RC2: 'Comment on egusphere-2026-1071', Wu Sun, 21 Apr 2026

The manuscript by Kirchner et al. implemented a parsimonious, fine-grained classification of shrub plant functional types (PFT) for the global Arctic–boreal region in the land surface model ORCHIDEE, meticulously identified and calibrated relevant parameters, and evaluated model simulations of biomass density and carbon fluxes against benchmark data products. The shrub PFT implementation is nicely done and well documented. In my opinion, two highlights of the work include: a parsimonious classification of shrub PFTs to capture the main variability of functional diversity among dominant Arctic–boreal shrub species while not overcomplicating it, and the systematic approach toward parameter selection and parameter optimization using ORCHIDAS, which puts the work on a rigorous footing. The manuscript is overall well written, although some clarifications would be helpful. My comments are mostly minor, listed as follows:

We thank reviewer Wu Sun (hereafter referred to as REF#2) for their constructive and thorough feedback on the manuscript. All comments are addressed below and implemented in the manuscript, strengthening it further.

1. A limitation of this work is that the partition from the total shrub coverage into the three shrub PFTs (tall deciduous, short deciduous, and short evergreen) is simplistic, with latitude as the only factor determining shrub PFT fractions. Empirical knowledge tells us that there is a strong west–east gradient in the northern limit of treelines over North America: the same latitude in southern Alaska where boreal forest dominates would be tundra around the Hudson Bay. There is also an east–west gradient in shrub coverage going from Finland to Norway. Potential misclassification caused by the latitude-only shrub distribution (Eqs. 5 and 7) may need to be discussed in comparison with the original CAVM and Macander et al. (2017) maps. In addition, the empirical representation of shrub PFT fractions seems ill-suited for CMIP-style future projections where PFT fractions are forced by evolving climate.

We agree with REF#2 that the partitioning of shrub coverage into PFTs is suboptimal. This is a direct consequence of the limited availability of shrub cover mapping products, and we did the best we could with the limited data available. Notably latitude is not the only determinant of shrub cover partitioning: within the CAVM region deciduous and evergreen shrub cover are derived from the different shrub tundra types mapped (P1, P2, S1 to evergreen, S2 to deciduous). Since CAVM does not explicitly distinguish between evergreen and deciduous shrubs, this assumption was necessary. The latitude-dependent relationship described in Equation 5 is only applied for gap-filling. South of the CAVM region we decided to partition evergreen and deciduous shrub following a spatially uniform fraction derived from a detailed mapping product over Alaska (Macander et al., 2022). We consciously decided to keep this partition simple, since we cannot extrapolate shrub distribution patterns from Alaska to the rest of the panarctic region.
We wonder, how is “a strong west–east gradient in the northern limit of tree lines over North America” related to the partitioning of different shrub types? Note that the total

shrub cover, as well as the tree line is prescribed directly from Harper et al. (2023) in our maps.

We further agree that the prescription of vegetation cover presents a limitation for future projections. Future projections would benefit from dynamic vegetation cover, evolving in response to climate, as calculated by dynamic vegetation modules, as included in some land surface models (e.g. LPJ-GUESS). The absence of a dynamic vegetation module in the current ORCHIDEE version is a generic limitation of the model, which is being addressed with ongoing developments in a parallel modelling effort. Our shrub implementation operates under the restrictions of the ORCHIDEE model and thus requires empirical vegetation cover maps. Note that the present manuscript consciously focuses on the historical period (where prescribed vegetation cover changes yearly in accordance with the Harper et al. (2023) maps), and does not include future projections. We are currently preparing a manuscript on future simulations with the new shrub PFTs in ORCHIDEE, focusing exactly on those limitations of prescribed vegetation cover.

2. This study claims to have obtained “regionally representative shrub traits.” If this means in a narrow sense that simulated aboveground biomass and GPP align well with pan-Arctic/boreal data products, then yes. But this claim is tenuous if it refers to parameter optimization, given that “sensitivity tests and optimisation were performed … primarily using the grid cell around Toolik Lake, Alaska” (L176–177) and that the GPP targets are based on data from only three eddy covariance sites (Table 2). Further clarifications on regional representativeness are needed. Besides, it’s unclear which target variables from Toolik Lake are used for the optimization.

We thank the reviewer for this relevant yet constructive critique. We would like to clarify that even though parameterisation and optimisation took place mainly in a single grid cell, this is not to be confused with site-level parameterisations as in many other model studies, since they were based on synthesised observations from across the pan-Arctic region, not on site-level observations. We tested different sites during manual sensitivity tests and optimisation, and found little sensitivity to the choice of grid cell, also due to the limited dependency on local environmental conditions in the targeted ORCHIDEE parameterisations. The fact that simulated shrub characteristics match synthesised observations not only at the optimisation grid cell, but across the pan-Arctic region, further strengthens our claim at having obtained regionally representative parameterisations.

To address the reviewer’s comment, we have:

a.) Expanded the analysis to include three more EC sites for GPP calibration targets and evaluation, now including all suitable sites from the FLUXNET and Ameriflux databases (for more details see answer to point 6 below).

b.) Clarified the approach in line (L.) 176 and following:

“Sensitivity tests and optimisation were performed separately for each shrub PFT at grid cell level, primarily using the 2° x 2° grid cell around Toolik Lake, Alaska (67.6°-69.6°N, 148.6-150.6°W). This area was found suitable both because it includes a well-studied diverse shrub tundra environment, and because initial ORCHIDEE simulations across the high-latitude region showed that it represents average growing conditions for the region. Different grid cells were tested during the development process, and parameterisation proved to be only weakly sensitive to grid cell-choice. While parameterisation and optimisation were limited to a single grid cell for computational reasons, they were based on regionally representative targets derived from synthesised panarctic observations.”

c.) Explicitly addressed the question of parameterisation and optimisation in a single grid cell in the discussion, L. 456:

“Contrary to the site-level calibrations in many other shrub implementations (e.g. Wolf et al. 2008; Meyer et al. 2021; Sulman et al. 2021), the ORCHIDEE shrub PFT classification and parameterisation presented here are constrained by synthesised observations spanning the entire high-latitude region, increasing its transferability and limiting site-specific biases (Alton et al. 2011; Kuppel et al. 2014). This is in line with recent work by Murphy et al. 2025, highlighting the limitations of model parameterisations based on plot-level observations from a single site. Thus, the methodological choices, including the shrub PFT classification scheme, calibration targets and vegetation distribution, are applicable beyond the ORCHIDEE model.

While parameter selection and optimisation were mainly carried out in a single grid cell due to computational limitations, the results indicate that parameterisations can be considered regionally representative, since simulated shrub characteristics match synthesised observations not only in the optimisation grid cell, but across the entire region. Parameterisation in a single grid cell was further deemed sufficient for the targeted variables like height and biomass, because in ORCHIDEE they are less sensitive to local environmental conditions than the observed variability indicates (cf. the relatively narrow ranges of height, diameter and biomass over the entire region given in Table 5, and the smaller variability in AGB in ORCHIDEE compared to observations in Figure 3). Notably, CO_2 flux-variables, with a stronger variability based on site conditions, were carefully evaluated at several locations to avoid site-specific biases. While this limited reproduction of spatial variability justifies the methodological choices in the present work, it calls for an enhanced representation of environmental dependencies in ORCHIDEE shrub parameter calculations in future work.”

d.) The question about target variables in the optimisation was addressed by explicitly adding the optimisation target variables in L. 252, see answer to point 7 below.

3. L57–62: It’s worth discussing in which aspects this shrub PFT implementation differs from Druel et al. (2017) and why the implementation presented in this study makes better sense.

As explained in L.57–62, the shrub implementation by Druel et al. (2017) was based on an old, fundamentally different version of ORCHIDEE. It is not possible to integrate their work into the current version of ORCHIDEE, necessitating an entirely new implementation of shrub PFTs, as done in this manuscript. Since they are based on essentially different models, no direct comparison of the implementations is possible. Regarding the choice of shrub PFTs, Druel et al. (2017) included only one type (broadleaf deciduous shrubs). The arguments for a more detailed shrub classification are discussed in the manuscript already (e.g. L.100 and following, L.445 and following).

4. L85: “adapted to harsh high-latitude conditions” - This statement only refers to Arctic/boreal shrubs because shrublands are common in mediterranean, xeric, and alpine ecosystems.

We thank REF#2 for pointing out this inconsistency. We adjusted the sentence to include shrublands in general and made the focus on high-latitude shrubs more explicit:

> L.85: *“Shrubs are low-stature woody plants - both deciduous and evergreen - adapted to limited growing conditions, such as in arid or cold regions (CAVM Team, 2024). In high-latitude regions, shrubs typically have lower height and stem diameter and therefore lower biomass, relative to boreal trees, […]”*

5. L99–104: Are there evergreen tall shrubs in the Arctic?

To the best knowledge of the authors, evergreen tall shrubs are not generally treated as a distinct pan-Arctic shrub class and were therefore not included in the classification. This is supported by the classifications in other models and data products, frequently including tall deciduous shrubs, but not tall evergreen shrubs, such as Macander et al. (2017), or the four-tier hierarchical PFT classification scheme suggested by Salmon et al. (2025).

6. Table 2: Is there a scientific reason to use different partitioning methods for different sites? How does the discrepancy between daytime and nighttime partitioning affect the calibration?
   Also, I have the same question as Reviewer #1 - Why did the authors select only three sites? There are more AmeriFlux and ICOS shrub sites in the high latitude (for example, US-EML).

We thank the reviewer for this important comment and address the second part of it first.

To address the second part of the comment, as well as comments by the other two referees, we have updated the selection to include in total six sites, clarified the selection criteria in the manuscript, and updated the relevant figures, as detailed below:

> L. 144: *"Data documenting the carbon fluxes between the atmosphere and shrub vegetation were extracted from the FLUXNET2015 (Pastorello et al., 2020) and AmeriFlux (Chu et al., 2023) datasets. We selected sites classified as open or closed shrubland (OSH/CSH), located above 50°N and with the full FLUXNET-standard post-processing available. Based on the available vegetation descriptions, further sites were excluded, including burn sites with fire succession vegetation, and one tussock-tundra site (US-ICt), resulting in six selected shrub sites (cf. Table 2)."*

Table 2. Eddy Covariance CO_2 flux measurement sites located in shrub tundra locations from FLUXNET and Ameriflux. Columns: IGBP = IGBP vegetation classification (CSH = closed shrubland, OSH = open shrubland). Veg = Vegetation classification by Oehri et al. (2022) derived from site descriptions based on CAVM (Walker et al., 2005) (S2 = Low-shrub moss tundra, P2 = Prostrate/Hemiprostrate dwarf-shrub lichen tundra, G4 = Tussock sedge, dwarf-shrub, moss tundra). E = elevation [m]. T = Mean annual temperature [°C]. P = mean annual precipitation [mm]. GPP = median (interquartile range) annual GPP [$g C m^{-2} yr^{-1}$]. GPP estimated using nighttime flux partitioning method.

Site ID	Location	IGBP	Veg	Lat(°N) / Lon(°E)	E	T	P	Years	GPP
US-TKs	Toolik Shrub Tundra, AK, USA	CSH	-	68.6337 / -149.5769	760	-9	316	2018-2025	365 (302-382)
US-ICh	Imnavait Creek Watershed Heath Tundra, AK, USA	OSH	P2	68.6167 / -149.3	940	-7.4	318	2008-2024	191 (163-212)
US-xHE	NEON Healy, AK, USA	OSH	S2	63.8757 / -149.2133	705	-4	320	2018-2021	496 (384-675)
US-EML	Eight Mile Lake Permafrost thaw gradient, Healy, AK, USA	OSH	G4	63.8784 / -149.2536	662	-1	378	2008-2019	416 (393-456)
RU-Cok	Chokurdakh, Russia	OSH	G4	70.8291 / 147.4943	48	-14.3	232	2003-2013	361 (303-529)
RU-Vrk	Seida, Vorkuta, Russia	CSH	S2	67.0547 / 62.9405	100	-5.6	501	2008	408 (408-408)

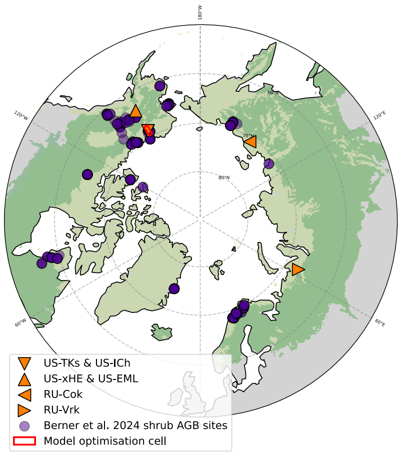

Figure 1. Locations of calibration data sites. Orange triangles: Six EC CO_2 flux sites from FLUXNET and AmeriFlux. Purple dots: 331 shrub-dominated aboveground biomass sites in 24 different areas from Berner et al. (2024). Red rectangle: Model grid cell used for parameter optimisation. Green shading indicates the Arctic-Boreal region as defined in Olefeldt et al. (2021), with the tundra (light green) and boreal (darker green) subregions Dinerstein et al. (2017).

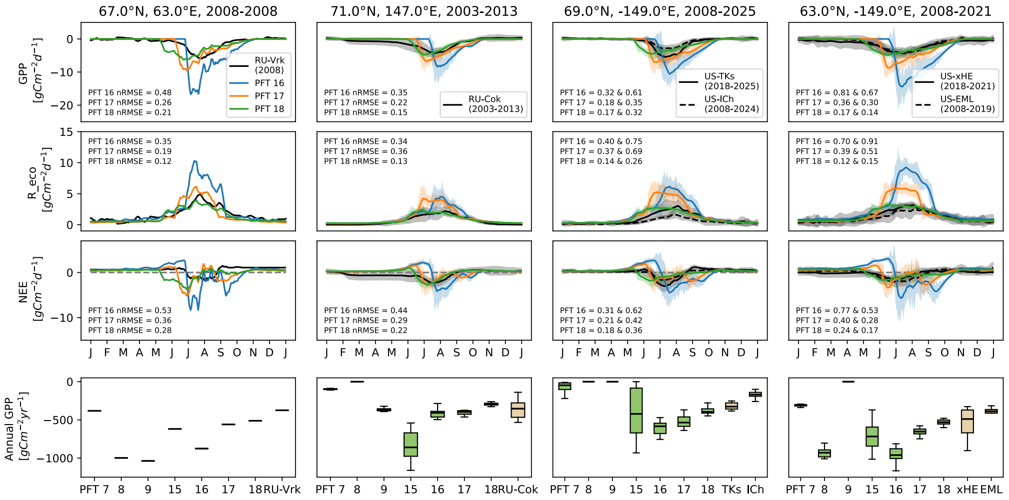

Figure 4. Observed (black) CO_2 fluxes at six shrub-tundra EC sites and simulated (color) shrub CO_2 fluxes at three ORCHIDEE grid cells (columns, where the coordinates above the figures represent the centre of the 2°x2° grid cells). Rows represent CO_2 fluxes: gross primary productivity (GPP), ecosystem respiration (R_{eco}), and net ecosystem exchange (NEE). Negative values indicate uptake of CO_2 from the atmosphere by the vegetation, while positive values denote release. Shown is the average seasonal cycle and standard deviation (shading) in daily resolution, smoothed with a 10-day running mean. Goodness of fit is measured with root mean square error normalised by amplitude (nRMSE). Last row: annual sum of GPP simulated for all high-latitude PFTs in ORCHIDEE (green) and observed at the EC sites (brown). Note that where two EC sites are located in one ORCHIDEE grid cell, the observed fluxes shown represent different time frames and the ORCHIDEE fluxes are shown for the combined time frame.

To address the first part of the comment: Both nighttime (Reichstein et al., 2005) and daytime (Lasslop et al., 2010) flux partitioning are standard eddy-covariance post-processing approaches. We originally chose the daytime method, where NEE is fitted using a light-response formulation combined with temperature-dependent respiration (see López-Blanco et al. (2017) for further details), since this approach is particularly useful at high-latitude sites, where true nighttime observations can be sparse or absent during summer. However, the northernmost site (RU-Cok, at 70.8°N) showed strong differences in GPP estimates between the two methods (see **Error! Reference source not found.**), due to positive GPP values throughout the winter season in the daytime method, while the nighttime partitioning yielded more realistic estimates, in line with the estimates of the other sites.

We note that the choice of partitioning method can influence the inferred GPP/Reco split. This is consistent with previous work, including López-Blanco et al. (2017), which showed that different partitioning approaches can lead to different estimates and associated uncertainties in Arctic CO_2 fluxes.

For the sake of consistency, and because Reviewer #2 raised the issue of using different partitioning methods across sites, we have revised the analysis to apply a single partitioning method consistently across all sites. This was done to improve comparability among sites, while acknowledging that uncertainty related to the partitioning approach remains and that an exhaustive assessment of partitioning uncertainty is beyond the scope of the present study.

After comparing both partitioning methods, we applied the nighttime partitioning to all six sites. As shown in **Error! Reference source not found.**, the nighttime method provided a more realistic estimate for the RU-Cok site, while the estimated annual GPP was similar at the other five sites for both methods, albeit slightly lower using the nighttime method.

Table 1: Median (interquartile range) annual GPP in $gCm^{-2}yr^{-1}$ for nighttime and daytime flux partitioning methods

	Five EC sites (excl. RU-Cok)	RU-Cok
Nighttime	335.73 (208.90-413.05)	360.72 (303.02-519.78)
Daytime	353.60 (234.23-494.48)	725.71 (466.71-866.64)

7. L252: What are the target variables in Y? Please spell them out. Also, better use an upright capital “T” to indicate matrix transpose in Eq. (4).

We thank REF#2 for this clarifying question. The description was adjusted to include *“The observational targets (Y) included height, peak summer AGB, minimum fraction of belowground biomass, mean GPP, peak summer leaf area index, and age (ref. Table A4).”* in line 254, moving this information from the supplementary material into the main manuscript.
The equation was adjusted following the reviewers’ suggestions.

8. L264: “boreal tree PFTs (80%) and boreal grass (20%)” - This feels ambiguous to me. Does this mean that a high-latitude grid cell would have 80% fractional coverage of boreal tree PFTs, and 20% fractional coverage of boreal grass? Or does

it mean that among all high-latitude grid cells, 80% of them are assigned boreal tree PFTs?

Thank you for raising this ambiguity. Here, we refer to a methodological choice made by the ORCHIDEE core team and implemented in the standard version of ORCHIDEE without shrub PFTs. In the absence of explicit shrub PFTs in ORCHIDEE, shrub fractional cover from Harper et al. (2023) maps is redistributed to existing ORCHIDEE PFTs.

In practice, across the high-latitude region, this means that in every grid cell where Harper et al. (2023) identifies shrub cover, that shrub fraction is reassigned to the existing boreal PFTs. Of the shrub cover fraction, 80% is allocated to boreal tree PFTs (ORCHIDEE PFT 7, 8, or 9, depending on shrub type), and the remaining 20% is allocated to boreal grass (PFT 15).

To make this clearer, we have rephrased line 264 as follows:

> L 264: *"Prior to the implementation of shrub PFTs in ORCHIDEE, the high-latitude shrub cover fraction in Harper et al. (2023) was redistributed at grid cell level to boreal tree PFTs (80%) and boreal grass (20%)."*

9. Fig. 3: Is there a similar comparison for belowground biomass, or any related measurable belowground traits?

Great question, but since belowground biomass is more difficult to measure, fewer data products on belowground biomass are available. As described in L. 139-143, we used two synthesis datasets to derive average fractions of belowground biomass for the shrub PFTs. In our manuscript we evaluate belowground biomass implicitly by evaluating the fraction of biomass allocated belowground (in Table 5) and aboveground biomass (in Figure 3).

10. Fig. 4: This is a central figure that requires some clarifications.
    First, do we expect these sites to host only one shrub PFT? It is unclear what this comparison aims to achieve. It is true that if we restrict the grid cell to only one PFT, then PFT 18 is the obvious winner. But is reality a mixture of multiple shrub PFTs? It seems a fair comparison can only be made between observations and PFT-aggregated grid-cell-scale carbon flux estimates.
    Second, why does PFT 18 (evergreen dwarf shrubs) show a more gradual spring onset than do PFTs 16 (tall deciduous shrubs) and 17 (low deciduous shrubs)?
    In addition, consider changing "FLUXNET" to "observations" in figure annotations to avoid potential confusion (FLUXNET usually indicates the global network of flux towers).

We thank the reviewer for raising this very valid point, which has actually been thoroughly discussed during the preparation of this manuscript.

This part of the results (section 3.1) aims at evaluating the three shrub PFTs individually. The second part of the evaluation (sections 3.3 and 3.4) then focuses on the overall model outputs taking all PFT contributions together. It is important to evaluate the three shrub PFTs individually, to exclude potential biases from other PFTs. For instance, the boreal grass PFT CO_2 fluxes include biases in ORCHIDEE at the moment, but those biases should not interfere with evaluation of the shrub PFTs.

The reviewer is correct in raising that the eddy-covariance CO_2 flux measurements capture a real-world mixture of PFTs and a comparison with individual PFTs is difficult. While individual studies have conducted a footprint analysis to separate contributions from different PFTs (e.g. Ludwig et al. (2024), as pointed out by referee #3), this information is not available for the selected FLUXNET and Ameriflux sites, and thus the best we could do was carefully select sites dominated by shrub tundra and use those shrub tundra ecosystem fluxes. We do believe that there is a value in evaluating the simulated PFT fluxes against this data, but have adjusted the manuscript to make the reader more aware of the limitations of this comparison:

- Adapted L. 148 and following to clarify that the data represent shrub tundra ecosystems:
  "It is important to note that due to the nature of EC flux measurements, the recorded fluxes represent the aggregate of the entire ecosystems around the tower within a variable footprint, and the data does not specify the contributions of individual PFTs. Therefore, the sites were not assigned to specific shrub PFTs, but used instead as a benchmark for shrub tundra ecosystems to calibrate and evaluate all three ORCHIDEE shrub PFTs against. Notably, the available vegetation descriptions indicate that dwarf and low shrubs seem to be more prominent than tall shrubs at most sites (e.g. van der Molen et al. (2007); NEON (National Ecological Observatory Network); cf. Table 2). Across all six sites, a range of average daily gross primary productivity (GPP) of 0.73 (0.18-2.45) $gCm^{-2}d^{-1}$ (median (interquartile range (IQR)), and average annual GPP of 336 (209-413) $gCm^{-2}yr^{-1}$ was extracted. The GPP statistics were calculated using nighttime flux partitioning, after excluding negative GPP estimates and years without positive values."

- Adapted Figure 4, as shown above, to make it clearer that the comparison happens between ORCHIDEE shrub PFT fluxes at the grid cell level and EC fluxes recording an entire tundra ecosystem at site level. We include in total six FLUXNET/Ameriflux sites, four of which are located in the same two ORCHIDEE grid cells. By reframing the figure as comparing individual PFT fluxes in a 2°x2° ORCHIDEE grid cell against composite flux estimates from individual EC tower sites, the reader should be more aware of the limitations of this comparison.

To address the second sub-question: The reason for the more abrupt spring onset in the deciduous shrub PFTs (PFT 16 and 17) compared to PFT 18 is explained in L. 360-363: *"In particular, the deciduous shrub PFTs experience a rapid increase in photosynthetic activity at the onset of the growing season - a behaviour that can be traced to model functionality where leaf onset for deciduous PFTs occurs within one single day."*.

We thank the reviewer for highlighting the potential confusion by using the FLUXNET label in Figure 4. We have changed it to the actual station names.

11. L329: What does the recruitment beta mean?

‘RECRUITMENT_BETA’ is an ORCHIDEE parameter controlling recruitment of new saplings based on light availability and stand density, as listed in Table 4. Through introducing young saplings into the shrub stands, it controls average plant size, as indicated in L. 329.

12. L362–363: Does ORCHIDEE ramp up Vcmax gradually after leaf onset or use a fixed Vcmax value throughout the growing season?

Vcmax is calculated dynamically throughout the growing season, as a function of leaf nitrogen content and nitrogen use efficiency. Therefore, it shows a dynamic increase and decrease throughout the course of the growing season.

13. L389: What does “forest-prescribed tundra” mean in this context?

We agree that this wording is confusing and thank the reviewer for pointing it out. We were referring to the prescription of boreal forest in place of shrubs in ORCHIDEE PFT maps without shrub PFTs, as explained above in point 8. We have changed the formulation in the manuscript (L. 389) as follows to be less ambiguous :

- From: *“This redistribution reduced the extent of forest-prescribed tundra and established the spatial baseline for subsequent changes in simulated carbon stocks and fluxes.”*
- To: *“Introducing explicit shrub PFTs prevented the reassignment of shrub fractional cover to boreal tree and grass PFTs in ORCHIDEE PFT maps, thereby removing erroneously prescribed forest cover in tundra regions, and established the spatial baseline for subsequent changes in simulated carbon stocks and fluxes.”*

14. L445: “more exhaustive and complete” - This seems pretty subjective. I would say that the classification is more fine-grained, for sure.

We thank the reviewer and have changed the wording from *“more exhaustive and complete”* to *“more detailed”* to be more objective.

15. L504–506: It is also worth noting that the shrub–snow albedo feedback goes the other way: more shrub coverage prompts earlier snow melt and amplifies warming, because protruding shrub branches are darker than snow. See, for example: Domine et al. (2025) JGR-Biogeosciences, https://doi.org/10.1029/2024JG008593; Belke-Brea et al. (2020) J Climate, https://doi.org/10.1175/JCLI-D-19-0318.1.

We thank the reviewer for highlighting the complicated and contradicting processes involved in snow-shrub feedbacks. We have adjusted the text (L. 498-506) to reflect the shrub–snow albedo feedback better as follows:

“Central feedback processes to consider when modelling shrubs include their interactions with snow, impacts on soil thermal regimes and permafrost dynamics, as well as albedo changes (Wullschleger et al., 2014; Mekonnen et al., 2021). For instance, snow cover influences shrub growth, by insulating and protecting shrub buds and tissues from frost, and shaping shrub height and growth form (Myers-Smith et al., 2011; Wheeler et al., 2014). Conversely, shrub presence increases snow accumulation and reduces its compaction, with impacts on soil temperatures and permafrost through the thermal insulation of the snowpack (Myers-Smith et al., 2011; Domine et al., 2016; Heijmans et al., 2022). Depending on shrub height and stature, shrub branches protruding above the snowpack can reduce winter albedo and accelerate snow melt (Belke-Brea et al., 2020; Shuman et al., 2025). These dynamics may potentially represent feedbacks on shrub growth and climate warming, and will thus be important to capture in modelling efforts of future high-latitude ecosystem-climate interactions in ORCHIDEE”

References:

Belke-Brea, M., Domine, F., Barrere, M., Picard, G., & Arnaud, L. (2020). Impact of Shrubs on Winter Surface Albedo and Snow Specific Surface Area at a Low Arctic Site: In Situ Measurements and Simulations. *Journal of Climate*, *33*(2), 597-609. https://doi.org/https://doi.org/10.1175/JCLI-D-19-0318.1

Lasslop, G., Reichstein, M., Papale, D., Richardson, A. D., Arneth, A., Barr, A., Stoy, P., & Wohlfahrt, G. (2010). Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: critical issues and global evaluation. *Global Change Biology*, *16*(1), 187-208.

López-Blanco, E., Lund, M., Williams, M., Tamstorf, M. P., Westergaard-Nielsen, A., Exbrayat, J.-F., Hansen, B. U., & Christensen, T. R. (2017). Exchange of CO 2 in Arctic tundra: impacts of meteorological variations and biological disturbance. *Biogeosciences*, *14*(19), 4467-4483.

Ludwig, S. M., Schiferl, L., Hung, J., Natali, S. M., & Commane, R. (2024). Resolving heterogeneous fluxes from tundra halves the growing season carbon budget. *Biogeosciences*, *21*(5), 1301-1321.

Macander, M. J., Frost, G. V., Nelson, P. R., & Swingley, C. S. (2017). Regional Quantitative Cover Mapping of Tundra Plant Functional Types in Arctic Alaska. *Remote Sensing*, *9*(10), 1024. https://www.mdpi.com/2072-4292/9/10/1024

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., & Granier, A. (2005). On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biology*, *11*(9), 1424-1439.

Salmon, V., Breen, A., Rogers, A., Ely, K., Kumar, J., Sulman, B., & Iversen, C. (2025). *NGEE Arctic Phase 4 plant functional type framework for pan-arctic vegetation* Next-Generation Ecosystem Experiments (NGEE) Arctic. https://doi.org/10.15485/2529470

Shuman, I. N. C., Serbin, S. P., Erb, A. M., Schaaf, C. B., & Yang, D. (2025). Fine-scale vegetation composition and structure shape spatiotemporal variation in surface albedo across a low Arctic tundra landscape. *Environmental Research: Ecology*, *4*(4), 045001. https://doi.org/10.1088/2752-664X/ae04ef