Dear Prof. Dr. Stoy,

Thank you very much for guiding this review process. Below you find the answers to the reviewers' comments as well as some additional minor wording changes we implemented in the new manuscript version.

We also thank the reviewers for evaluating our manuscript.

Best regards on behalf of all co-authors,

Stephen Wirth

Reviewer 3

Functional diversity plays an important role in the resistance and resilience of an ecosystem towards the impacts of changing conditions and might be essential to maintaining the ecosystem functions of permanent grasslands under climate change. This study implemented a representation of functional diversity based on the CSR theory and the global spectrum of plant form and function into the LPJmL dynamic global vegetation model forming LPJmL-CSR. The paper is a relevant and important scientific contribution, and the authors have addressed the comments from the first round of revision very well. I would encourage the authors to address the following minor comments before accepting the paper for publication.

Abstract: spell out each acronym when it appears for the first time in the paper.

Thank you for pointing this out. We added the missing explanations in the abstract (L7ff).

Line 40: Some recent studies also reported the role of rainfall in C3 and C4 grass compositions, e.g., Xie, Qiaoyun, et al. "Satellite-observed shifts in C3/C4 abundance in Australian grasslands are associated with rainfall patterns." Remote Sensing of Environment 273 (2022): 112983.

Thank you for bringing this up. We added rainfall patterns as a driver of shifts in the C3/C4 composition in L41f.

Line 110: "cold steppe pasture in Inner Mongolia (China)" is contrary to "Mongolia" in Table 1. Mongolia is a different country, whilst Inner Mongolia is in China.

Thank you. We corrected this in Table 1

Figures 1 and 3: some x-axis labels overlap and are hard to read.

Thank you. We have updated the x-axis labels of figure 3.

The paper is too long and would benefit from more concise language.

We agree that the paper is long but believe that in order to reach scientists beyond the vegetation modelling community, the level of detail we provided is necessary. Nevertheless, we made some small adjustments listed within the additional changes section.

Reviewer 4

Grasses and herbaceous vegetation are typically represented only by C3 and C4 grass PFTs in DGVM, while trees are represented by multiple PFTs. The presented study aims to increase the level of grass diversity in LPJmL by including additional grass PFTs. Those additional PFTs represent CSR strategies. The updated model is calibrated by field data for three different study sites and showed higher data-model agreement than the original model version. Overall, I agree with the authors that the number of the grass PFTs should be increased in DGVMs and I like the idea of using the well-established CSR concept for such model improvements.

General comments.

Eight different traits are used to represent different CSR strategies and the traits and the hierarchy of those traits for different strategies are presented. Yet, I think it not clear for all of these traits what high and low values mean and why different values represent different strategies. I suggest the be more explicit to make clear why a low or high value of a trait represents CSR strategies. Ideally, this could be done in a schematic figure or a table.

Thank you for pointing out that this is still not sufficiently clear. We added an overview figure (Fig. 1) that shows the CSR triangle and connects the three strategies, the two gradients and the eight traits. Additionally, we explain what kind of strategy is represented by a low or a high trait value in section 2.4.1 (L296,304,308,312,325f, 332, 338 and 341f).

It is mentioned that only a low number of PFTs (ie three PFTs) was added. But if I understood the parametrization process correctly, trait values for each PFT were calibrated for three sites and two scenarios at each site, which means that 18 PFTs (3 CRS PFTs x 3 sites x 2 treatments) were parameterized. This parametrization shows how optimal PFTs should look like for these different scenarios and sites. However, I was wondering how to move from those site-specific parameters to larger scales and additional sites. Is it necessary to reparametrize for each site? Would it be possible to calibrate the models such that there are only 3 PFTs for CRS strategies per site or for C3 and C4 grasses, and then fit some competition parameters such that the introduction of grazing or other disturbances modifies the fractional covers of those strategies in agreement with observations? This may provide a more general parametrization of the model I suggest to be more explicit about such aspects in the discussion.

The reviewer raises an interesting point. For this study we indeed calibrated 18 PFTs in total and doing so for a large number of sites and scenarios is infeasible. However, LPJmL has successfully been calibrated at the global scale in the past using a genetic optimization algorithm and remote sensing data (Forkel et al., 2014, 2019) and we believe this to be a promising approach.

We added “While separate calibrations are feasible for a small number of sites and scenarios, for large scale or global assessments the lack of data and the computational requirement for the calibration make a site-specific calibration infeasible. However, using a more efficient calibration method and remote sensing data instead of on-site experiments can be used to derive a set of PFTs which are representative of the entire globe or at least climatic regions. For LPJmL, a genetic optimisation algorithm has been used to successfully calibrate the phenology (Forkel et al., 2014) and vegetation dynamics (Forkel et al., 2019) of natural ecosystems. Following this approach, we believe it is possible to identify C-, S- and R-PFTs for the tropical, temperate and polar regions ending up with nine PFTs in total.” in L839-845.

One variable analyzed in the study is forage offtake. To me, this notation suggests that it is the biomass removed by mowing or grazing. This would then be a fixed value prescribed by the observations but not a modeled variable (unless grazing animals and their demand are simulated

dynamically). Yet, in the study offtake seems to be considered as variable simulated by the model. Does offtake represent the maximum amount of biomass that can be removed (representing maximum sustainable yield), or whether the demand of animals can be met? Please clarify.

Thank you for pointing this out. We defined forage offtake as the amount of biomass removed through mowing or grazing (L36f). In LPJmL mowing removes all biomass above a defined threshold while daily grazing removes biomass dependent on the feed demand of the livestock unit. Therefore, forage offtake is variable.

We added "[…] to determine forage offtake. While mowing removes all biomass above a threshold of 50 gCm^2, the forage offtake from daily grazing depends on the livestock units' feed demand (details in Appendix A5 and Rolinski et al., 2018)." in L157f to provide a brief overview and a reference to further literature.

Minor comments.
L4 delete "Especially"

Thank you. We accept the suggestion.

L54 consistent instead of uniform?

We made the replacement.

L62 traits instead of means?

Thank you. We accept the suggestion.

L 63 maybe "that influence the performance of different species"

Thank you. We accept the suggestion.

L 70 overall strategy of a community: reword? I'm not sure if a community has a strategy? Maybe say community composition?

In line with the CSR theory we changed "overall" to "average" (L71).

L 84 what is meant by "compare the CSR strategies"? Compare fractional cover of different strategies? Or classify species into one of these strategies?

To clarify, we changed "[…] a method to compare the CSR strategies of vascular plants […]" to "[…] a method to classify and compare the CSR strategies of different vascular plants […]" in L84.

L 99 not sure if it's necessary to highlight the soil module here (and not other important components such as ecophysiology or biogeochemical cycles)

Thank you. We accept the suggestion.

L103 management scenarios?

Thank you. We accept the suggestion.

L124 in the fractional cover of ...?

Thank you. We accept the suggestion.

L150, 151 mixture of "was" and "is", I suggest to check for consistency of tenses in ms

We reviewed the manuscript and changed the tense at several places (L152, L245, 250 and 254).

L170 delete "here"

Thank you. We accept the suggestion.

L170 dominant instead of advantageous?

The sentence the reviewer refers to is now in L174f. However, it already contained the verb “dominate” and did not make use of “advantageous”. We believe the reviewer wanted to refer to L183 and replaced “advantageous” with “dominant” here.

L189 based on PFC?

Thank you. We accept the suggestion.

L243 share the same properties: so all individuals are identical? Does recruitment imply heterogeneity of the population and some age and height structure?

No, as explained in L138ff, LPJmL uses an average individual approach which does not include heterogeneity of the population. To make this more explicit we changed “[…] that share the same properties […]” to “assuming a homogeneous population (i.e. individuals of the same PFT share the same properties)” in L247.

L250 prohibit infinite growth: but if space and resources are limited, plants shouldn't grow infinite. Why is it necessary to constrain growth? Isn't there saturation of growth as plant get taller, competition gets more intense or all cells ore occupied?

Thank you, we realized that the term “growth” is misleading in this context as it may easily be interpreted as plant growth. However, what we mean is that we limited the number of individuals per grid cell. We replaced “growth” with “increase” to avoid such a misconception (L256).

L271-272 if there is a stress gradient, then there is a large number of stress categories, why is it important that stress categories are not distinguished?

The stress gradient expresses the level of stress and is therefore not a gradient across stressors but across stress intensities caused by one or several stressors. We replaced “level” with “intensity” in L277 and rephrased “[…] but does not distinguish individual stress categories” to “[…] and can include the combined impacts of several stressors.” in L278 to increase clarity.

L277 a more general response to stress: this is vague, what is meant by a more general response?

We rephrased “[...] more general response to stress, […]” to “[…] general response to stress independent of the stressor, […]” in L284 to increase clarity.

L327 seedlings additional to what?

We mean additional to the already established plants. However, this is already clearly described by the term establishment and the word additional may lead to the interpretation that the model represent multiple different establishment processes. To avoid the misconception we deleted additional (L334).

L377 but ensured

Thank you. We accept the suggestion.

L390 made it impossible

Thank you. We accept the suggestion.

Fig 1 forage offtake instead of supply in panel a? Labels in c, d, i overlap (also in other figures). How were bias, phase and variance calculated? This should be mentioned in the caption or the methods.

We have updated the labels of figure 2 and added the equations for the components of the mean square error in the appendix (L996-1003) to which we refer in L393.

L368, 477 and elsewhere, the words "shifted" and "change". These words suggest to me that traits change during the simulations eg after switching on grazing. But these differences in trait values are the outcome of the calibration process and are therefore equilibrium or optimal trait values, right? I suggest to reword for example by saying the algorithm selected for less explorative strategies or that traits were lower/higher for grazing treatments.

We agree with the reviewer that this might be confusing to some reader and have reworded the ambiguous phrases in section 3.2 and 4.2.2. (L475ff, 479, 481f, 492f, 494 and 763)

Fig 2 replace abiotic and biotic by disturbance and stress

Thank you. We have updated the labels of figure 2.

L480, 481 reword secondary and primary role of traits?

We rephrased the respective sentences removing the terms primary and secondary role (L486f).

Fig 3 forage offtake instead of supply in a? Panel b) means that the same amount of biomass is removed each month in each year, do I interpret this correctly? Wy are the red an black line not identical in 2005 as the lines in e and f? Years in d and f overlap and can't be read.

Thank you for pointing this out. We have updated the label and x axis labels of figure 3. Indeed, in panel b) the values are the same for each timestep. As we explained in L549, the animal forage demand is always met in both scenarios. In panels d) to f) the colors show the different scenarios. In panel d) the red and black line represent the different fertilization scenarios which are already different before 2005. In panel e), black and blue distinguish the grazed and the ungrazed scenario which are also already different in 2005. Only at the cold steppe (f), both scenarios only start to differ in 2005. To make this clear, we added “For the temperate grassland and the hot steppe, the different management of the unfertilised and fertilised and ungrazed and grazed scenario led to differences in soil carbon before the first year shown in Fig. 4.” in L519f.

L680 equilibrium state instead of finality?

Thank you. We accept the suggestion.

L871 delete "existence of a"

Thank you. We accept the suggestion.

Additional changes

We replaced ecosystem functions with ecosystem services in L1, 4, 24, 26 and 36 and with ecosystem functioning and service provision in L34, 86 and 889.

Deleted “of permanent grasslands” in L26.

Added (Guuroh et al., 2018) in L35.

Added plant in L39.

Added active in L48.

Replaced (Milchunas and Lauenroth, 1993; Oesterheld and Loreti, 1999; Semmartin and Oesterheld, 1996) with (Ruppert et al., 2015) in L51.

Added the reference to (Buzhdygan et al., 2020) in L67

Removed pasture in L112.

Rephrased "[…]between large investments in reproduction but a small stature (R) and small investment […]" to "between plant species with large investments in reproduction but a small stature (R) from plant species with small investments" in L120f.

Added a reference to section 2.3 in L124.

Added (Scheiter et al., 2023) in Table 1.

Added "of a given grassland area" in L212f.

Replaced leave with leaf in L214.

Added resource in L217.

Added and "[…] age-related mortality is common in natural grasslands (Zimmermann et al., 2010),[…]"in L255f.

Replaced "such as embolism." with "such as drought or fire (Zimmermann et al., 2010)" in L259f.

Replaced "inherited" with "retained" in L265.

Changed functional plant traits to plant functional traits in L273f.

Replaced "that can be caused" by "and can be caused" in L276.

Replaced stress categories with stressors in L278.

Replaced leaf economic spectrum with LES in L280.

Replaced "that we simulated in our study" with "simulated by us" in L285.

Deleted "in this first application of LPJmL-CSR" in L285.

Added "standing" to the caption of figure 5.

Replaced "contained" with "also included" in L651.

Added (Scheiter et al., 2023) in L657 and L661.

Replaced "The R-PFT was better suited to withstand the grazing and out-competed the C-PFT in the grazed scenario due to its higher ability to deal with disturbances." with "The R-PFT was more tolerant towards grazing disturbances and gained dominance in the grazed scenario, replacing the C-PFT which had a lower ability to deal with disturbance." In L662f.

Replaced "[…] would increase the competition for light and space […]" with "would increase the competition for light due to self-shading effects (Zimmermann et al., 2010)[…]" in L 671.

Replaced "determined" with "led to biased" in L761.

Added "plant" in L889.

Replaced "including intermediate habitats" with "considering habitats with intermediate environmental conditions" in L892f.

References

Buzhdygan, O.Y., Meyer, S.T., Weisser, W.W., Eisenhauer, N., Ebeling, A., Borrett, S.R., Buchmann, N., Cortois, R., De Deyn, G.B., de Kroon, H., Gleixner, G., Hertzog, L.R., Hines, J., Lange, M., Mommer, L., Ravenek, J., Scherber, C., Scherer-Lorenzen, M., Scheu, S., Schmid, B., Steinauer, K., Strecker, T., Tietjen, B., Vogel, A., Weigelt, A., Petermann, J.S., 2020. Biodiversity increases multitrophic energy use efficiency, flow and storage in grasslands. Nat Ecol Evol 4, 393–405. https://doi.org/10.1038/s41559-020-1123-8

Forkel, M., Carvalhais, N., Schaphoff, S., v. Bloh, W., Migliavacca, M., Thurner, M., Thonicke, K., 2014. Identifying environmental controls on vegetation greenness phenology through model–data integration. Biogeosciences 11, 7025–7050. https://doi.org/10.5194/bg-11-7025-2014

Forkel, M., Drüke, M., Thurner, M., Dorigo, W., Schaphoff, S., Thonicke, K., von Bloh, W., Carvalhais, N., 2019. Constraining modelled global vegetation dynamics and carbon turnover using multiple satellite observations. Sci Rep 9, 18757. https://doi.org/10.1038/s41598-019-55187-7

Guuroh, R.T., Ruppert, J.C., Ferner, J., Čanak, K., Schmidtlein, S., Linstädter, A., 2018. Drivers of forage provision and erosion control in West African savannas—A macroecological perspective. Agriculture, Ecosystems & Environment 251, 257–267. https://doi.org/10.1016/j.agee.2017.09.017

Milchunas, D.G., Lauenroth, W.K., 1993. Quantitative Effects of Grazing on Vegetation and Soils Over a Global Range of Environments. Ecological Monographs 63, 327–366. https://doi.org/10.2307/2937150

Oesterheld, M., Loreti, J., 1999. Grazing, fire, and climate effects on primary produc- tivity of grasslands and savannas, in: Walker, L. (Ed.), Ecosystems of Disturbed Ground. Elsevier Science, Oxford, pp. 287–306.

Rolinski, S., Müller, C., Heinke, J., Weindl, I., Biewald, A., Bodirsky, B.L., Bondeau, A., Boons-Prins, E.R., Bouwman, A.F., Leffelaar, P.A., te Roller, J.A., Schaphoff, S., Thonicke, K., 2018. Modeling vegetation and carbon dynamics of managed grasslands at the global scale with LPJmL 3.6. Geosci. Model Dev. 11, 429–451. https://doi.org/10.5194/gmd-11-429-2018

Ruppert, J.C., Harmoney, K., Henkin, Z., Snyman, H.A., Sternberg, M., Willms, W., Linstädter, A., 2015. Quantifying drylands' drought resistance and recovery: the importance of drought intensity, dominant life history and grazing regime. Global Change Biology 21, 1258–1270. https://doi.org/10.1111/gcb.12777

Scheiter, S., Pfeiffer, M., Behn, K., Ayisi, K.K., Siebert, F., Linstädter, A., 2023. Managing southern African rangeland systems in the face of drought - a synthesis of observation, experimentation, and modelling for policy and decision support, in: von Maltitz, G.P., Midgley, G.F., Veitch, J., Brümmer, C., Rötter, R.P., Viehberg, F.A., Veste, M. (Eds.), Sustainability of Southern African Ecosystems under Global Change, Ecological Studies. Springer.

Semmartin, M., Oesterheld, M., 1996. Effect of Grazing Pattern on Primary Productivity. Oikos 75, 431–436. https://doi.org/10.2307/3545883

Zimmermann, J., Higgins, S.I., Grimm, V., Hoffmann, J., Linstädter, A., 2010. Grass mortality in semi-arid savanna: The role of fire, competition and self-shading. Perspectives in Plant Ecology, Evolution and Systematics 12, 1–8. https://doi.org/10.1016/j.ppees.2009.09.003