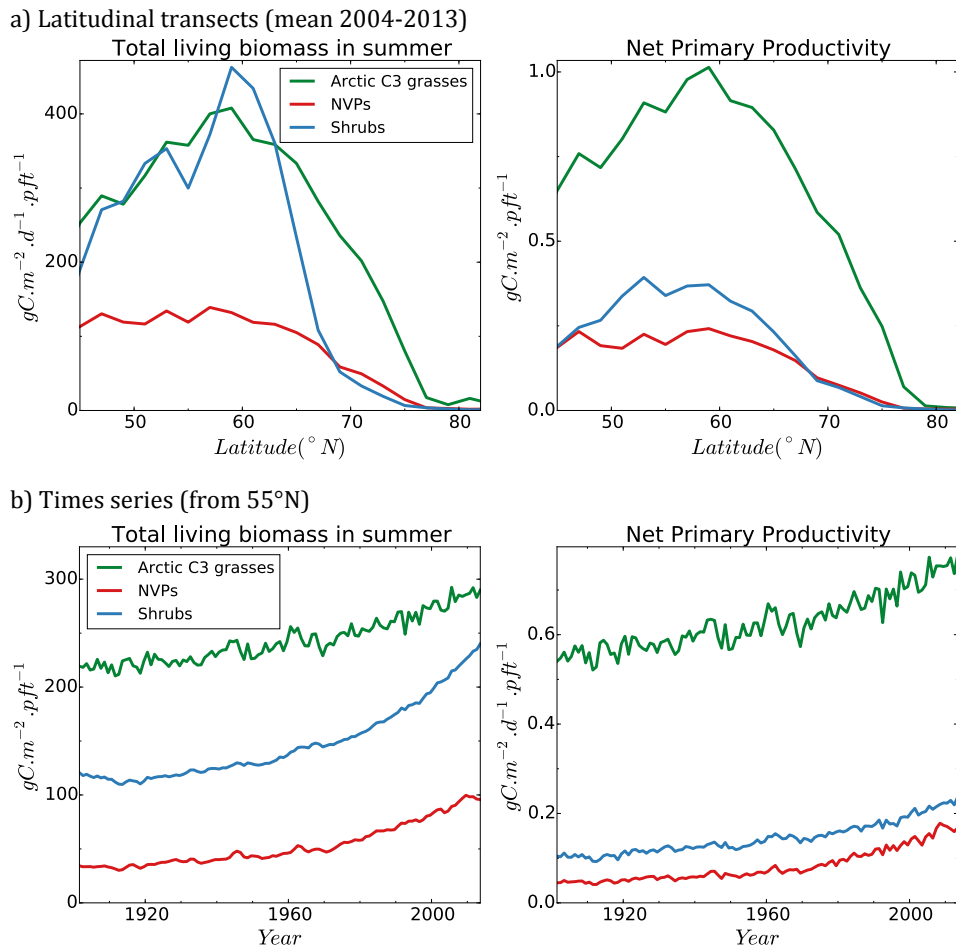
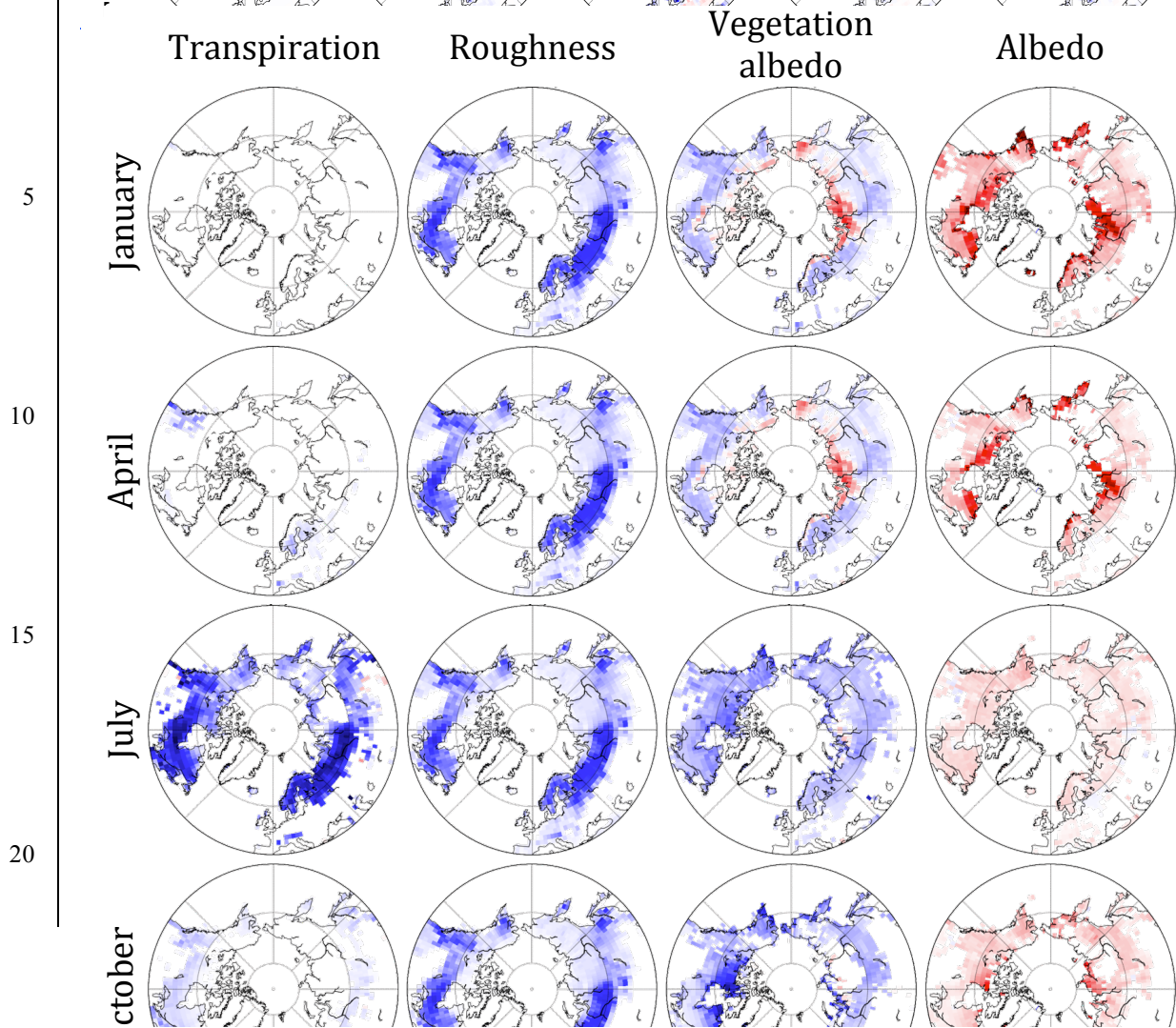
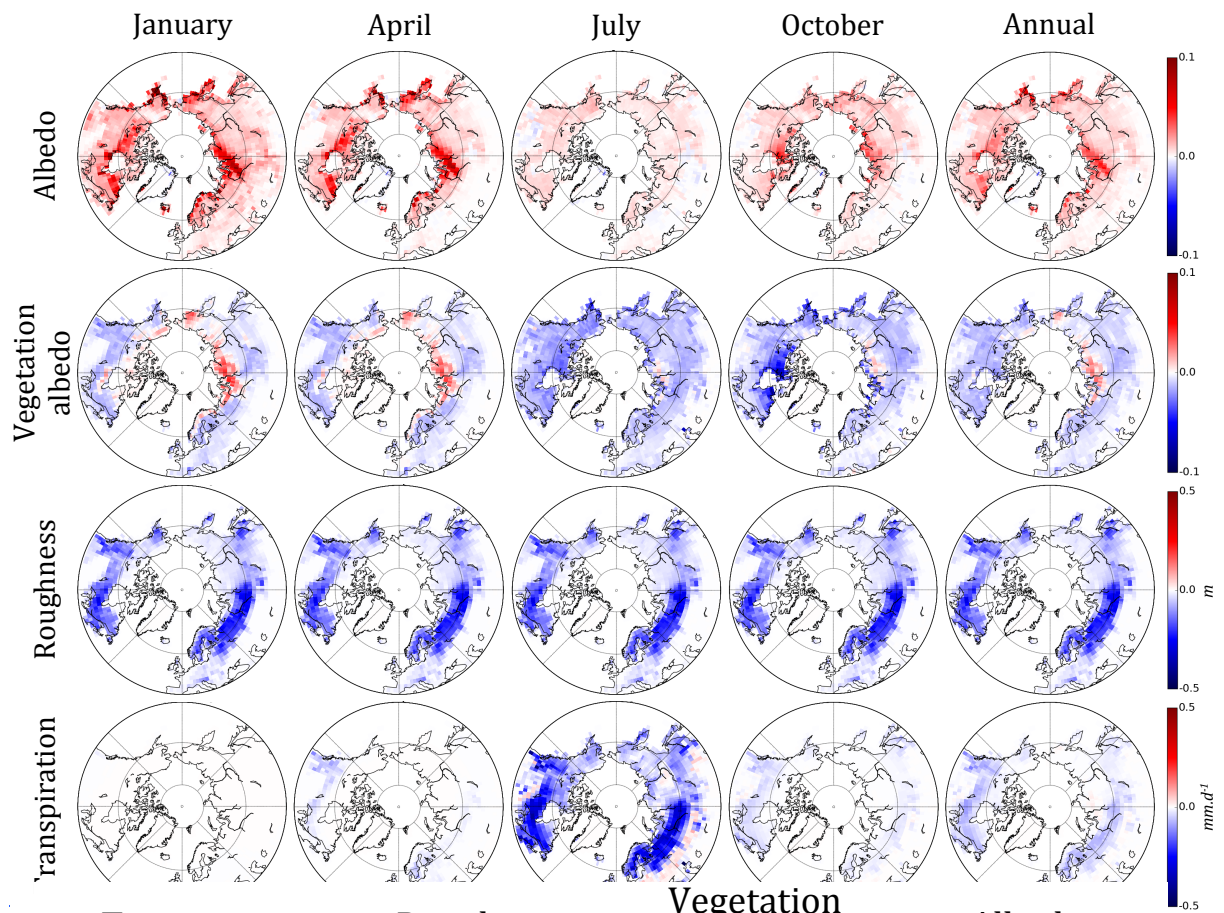


Figure 11: Latitudinal transects (mean 2004-2013) (a) and time series (from 55°N) (b) of the total living biomasses (left) and the net primary productivity (NPP) (right) of new PFTs (boreal C3 grasses in green, NVPs in red and boreal shrubs in blue), simulated in ORC16. The total living biomasses are the mean of July, August and September.

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Figure 12: Maps of the **significant** differences ($p_{\text{value}}=0.05$) between the simulation with 16 PFTs (ORC16 with new boreal PFTs) and the simulation with the 13 PFTs (ORC13 standard version), for albedo (total albedo and vegetation only without snow and bare soil contribution), roughness and transpiration for January, April, July, October, and the annual mean (mean over the period 2004 to 2013).

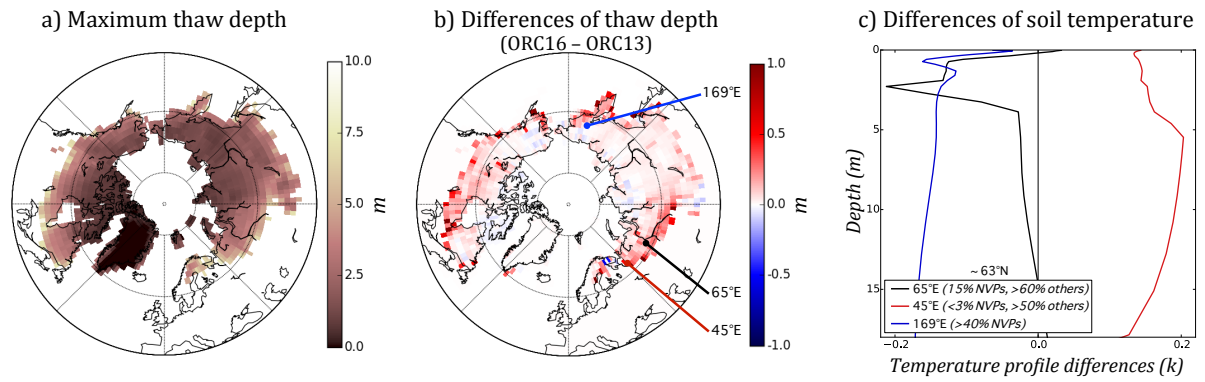


Figure 13: Map of a) the maximum thaw depth (i.e., the active layer thickness or the maximum depth of the 0°C isotherm) for the simulation with 16 PFTs (ORC16); b) differences between ORC16 and the simulation with the 13 PFTs (ORC13) and c) soil temperature profile differences (mean over 2004-2013) at three selected points (63°N and 45°E, 65°E and 169°E) between ORC16 and ORC13.

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Table S1: Conversion table use to obtained vegetation coverage map from the ESA CCI LCC map.

ID	CCI ESA Land Cover Class Description	Trees				Shrub				Herbaceous		NVPs	Non-vegetated				
		BE	BD	NE	ND	BE	BD	NE	ND	Natural	Crops		Bare soil	Water	Snow/Ice	Urban	No data
0	No data															100	
10	Cropland, rainfed										100						
11	Herbaceous cover										100						
12	Tree or shrub cover					50					50						
20	Cropland, irrigated or post-flooding										100						
30	Mosaic cropland (>50%) / natural vegetation (<50%)	5	5			5	5	5			15	60					
40	Mosaic natural vegetation (>50%) / cropland (<50%)	5	5			7.5	10	7.5			25	40					
50	Tree cover, broadleafbroadleaved , evergreen, closed to open (>15%)	90				5	5										
60	Tree cover, broadleafbroadleaved , deciduous, closed to open (>15%)		50				20				30						
61	Tree cover, broadleafbroadleaved , deciduous, closed (>40%)		70				15				15						
62	Tree cover, broadleafbroadleaved , deciduous, open (15-40%)		30				25				45						
70	Tree cover, needleleafneedleleaved , evergreen, closed to open (>15%)			50		2.5	2.5	15			30						
71	Tree cover, needleleafneedleleaved , evergreen, closed (>40%)			70		5	5	5			15						
72	Tree cover, needleleafneedleleaved , evergreen, open (15-40%)			30				25			45						
80	Tree cover, needleleafneedleleaved , deciduous, closed to open (>15%)				50	2.5	2.5	2.5	12.5		30						
81	Tree cover, needleleafneedleleaved , deciduous, closed (>40%)				70	5	5	5			15						
82	Tree cover, needleleafneedleleaved , deciduous, open (15-40%)				30				25		45						

90	Tree cover, mixed leaf type (broadleaf broadleaved and needleleaf needleleaved)	30 20 10	5 5 5	25		
100	Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	7 15 4 5	8 15 6	40		
110	Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	4 7 4	6 13 6	60		
120	Shrubland		15 30 15	40		
121	Shrubland evergreen		30 30	40		
122	Shrubland deciduous		60	40		
130	Grassland			100		
140	Lichens and mosses			10	70	20
150	Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	4.7 4.7 3.1	4.7 4.7 3.1	10.0	45.0	20.0
151	Sparse tree (<15%)	9.4 9.4 6.2		10.0	45.0	20.0
152	Sparse shrub (<15%)		7.5 7.5 5.0	15.0	45.0	20.0
153	Sparse herbaceous cover (<15%)			35.0	45.0	20.0
160	Tree cover, flooded, fresh or brakish water	37.5 37.5		25		
170	Tree cover, flooded, saline water	75	25			
180	Shrub or herbaceous cover, flooded, fresh/saline/brakish water		25 15	30	30	
190	Urban areas					100
200	Bare areas					100
201	Consolidated bare areas					100
202	Unconsolidated bare areas					100
210	Water bodies					100
220	Permanent snow and ice					100

BE : Broadleaf Evergreen, BD : Broadleaf Deciduous, NE : Needleleaf Evergreen and ND : Needleleaf Deciduous.

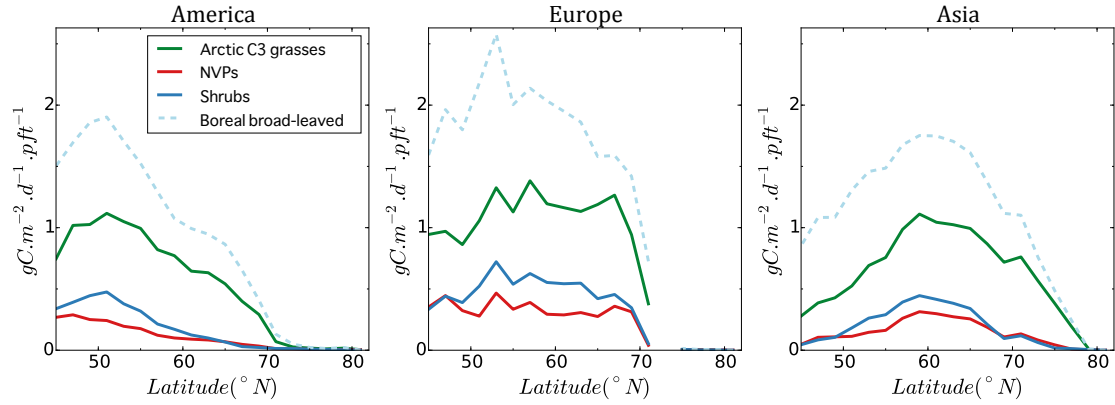
Bold: modified values for the introduction of new boreal vegetation (i.e., shrubs, NVPs and cold climate grass PFTs)

Table S2: Description of the optimised parameters, with their initial value (prior), minimum (min), maximum (max) and the value obtained (POST). The value of the cost function is included in an indicative way.

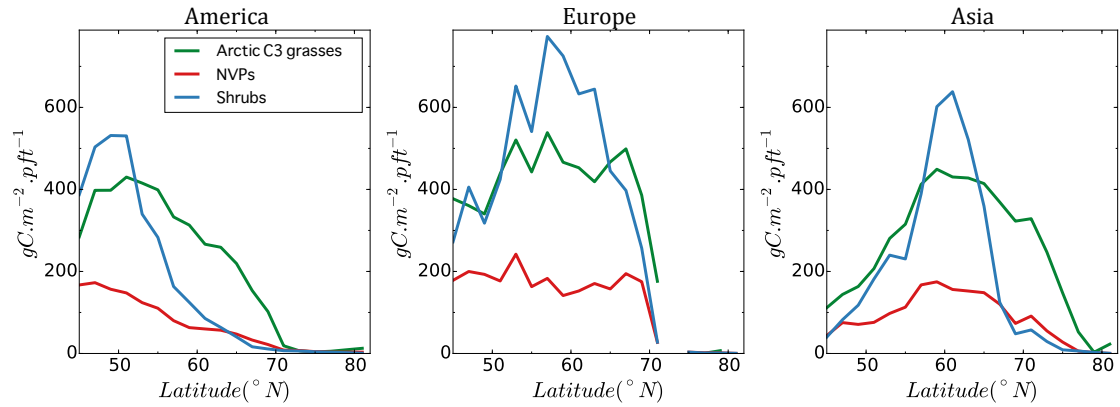
Description (units)	Parameters	prior	min	max	POST
Non-Vascular Plants		(cost J(x) : before 40 880, after 28 240 (-31%))			
Stomatal conductance when irradiance is null ($\text{Cmol.m}^{-2}.\text{s}^{-1}.\text{bar}^{-1}$)	g_0	0.103	0.006	0.2	0.052
Empirical constants for conductance (-)	b_l	0.35	0.15	0.45	0.41
Senescence (day)		455	180	730	470
Maximal fraction of biomass loss (if $\text{NPP} \leq 0$) (day)	k_{lmax}	0.015	0.005	0.025	0.0050
LAI seuil avant turnover	LAI_{lim}	2.5	2.3	2.7	2.4
Threshold leaf area index for turnover (day^{-1})	l_{coef}	0.007	0.0025	0.02	0.014
Root profile control parameter (-)	r_p	40	10	70	18
Offset of desiccation effect (-)	d_{off}	0.3	0.01	0.6	0.55
Maximum Leaf Area Index ($\text{m}^2.\text{m}^{-2}$)	LAI_{max}	3	2	4	3.06
Maximum rate of carboxylation at 25°C ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$)	$V_{c_{max}(25)}$	30	20	40	28
Specific Leaf Area ($\text{m}^2.\text{gC}^{-1}$)	SLA	0.017	0.004	0.03	0.0084
Maintenance respiration coefficient at 0°C ($\text{gC.gC}^{-1}.\text{jour}^{-1}$)	$f_{m\ resp}$	0.0018	0.001	0.0026	0.0026
Boreal Shrubs		(cost J(x) : before 523 100, after 190 900 (-64%))			
Maximum height (m)	H_{max}	3	2.5	3.5	3.5
Specific Leaf Area ($\text{m}^2.\text{gC}^{-1}$)	SLA	0.02	0.012	0.028	0.027
Maximum Leaf Area Index ($\text{m}^2.\text{m}^{-2}$)	LAI_{max}	3.5	2.5	4.5	2.5
Maximum rate of carboxylation at 25°C ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$)	$V_{c_{max}(25)}$	45	30	60	38
Residence Time (y)		30	10	50	32
Fraction of GPP which is lost as growth respiration (0-1)	$f_{g\ resp}$	0.45	0.3	0.6	0.59
Boreal C3 Grasses		(cost J(x) : before 132 400, after 61 460 (-54%))			
Maximum rate of carboxylation at 25°C ($\mu\text{mol.m}^{-2}.\text{s}^{-1}$)	$V_{c_{max}(25)}$	50	30	70	40
$V_{c_{max}}$: Deactivation energy (J.mol^{-1}) *	E_d	195000	190000	200000	200000
$V_{c_{max}}$: Entropy constant ($\text{J.mol}^{-1}.\text{K}^{-1}.\text{°C}^{-1}$) *	b	-0.54	0	-1.08	0
Maximum rate of electron transport at 25°C					
$V_{j_{max}}$: Deactivation energy (J.mol^{-1}) *	E_d	195000	190000	200000	200000
$V_{j_{max}}$: Entropy constant ($\text{J.mol}^{-1}.\text{K}^{-1}.\text{°C}^{-1}$) *	b	-0.38	0	-0.76	0
Root profile control parameter (-)	r_p	7	4	10	5.6
Specific Leaf Area ($\text{m}^2.\text{gC}^{-1}$)	SLA	0.023	0.02	0.026	0.022

* J_{max} and $V_{c_{max}}$ parameters, namely E_d and b , were linked for the optimisation.

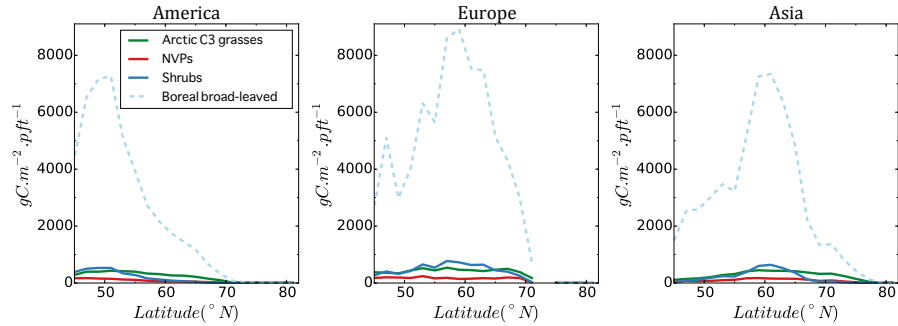
a) Net primary productivity ($\text{gC}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$)



b) Total living biomass in summer ($\text{gC}\cdot\text{m}^{-2}$)



a) Latitudinal transect of the mean 2001-2013 of living biomass ($\text{gC}\cdot\text{m}^{-2}$) with boreal broad-leaved trees



b) Continental time series from 1901-2013 of living biomass ($\text{gC}\cdot\text{m}^{-2}$) with boreal broad-leaved trees

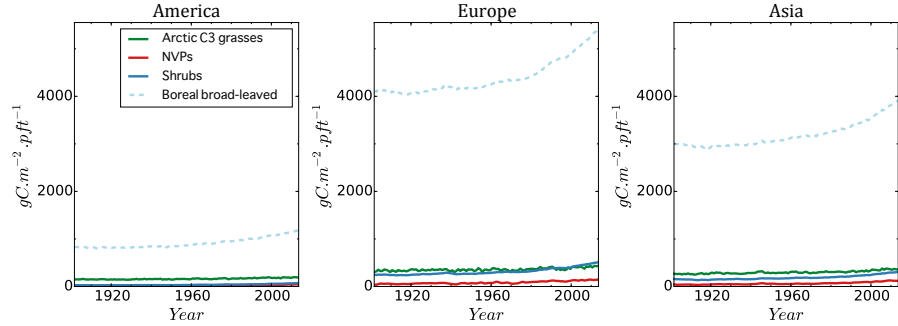


Figure S1: Latitudinal transects of the annual mean 2004-2013 net primary productivity (NPP) (a) and total living biomasses (b) of new PFTs (boreal C3 grasses, NVPs and boreal shrubs) and boreal broadleaf tree (dashed, only in a), simulated in ORC16. The results by PFT are averaged over North America (-180°E to -60°E, without Greenland), Europe (-20°E to 40°E) and North Asia (40°E to 180°E).

5 Figure S1 displays latitudinal transects of NPP and living biomass between 45°N and 82°N for each region. On average we obtain a similar latitudinal gradient in terms of productivity and biomass for all PFTs, with roughly a maximum in North America around 52°N (with above a continuous decrease until 72°N) and in Asia around 58°N (with a decrease until 78°N) and with a plateau in Europe between 50°N and 70°N (follow by an abrupt decrease). The shape of these latitudinal gradients is primarily controlled by the climate, especially the precipitation and temperature gradients with a strong influence of the topography. For example in Asia the precipitation gradient increases from 45°N (less than 280 mm.y⁻¹.m⁻²) to a maximum around 55°N - 60°N (400 mm.y⁻¹.m⁻²) and then decreases again northward, while the growing season (AMJ) mean air temperature (at 2m) decreases gradually from 45°N (+14°C) to 75°N (-7°C). For this region the decrease of precipitation from 60°N to 45°N explains the decrease of NPP and biomass. In Europe the climatic conditions are on average more favourable (e.g. +15°C at 45°N to +4°C à 70°N) which explains the higher productivity and biomasses at high-latitude (i.e. around 70°N).

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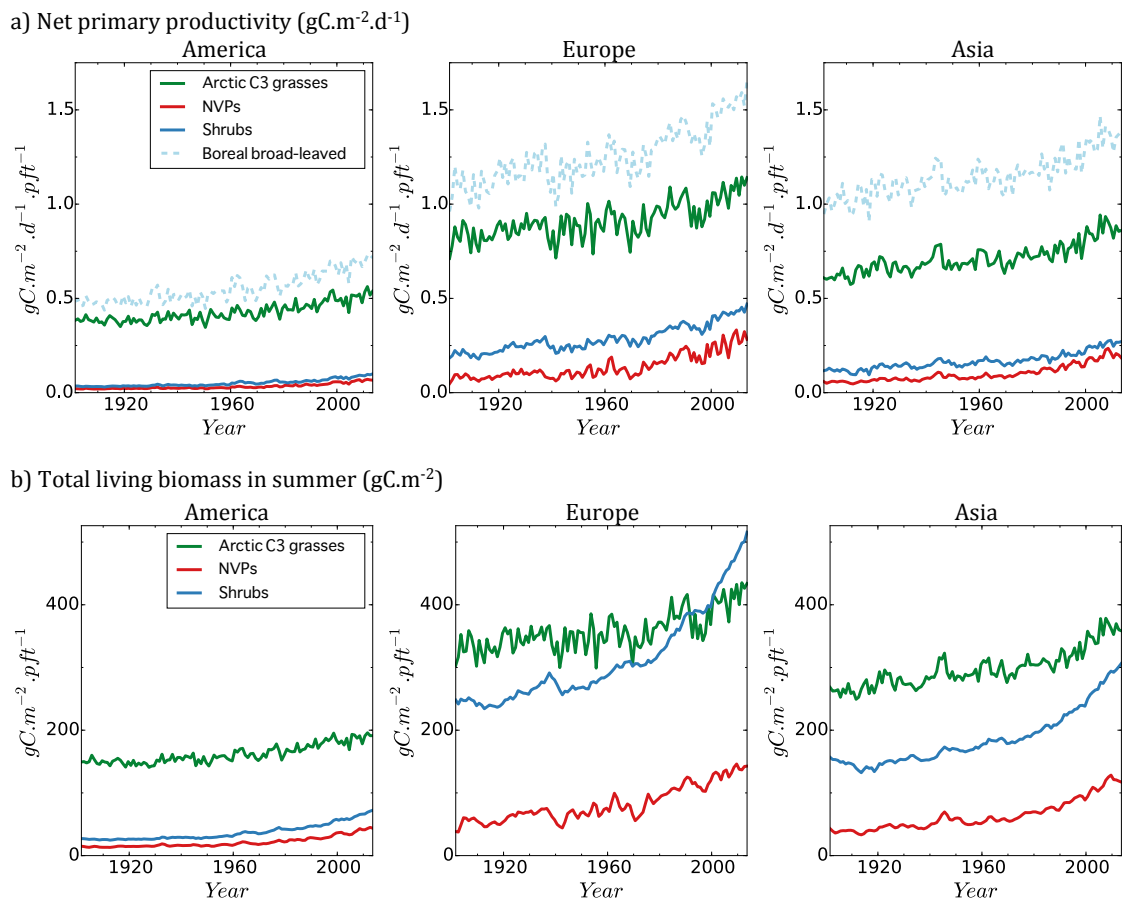


Figure S2: Time series from 1901 to 2013 and from 55°N of Net Primary Productivity (a) and total living biomass (b) of new PFTs (boreal C3 grasses, NVPs and boreal shrubs) and boreal broadleaf tree (dashed, only in a). The results are averaged over North America (-180°E to -60°E, without Greenland), Europe (-20°E to 40°E) and North Asia (40°E to 180°E).

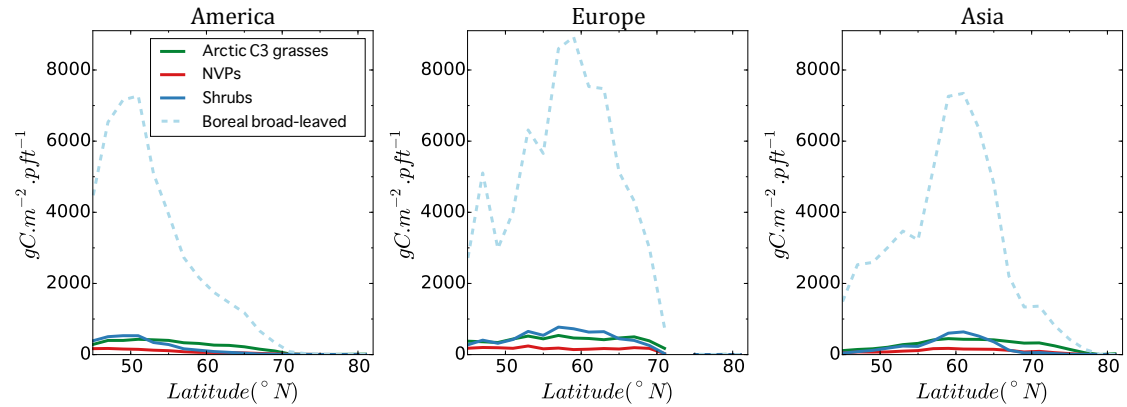
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Figure 10 shows the yearly time series from 1901 to present day for both NPP and living biomass, averaged north of 55°N. The simulated productivity increases on average for the three regions from 1950 to 2013: the increase of both NPP and biomass over the last 60 years is substantial for all PFTs, but largest for non-vascular plants and shrubs.

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The combination of lower mortality and higher photosynthesis (due to temperature) in Europe, where the precipitation and the growing season temperatures are substantially larger (twice the precipitation and +6°C and +10°C compared to America and Asia respectively), explains the higher increase in simulated biomass and NPP.

a) Latitudinal transect of the mean 2001-2013 of living biomass ($\text{gC}\cdot\text{m}^{-2}$) with boreal broad-leaved trees



b) Continental time series from 1901-2013 of living biomass ($\text{gC}\cdot\text{m}^{-2}$) with boreal broad-leaved trees

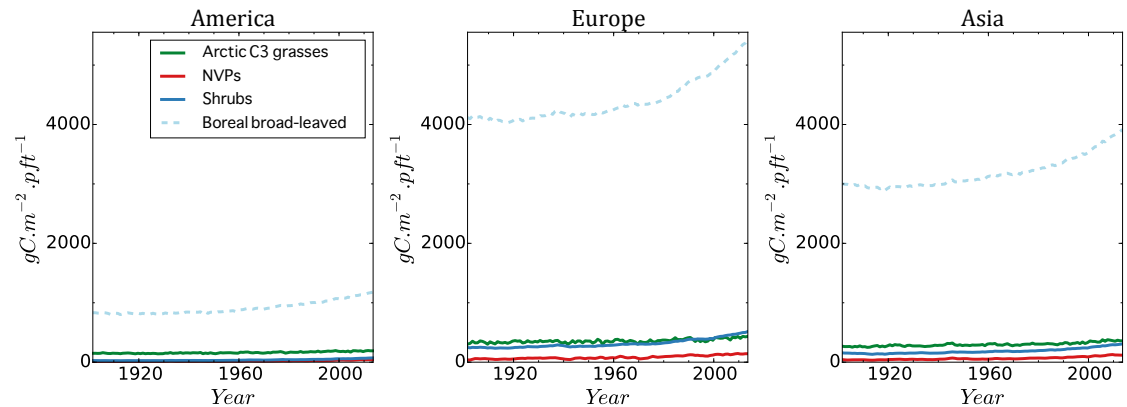


Figure S3: Latitudinal transects of the mean 2001-2013 (from 45°N) and time series from 1901 to 2013 (from 55°N) of total summer live biomass of new PFTs (cold climate C3 grasses, NVPs and boreal shrubs) and boreal broadleaf broad-leaved tree (dashed).

5 [Only the new PFTs are shown \(i.e., boreal C3 grasses, NVPs and shrubs\), along with the boreal broad leaf deciduous trees \(from which shrubs are derived\).](#)

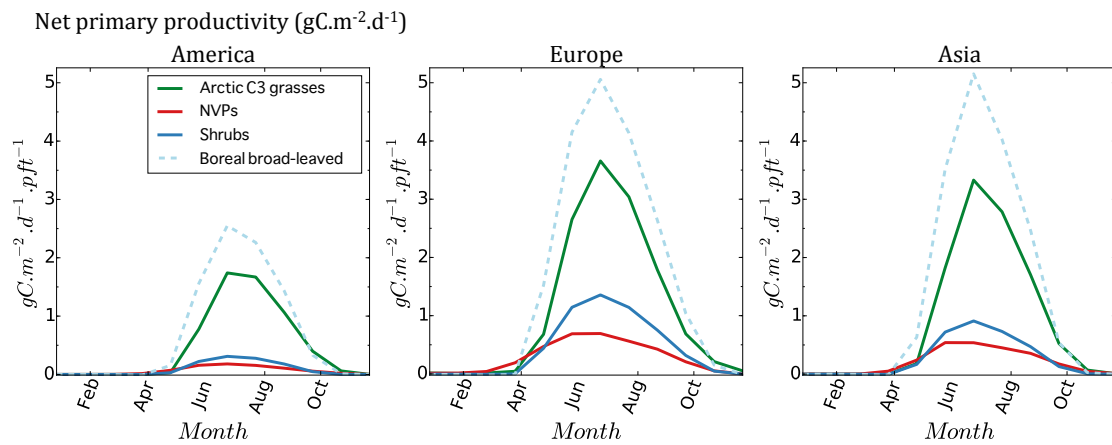
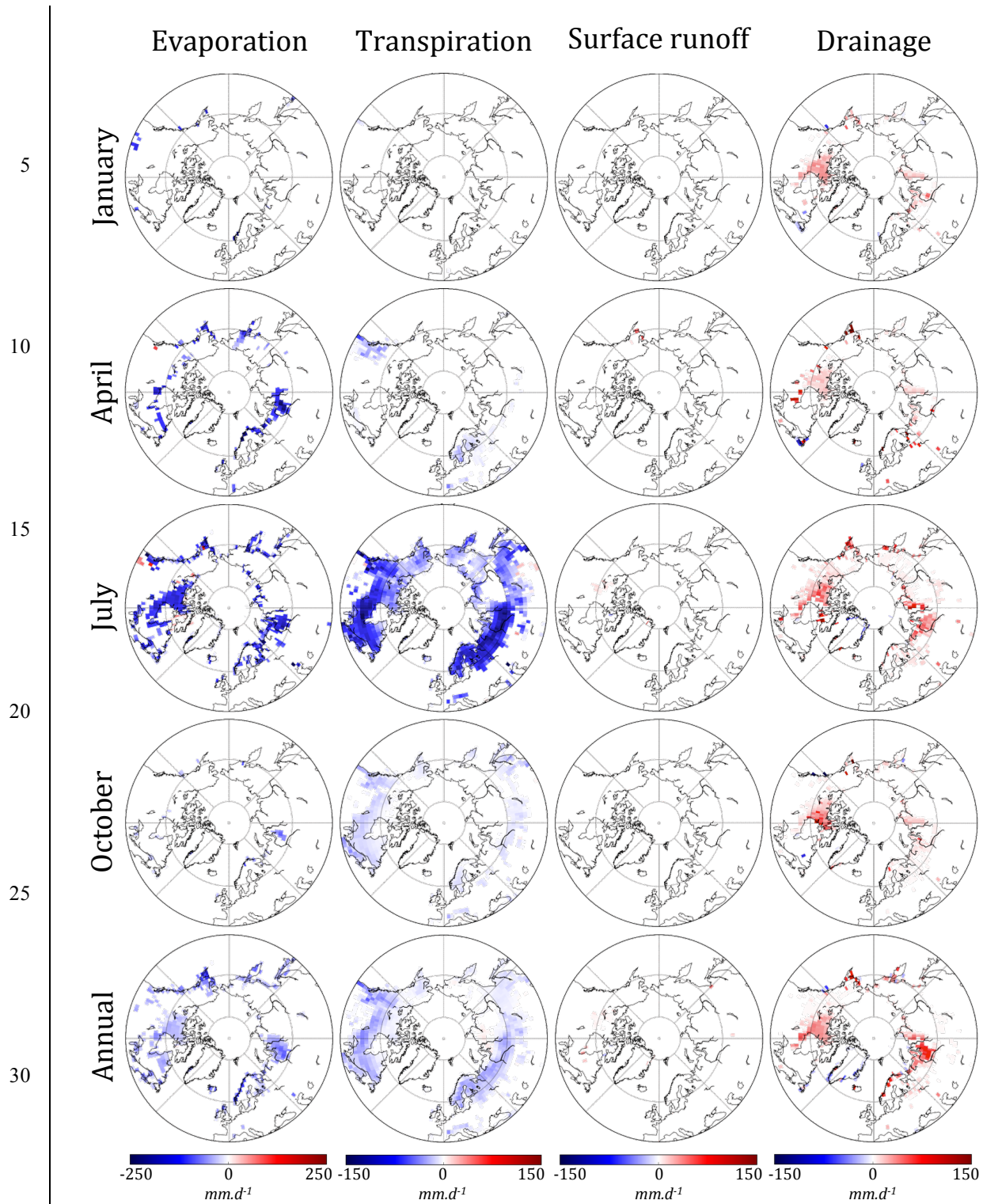


Figure S4: Inter-annual net primary productivity time series (mean 2004-2013) of new PFTs (boreal C3 grasses, NVPs and boreal shrubs) and boreal broadleaf tree (dashed).

Figure S4 displays the mean seasonal cycle of NPP for the three continental regions (mean over 2004-2013 and above 55°N). As expected, the growing season starts late spring with a sharp increase of the NPP up to July and then a slower decrease up to November, for all PFTs. The seasonality is slightly different for NVPs, for which the maximum is reached earlier (in June), with a small decrease over the summer (with sometimes locally a summer minimum in August) before the large decrease from September on.

Contrary to the other boreal PFTs, The NVPs display an earlier start of the growing season in spring (from March in Europe or April elsewhere) and a later end of season in autumn (after October) (not shown). During these two periods, more than 20% of the annual increase in NPP (Fig. S2) for NVPs occurs, while there is almost no increase for other PFTs.



35 **Figure S5: Maps of the significant differences ($p_{value}=0.05$) between the simulation with 16 PFTs (ORC16 with new boreal PFTs) and the simulation with the 13 PFTs (ORC13 standard version), for different components of the water balance: evaporation, transpiration, surface runoff and deep drainage for January, April, July, October, and the annual mean (mean over the period 2004 to 2013).**