RC1: 'Comment on egusphere-2026-1071', Anonymous Referee #1, 18 Mar 2026

The manuscript "Introducing shrubs enhances the representation of high-latitude vegetation and carbon cycling in the ORCHIDEE land surface model" refined PFTs for shrublands and improved a LSM using updated PFT maps for the Arctic region. The study also investigated the influence of shrub PFT incorporation on estimates of biomass and carbon fluxes and used ground-truth data for model evaluation. In general, this manuscript is well written and follows a clear logical flow. The improved PFT methodology can benefit the broader modeling community and should be relevant to the general audience of Biogeosciences.

I have a few minor suggestions that may help the authors further improve the manuscript:

We sincerely thank the reviewer for their careful reading and constructive comments. The suggestions have been very helpful and have led to substantial improvements to the manuscript. All comments are addressed below.

L147. Three is a relatively small number, given that more sites could be categorized as shrublands according to the IGBP classification. Please provide more detail on why other sites were excluded based on specific criteria.

We thank Referee 1 (REF#1) for highlighting this limitation. The selection of sites was based on their vegetation descriptions, excluding, for instance, burn sites within the boreal forest, with fire succession vegetation, that consists mostly of young trees instead of shrubs (i.e. CA-NS6, CA-NS7, CA-SF3, CA-LU1, CA-LU2). Furthermore, we limited our selection to three sites for practical reasons and selected them based on their geographic location to account for maximum representativeness coverage within the pan-Arctic region.

However, to address the comments of Referee 1, 2, and 3 pointing to the same issue, we have revisited this choice and included three further sites into the analysis, including recently published data. Now the manuscript includes all sites suitable to represent high-latitude shrub vegetation according to our criteria from the FLUXNET and Ameriflux datasets at the time of writing. We have specified the site selection criteria in L.144 and following, as listed below:

> *"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).*
> *It is important to note that due to the nature of EC flux measurements, the recorded fluxes represent the aggregate of the entire ecosystem 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.”*

Accordingly, we have updated Table 2, Figure 1, and Figure 4 to include the additional sites:

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 [$gCm^{-2}yr^{-1}$]. 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)

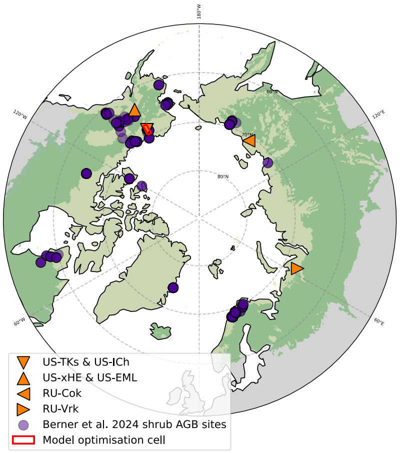

Figure 1. Locations of calibration data sites. Orange triangles: Six EC CO_2 flux sites from FLUXNET and AmeriFlux. Purple dots: 331 shrub-dominated aboveground biomass sites in 24 different areas from Berner et al. (2024). Red rectangle: Model grid cell used for parameter optimisation. Green shading 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).

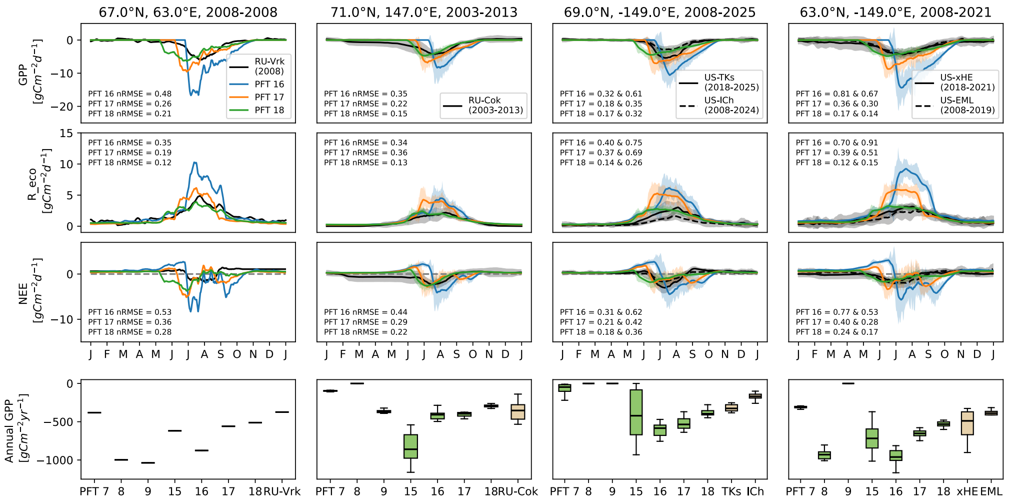

Figure 4. Observed (black) CO_2 fluxes at six shrub-tundra EC sites and simulated (color) shrub CO_2 fluxes at three ORCHIDEE grid cells (columns, where the coordinates above the figures represent the centre of the 2°x2° grid cells). Rows represent CO_2 fluxes: gross primary productivity (GPP), ecosystem 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.

The additional sites show similar patterns as already described in the manuscript, both in the flux exchange magnitude and seasonality, and the degree of agreement with the ORCHIDEE flux estimations at the respective locations. Their patterns and fits with the simulated fluxes are added to the results in L. 346 and following, without changing the message. We have added a comparison between average GPP from all six sites and across the entire tundra region for all ORCHIDEE shrub PFTs.

> L. 369: *"Over the entire tundra region, median (IQR) annual GPP (1992-2020) is 587 (414-791) gCm*$^{-2}$*yr*$^{-1}$ *for PFT 16, 453 (357-561) gCm*$^{-2}$*yr*$^{-1}$ *for PFT 17 and 321 (233-403) gCm*$^{-2}$*yr*$^{-1}$ *for PFT 18; the latter matching the 336 (209-413) gCm*$^{-2}$*yr*$^{-1}$ *estimated at the six EC flux sites best."*

L155. Given the importance of the ORCHIDEE model for this study, consider adding a diagram and/or additional description of the model (perhaps in Appendix if space is limited) for a broader audience. This would help readers understand how this model compares with other LSMs and to what extent the findings can inform other modeling efforts.

We thank REF#1 for the good suggestion and admit that a conceptual diagram of ORCHIDEE in such context would indeed be useful. However, we also acknowledge that representing such a complex model in one single diagram is a complex task that may add additional generic ORCHIDEE details which can ultimately distract the reader from the main purpose of the paper. ORCHIDEE has been extensively reported in a large number of studies, and a dedicated publication describing the newest ORCHIDEE version (including updated diagrams and full description of the model) is currently in progress (Peylin et al. in preparation). To address REF#1 comment we chose to include a more detailed model description in the appendix:

> *"ORCHIDEE (Organising Carbon and Hydrology In Dynamic Ecosystems) is the land surface component of the French ESM IPSL-CM (Boucher et al., 2020) developed by the Institute Pierre Simon Laplace (IPSL). ORCHIDEE can be run in a coupled set-up interacting with the IPSL atmospheric, ocean and ice sheet models, or as a stand-alone model, offline, as done in this work. Inputs required for the simulations include atmospheric forcing (air temperature, humidity, wind speed, surface pressure, and radiation), land surface characteristics (PFT distribution and dominant soil type), and initial conditions for energy, water, carbon, and nitrogen pools. These inputs are sourced from global datasets such as atmospheric reanalysis products, land cover maps, and soil texture databases. ORCHIDEE simulates carbon, nitrogen, energy and water cycling within the terrestrial biosphere, and the exchanges along the soil-vegetation-atmosphere interface (Krinner et al., 2005; Vuichard et al., 2019).*
> *Different biomes are represented by fifteen generic PFTs, including forests, crops and grasslands. They are differentiated based on climate zone (tropical/temperate/boreal), leaf habit (evergreen/deciduous), leaf type (broadleaf/needleleaf) and photosynthetic pathway for grasses and crops (C3/C4) (Box, 1996) (see Table A1). Woody vegetation is represented using a dynamic, vertically discretised canopy scheme that enables explicit simulation of tree-scale demographic and growth processes, including light penetration allowing photosynthesis to be calculated at each canopy level, sapling establishment and density-dependent self-thinning (Naudts et al., 2015). Three diameter classes within each woody PFT allow simulation of different plant sizes within a stand. Mortality due to fire, wind, bark beetles and forest management are implemented in ORCHIDEE, but deactivated in this work (Chen et al., 2018; Marie et al., 2024; Yue et al., 2014; Yue et al., 2018).*

> *The terrestrial carbon cycle, including processes of photosynthesis, respiration, soil carbon dynamics and plant carbon allocation and phenology, is simulated in the STOMATE module. Carbon assimilation and stomatal conductance are described following the concepts of Farquhar et al. (1980) and Ball et al. (1987), as implemented through the analytical solution proposed by Yin and Struik (2009). Photosynthetic processes are resolved at a half-hourly temporal resolution, whereas the allocation of carbon and nitrogen to vegetation compartments (namely leaves, fruits, roots, above-and belowground sapwood and heartwood, labile, and carbohydrate reserve pool), litter, and soil pools is simulated on a daily time step. The allocation of carbon to leaves, roots and wood follows allometric relationships, based on the pipe model theory (Shinozaki et al., 1964). Soil mineral properties are prescribed at the grid cell scale based on the 12 class USDA soil taxonomy (Forbes et al., 1987).*
>
> *The hydrological and biophysical processes of water and energy exchange are described by the surface-vegetation-atmosphere transfer scheme SECHIBA (de Rosnay & Polcher, 1998; Ducoudré et al., 1993). Energy fluxes in the model are calculated uniformly at the grid cell scale, without explicit representation of sub-grid heterogeneity, with the exception of snow processes, for which a distinct energy balance is evaluated over the snow-covered fraction of each cell. In contrast, hydrological processes are simulated separately for different vegetation components within a grid cell, employing three distinct soil columns representing bare soil, tall vegetation (e.g. trees), and short vegetation (e.g. grasses). Vertical discretisation differs among model components: soil hydrology is represented using an 11-layer profile extending to a depth of 2 m, with layer thickness increasing with depth according to a geometric spacing. Thermal processes and soil carbon and nitrogen dynamics share the same grid, but extended downward by seven additional layers to a total depth of approximately 90 m.”*

L177. Provide more detail about the specific grid cell, including its resolution and representativeness, and explain why a single cell is sufficient for sensitivity tests and optimization.

We thank the referee for raising this concern and apologise that we were not clearer in the explanations around this point.

The site-level simulations were run at the same resolution as the pan-Arctic simulations, i.e. 2 x 2 degrees. We now clarify that in the manuscript in L.177.

Different locations were tested during the initial calibration phase and compared to ORCHIDEE outputs over the entire region. The grid cell around Toolik Lake was chosen because the average values of the relevant variables at this grid cell were close to the average values over the entire region, making it a representative site.

Generally, one location was deemed sufficient for calibration of variables like height and biomass, because in ORCHIDEE they do not show a strong dependence on site-specific conditions (cf. the relatively narrow ranges of height, diameter and biomass over the entire region given in Table 5). Parameterisation in one representative grid cell against target values capturing averages of the whole region is a reasonable setup to avoid site-specific biases, while still complying with model limitations, such as computational resources. In this context, optimisation with ORCHIDAS had to be limited to one site for computational reasons. However, test optimisations were also carried out at further sites. Please also note that the CO_2 related flux-variables, with a stronger variability based on site conditions, were evaluated at several locations to avoid site-specific biases.

To address the reviewers' comment, we have added these aspects to the discussion in L. 456 and following:

> *"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."*

L318-322. The writing in this paragraph is somewhat unclear. Please clarify how the three datasets were selected and what distinct aspects they represent, such as ground-truth data versus data-fusion products. In the later discussion section, the comparison with these datasets could also mention a bit more on uncertainty from the observations/ products.

We thank the reviewer for this constructive feedback, which highlights an important aspect of our benchmarking strategy. We agree that clarifying the distinct nature of these datasets and discussing their inherent uncertainties strengthens the manuscript.

1. Clarification on Dataset Selection: Our rationale for selecting these three specific datasets was deliberate: we aimed to evaluate the model against an ensemble of independent, methodologically distinct products. Rather than relying on a single estimate of regional GPP, we selected datasets that represent fundamentally different ways of quantifying the same metric. Specifically, we chose FLUXCOM to represent machine-learning upscaling of eddy-covariance data, Virkkala et al. (2021) for statistical upscaling of synthesised CO_2 flux data, and CARDAMOM to represent a model-data-fusion approach. This approach ensures that our model evaluation is not biased by the specific assumptions, algorithms, or spatial scaling limitations inherent to any single observational methodology. We will rewrite the paragraph at L.318-322 to explicitly categorise each dataset and outline the distinct perspective it provides as follows:

> *"To ensure a robust evaluation of regional GPP, we benchmarked our simulations against an ensemble of three independent data-based products, all remapped to the ORCHIDEE grid. These were deliberately chosen to represent distinct methodological approaches: (1) the FLUXCOM product (Jung et al., 2019), representing a machine-learning approach that upscales FLUXNET eddy-covariance observations using remote-sensing and meteorological predictors; (2) the Virkkala et al. (2021) dataset, representing a statistical modelling approach to upscale synthesised* CO_2 *flux data; and (3) CARDAMOM (Hugelius et al., 2024; López-Blanco et al., 2019), representing a model-data-fusion approach that assimilates remote sensing and gridded datasets into a structurally simple ecosystem carbon model, allowing for observation-constrained parameter retrieval. By utilising this structurally diverse ensemble, we mitigate the risk of evaluating our model against the biases or scaling assumptions inherent to any single upscaling method."*

2. Addressing Observational Uncertainty in the Discussion: We entirely agree with the reviewer's point regarding the uncertainty of the benchmark data itself. Observational and data-fusion products are often treated as absolute benchmarks, yet they carry significant uncertainties stemming from sensor limitations, gap-filling algorithms, spatial heterogeneity, and upscaling errors. In fact, as noted in Section 4.4, the spread among these upscaled products implies that absolute GPP bias cannot be uniquely diagnosed from any single regional benchmark. The divergence among the three independent datasets provides a practical boundary of this observational uncertainty. We will expand the discussion to emphasise that model-data mismatch must be viewed through the lense of these observational constraints.

L336 and L345: Elaborate more on why the simulated range is much smaller than the observed range (Figure 3) and discuss the implications.

That is an interesting point, we thank the reviewer for raising this. The simulated ranges in ORCHIDEE of aboveground biomass (as well as height, diameter, belowground biomass) show a narrower range than the observations. This suggests that the relevant processes in ORCHIDEE are somewhat less sensitive to environmental conditions than the observed variability indicates. The limitations in reproducing local heterogeneity are a known weakness in large-scale modelling in general. ORCHIDEE is working on addressing them by introducing further dependencies on environmental conditions (e.g. climate or soil type) in parameter calculations, such as making the calculation of tree height dependent on precipitation (as mentioned in the discussion, L.471). The limited variability in shrub height and biomass indicates that the model's shrub representation would benefit from dynamic parameter calculations to capture the full range of observed variability. We hope to address this in future model developments and have now explicitly addressed it in the revised discussion from L.456 on, as shown already above:

> *"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."*

Figure 4: It appears that the uncertainty range is truncated for GPP and NEE in some cases.

We thank REF#1 for pointing this out. We adapted the figure margins accordingly, so that the full range of standard deviation is visible now.

L405-406: Explain why the modeled trends show a clear increase over time for biomass (Figure 6) and GPP (Figure 7), whereas this pattern is much less evident in the datasets used for comparison.

We thank the reviewer for raising that interesting point. The increase in aboveground biomass over the shown period can be almost exclusively attributed to the boreal tree PFTs dynamics. Since the PFT maps prescribe no noteworthy increase in tree cover over the analysed time period (1992-2020), the trend indicates a growth response to warming that is stronger than observed in the data products. This may partly be explained by the absence of forest disturbance mechanisms in the simulations, which should provide a balance to the warming growth response. In ORCHIDEE, forest disturbances through fire, wind, bark beetles and anthropogenic management are implemented (Chen et al., 2018; Marie et al., 2024; Yue et al., 2014; Yue et al., 2018), but were not activated in the present setup, since the focus was on the implementation of new shrub PFTs.

Table 6. Consider adding a column that specifies the thresholds or definitions associated with these shrub classes, since these definitions can differ substantially across ESMs.

This is a great suggestion. We will add a column with information on the shrub PFTs to the table accordingly, as far as it is available for the listed models.

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