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Geoscientific Model Development Discussions

Interactive comment on "Modeling vegetation and carbon dynamics of managed grasslands at the global scale with LPJmL 3.6" *by* Susanne Rolinski et al.

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Overview

This manuscript describes the implementation of 3 new grassland management options into the dynamic vegetation model LPJmL. The new grassland management options were set up in order to model the major ways of how grasslands are managed worldwide. These options were parametrized using reference values from the literature. Then, global simulations of LPJmL over the period 1901-2009 with a daily time step are conducted. The results show global maps of simulated grass growth (NPP), harvest and soil carbon values for the different grassland management options. Then,

observed grassland harvest data for Europe were used for comparison to simulated values. Lastly, a sustainable potential livestock density map is drawn, depicting the optimal livestock unit density which allows maximum simulated harvest. In the last section (discussion), global results are discussed and compared to other findings in the literature, and perspectives for global simulations are presented.

The paper is nicely written and well structured. It is well-sourced with relevant references in the introduction, the methods (where references values are used for designing the management options) and in the discussions. Figures are well done, although a better choice of some colour scales could be made. It presents new interesting features for grassland modelling with LPJmL, and for the wider DVGM community. Beside the particular issue of the calibration/validation, this paper is nearly ready for publication in GMD.

We thank the reviewer for the constructive feedback. Our responses are inserted below, following their original comments.

General comments

No calibration/validation: This paper presents an implementation of grassland management techniques but no calibration of the model parameters is presented. Though a database of direct observations of grassland productivity at the global scale is not existing, some indirect global products may help to somehow calibrate and validate the approach. For instance, LSUmax densities appears too optimistic in arid areas compared to existing database on livestock densities (see next remark). In particular, a global map of grassland areas (from Globcover for instance) might be used to validate the extent of grassland in arid areas. Validation is presented but only for Europe and only for one of the grazing options. This should be addressed or better discussed in the manuscript.

We agree that an evaluation of model results is important and not well covered in the paper due to lack of good reference data. We will discuss this more thoroughly in the discussion section (section 4.2). For similar reasons, we chose not to calibrate any of the literature-based parameters. The observed extent of grassland is not a good reference as it is a) subject to uncertainties in delineating it from forests/shrubland/fallow land and b) the model does not predict the extent of grassland but its productivity and carbon/water balance. In the simulations conducted here, we prescribe 100 % grassland to all land area to analyze spatial patterns of grassland productivity and dynamics rather than identifying their actual extent.

Nevertheless, we see the need to make parameter choices better comprehensible and compare results better to existing estimates. We will tackle this by 3 major changes:

- We will include better references to the parameter discussion in 4.2 at the beginning of the results section such as:
  'The effect of the harvest options are described for grass yield, NPP, and total soil carbon of the 3 m soil column and analyzed with respect to the underlying processes (see also discussion on strengths and weaknesses of the chosen approach in section 4.2).'
- Section 3.2 will be rewritten completely so that the comparison with reported grass yield now serves the purpose to evaluate the spatial distribution of different management options and the probability of the applied management for the reported values. We test 3 hypotheses, namely if 'European grass harvest
  1. can be achieved by grazing animals only,
  2. is determined by management and only to a minor degree by climate and
  3. per geographical entity, a dominant management option can be identified that results in similar harvest values as reported.'

  by analyzing different selections from the simulation results. This allows to check the value range within the results and the plausibility of the distribution of management options in Europe although a detailed dataset does not exist.

- The calculation of potentials will be complemented as described below.

Figure 14 & Sustainable potentials: I'm rather surprised of the LSU$_{max}$ densities values in the global map of Fig. 14. It seems that LSU$_{max}$ densities are overestimated in many arid regions. For instance, all of Morocco area has a LSU$_{max}$ value around 1, while this country is partly covered by arid deserts where no cattle grazing is possible (except in small irrigated areas). IMHO, LSU$_{max}$ values seems also overestimated in Lybia, central Australia & Saudi Arabia. I understand that the LPJ simulations do not take into account all processes involved in land degradation (such as historical overgrazing) but the grasslands production in arid regions seems clearly overestimated. In order to quantify this, it would be interesting to compare grassland production and/or livestock densities with other database. Robinson et al. PloS One, Mapping the Global Distribution of Livestock, 2014 and the companion website http://livestock.geo-wiki.org/ provides livestock densities data worldwide. I understand that Fig. 14 presents a potential maximal LSU (i.e., with 100% of land use affected to grasslands), but a comparison of your findings to the geo-wiki database (or others) would allow to somehow validate your findings about sustainable potentials. Maybe your model parameters should be adapted in order to reflect a better view of grass production in arid areas.

We see that the term LSU$_{max}$ was ambiguously used and not well framed. These numbers represent the livestock density under which the maximum grass yield is obtained and in most areas this number is not the livestock density that can be fed by the grass, i.e. that livestock density would need supplement feed from elsewhere. This is especially true in the arid regions mentioned. Here, short rain events allow grass growth for a short vegetation period. Grass harvest under these conditions are highest with a moderate to high LSU, owing to the feedback from grazing on productivity (LAI, respiration). But the harvest itself is very low (mean $\pm$ standard deviation are for Libya 9$\pm$15, for Morocco 73$\pm$42, for Australia 80$\pm$73 and for Saudi-Arabia 6$\pm$9 gC m^{-2}). Therefore, we choose a different name for this variable with LSU$_{harv}$ suggesting that this livestock density is optimized with respect to the obtained harvest.

We will adjust the description in section 2.6.2 with the new title
'Determination of harvest potentials under G_D'
and describe the number of LSU that can actually be fed exclusively LSU$_{feed}$ at the end of the paragraph with
'To obtain the maximum livestock density that can be fed with the grass available throughout the year, the maximum livestock density is chosen under which harvest meets the demand. LSU$_{feed}$ is thus maximized with respect to the livestock that can be supported by the local grass production.'

For LSU$_{feed}$, the result is included as Figure 14b (Fig. 1) and described in the text with 'The distribution of the maximum livestock density that can be fully supported by the local grass production (LSU$_{feed}$) (Fig. 14b) differs from LSU$_{harv}$ especially in arid regions like inner Australia, North Africa, western North America and the Middle East where values close to 0 LSU ha^{-1} are derived for LSU$_{feed}$. Also in polar areas in North America and Asia (region 1 in Fig. 2), values for LSU$_{feed}$ are reduced considerably. Even though grass productivity can be high in parts of the year, this is not sufficient to continuously supply the feed demand of higher livestock densities.'

In addition, we will compare LSU$_{max}$ and LSU$_{feed}$ to actual livestock densities LSU$_{fao}$ as given by Robinson et al. (2014) as Figure 14 c (Fig. 2). These combine all ruminant animals and livestock production systems so that the distribution of pastoral and mixed systems has to be considered for the analysis. We will also discuss possible mismatches where local feed supply is not sufficient, as also highlighted by Herrero and Thornton (2013).

Specific comments

- *P3L1: Title of section 1.2 (Representation of managed grasslands in DVGMs) is misleading because the section only states about representation of managed grasslands in LPJ and ORCHIDEE (that partly originates from LPJ). There are no discussions about how this is done in other DVGM, if any.*

To our knowledge, only ORCHIDEE and LPJmL do have managed grassland representations. We state that now clearly at page 3 line 14:
'To the knowlegde of the authors, managed grasslands are not represented in further DGVMs.'
If required or appropriate, we include the chosen approaches of DGVMs such as CLM or JSBACH for pasture areas.
'The Community Land Model (CLM) treats pasture in the version with representation of agricultural activity (CLM-Crop, Drewniak et al., 2015) as natural grassland without harvest procedure whereas JSBACH (Reick et al., 2013) simulates fire disturbances on grassland but no other harvest is taken into account.'

- *P3L8: There is no adequate description of the way managed grassland was simulated so far in LPJ. The statement "It has been represented as grassland ecosystem with human management" is too vague.*
We agree although we have a little problem here. In the description of the implementation of agricultural activities by Bondeau et al. (2007), the focus was on the description and parametrization of the crop functional types. Grassland was introduced as agricultural activity with a productivity-dependent removal from the aboveground carbon pool and daily allocation. There were no specific descriptions of e.g. allocation rules. When the code was transferred from C++ to C, the implementation of managed grassland was changed but not documented in a further publication. Thus, we aim at a first detailed description of managed grassland in LPJmL in this paper without going into details of the prior unpublished implementation. We would like to avoid a detailed description of the now obsolete implementation. Obviously, this approach is not satisfying so that we will exchange lines 8 to 10 in section 1.2 to
'It has been implemented as grassland ecosystem with a harvesting rule. Grass plants grew and competed for light and water. Harvest was depending on grass productivity solely. When more than 100 gC m^{-2} was assimilated since the last

harvest event, half of the aboveground carbon pool was removed. Assimilated carbon was allocated to leaves and roots prior to harvest and at the end of the year following the rules for natural grasses.'

- *P3L15-19: At this stage of reading, there is a contradiction about the number of management options that were implemented: is it 3 or 4? The reader understands only later that there 3 new options + 1 default option.*
  We will clarify from the beginning that we are describing 4 management options. The default option that was applied before is also reformulated within the development of the 3 new options so that they should be mentioned as a group of 4 options. The only distinction of the default setting is the possibility to apply it without further knowledge on the distribution of grassland management. This will be taken up in the entire manuscript.

- *P3: The objective(s) of the manuscript is (are) explained on L27-32 but they could be more clearly defined, maybe using bullets points. Is it to test/calibrate/validate the implementation of new functionalities in the simulation of managed grasslands? To evaluate the importance of accounting for grassland management in NPP global estimation?*
  We see the point and will exchange lines 27-30 by
  'Without being able to represent actual grassland management at this stage, we are aiming with this implementation at the following objectives:

  - a much better representation of the diversity in grassland management at the global scale in model simulations of agricultural productivity and biogeochemical cycles,
  - a demonstration of the role of grassland management for biogeochemical simulations by analyzing the effects on Net Primary Productivity (NPP) and soil carbon stocks,

  - an assessment of potentials of agricultural productivity by determining maximum harvest and the associated livestock densities with and without the condition of maintaining soil carbon stocks.
  - to evaluate model performance by comparing simulated harvest with a European data set (Smit et al., 2008) and potential livestock densities with data from the Gridded Livestock of the World v2.0 (Robinson et al., 2014).'

- *P6L24-30: The way the model reacts after an harvest event is central to the modelling of mowing. More details or explanations on the feedbacks could be interesting. For instance, how much time does it takes to the photosynthetic activity to recover from the cut (in general)? Is some transfer of C from roots to leaves after a cut simulated?*
  The recovery period depends on the climatic conditions since they determine net primary productivity from the actual leaf carbon content. We follow the common rules for allocation of assimilated carbon as described in section 2.3.2 which have two consequences for the period after a mowing event: very low leaf carbon reduces NPP but lower leaf biomass that still intercepts large fractions of incoming light may also enhance NPP, as the maintenance respiration is reduced more strongly than the light interception. We will extend the methods section 2.3.2 by a more detailed description of the water limitation of photosynthesis and include the sentences:
  'After a harvest event, leaf carbon and thereby lr is reduced. Carbon allocation in the following period will try to reestablish the actual leaf to root mass ratio lr. Depending on the water supply to demand ratio, the assimilated carbon is incorporated more or less to the leaves so that the actual water conditions determine the recovery time of the leaves. A 10 % reduction of the water supply alone would result in a slower recovery time of several days and leaves would have less carbon when the new lr is established. Even more important is the feedback on primary productivity connected to the leaf carbon content.'

and at the end of the paragraph:
'This dependency of light absorption and photosynthesis on leaf carbon content leads to a negative feedback of harvest on absorbed radiation. When leaf carbon is reduced to 50 %, the reduction of fAPAR is about 30 % for $L = 100$ gC m^{-2} and is diminished to 2 % for $L = 500$ gC m^{-2}.'

- *P6L27 or eq. (3): SLA units are missing.*
  We will include 'SLA in m^2 gC' in the brackets in line 27.

- *P7L8-10: IMHO, many pastures worldwide cannot be mowed (by machines) because of impractability (very steep pastures, presence of stones/trees, non-portable soil because it is too wet, : : :).*
  Thank you for the suggestion. We change the second sentence in line 9 to:
  'When mowing is not an option due to the steepness of the landscape, soil wetness or obstructing trees and boulders, grazing by smaller ruminants might still be possible but mowing and grazing by livestock are often used in combinations.'

- *P10 & Fig. 2: What are the rationales behind this climate classification? Why not using classical classification such as the one of Köppen?*
  With this classification, we try to connect the maps (e.g. Fig. 3) and the figures (e.g. Fig. 4). The chosen thresholds are motivated by the values in the climate response figures. Especially region 6 evolved because there the NPP increase with increasing livestock densities (Fig. 9) prevailed. I am not aware that the Köppen Geiger classification would serve the same purpose being much more detailed and including seasonality characteristics. To better motivate the chosen thresholds we change the sentence page 10 lines 22 to 24 to
  'Ranges of temperature and precipitation for which grassland management results in similar changes in the carbon dynamics are classified as bioclimatic regions (Fig. 2 a) only for a better visualization of locations of similar climatic conditions (Fig. 2 b).'

- *P23 L29-30: I suggest to move this sentence at the beginning of the section 4.1.*
  Done.

- *P23 L33: I would not say that the comparison with European grassland data showed "good agreement".*
  We see the point and have 2 remarks:

  - Unfortunately, the determination of the average harvest per geographical unit was incorrect and mostly a bit too low. With the corrected version, the correlation in Figure 12c increases from 0.8 to 0.88 and the standard deviation from 65 to 78 gC m^{-2} which is closer to the presented data. Additionally we include a third selection of simulation results that gives a correlation of 0.9 with a standard deviation of 93 gC m^{-2}.
  - We rewrite the whole section and concentrate on the plausibility of management distributions (see above) because the assumptions on management were homogeneous in the simulations which is definitely not the case in Europe. We state that in the beginning with
    'Since management assumptions for the simulations were spatially homogeneous and management in Europe is known to vary spatially as well as temporally, we use the comparison to find out whether climate- and management-induced variations in grass harvest can be captured by the applied options.'

- *P25 – 4.3 Further developments: This paper lacks of further validation. I would suggest to add in this section as a perspective a short review of literature about the use of remote sensing data to further validate the implementation of grassland management options. For instance, although I did not find adequate references, change detection techniques based on remote sensing data can detect hay mowing. More well-known is the use of vegetation indices derived from remote sensing data to estimate standing biomass.*

We thank the reviewer for mentioning this point. We know of the approach of the group of Patrick Hostert at Humboldt University Berlin to identify the timing and extent of deforestation events from satellite data (Kuemmerle et al., 2013; Joshi et al., 2016) and were in contact to explore possibilities to extend the methods on grasslands. So far, we are not aware of already undertaken attempts to relate remote sensing analysis to grass harvest but we would be very interested in such approaches. Since we also did not find respective references, we would like to include this aspect in the first paragraph of discussion section 4.3:
'A promising approach to extract cutting events on grassland from remote sensing data could be the time series analysis as applied for the detection of deforestation events (Kuemmerle et al., 2013; Joshi et al., 2016).'

- *P 26 - 5. Conclusions: The "Conclusions" section is short and does not present key numerical results. This could be improved.*
  We will extend the conclusions and relate the discussed topics back to the now formulated objectives of the manuscript. The outline would be like this:
  'The presented implementation of grassland management in the DGVM LPJmL captures the substantial diversity of possible management practices. Our results highlight the importance of management to understand and quantify feedbacks between biomass removal on global pastures and net primary production (NPP), carbon fluxes and soil dynamics. We investigated the effect of different management practices on the global terrestrial carbon budget and found that yield and productivity of herbaceous plants show feedbacks with the development of soil carbon under different climatic conditions that are consistent with regional studies and theory. Moreover, we can reproduce many non-linear and climate-dependent effects of livestock density and grazing intensity on biochemical cycles, as evidenced in various field studies. The magnitude of simulated impacts of the proposed grassland management options on biochemical processes and fluxes underlines the relevance of grassland management for assessing implica-

tion of agricultural activities for the global carbon balance.
  Our results on the distribution of livestock density that triggers maximum grass harvest, as well as the maximum livestock density that can be supported by local grass production, quantify the influence of local climatic conditions on agricultural productivity, where we additionally consider the impact of these practices that exploit the full biomass harvest potential on soil carbon stocks. Comparison of simulated grass harvest under different grazing options with European grassland productivity (Smit et al., 2008) reveal that best agreement with observed grass yields can be achieved assuming heterogeneous livestock densities.
  Managed grasslands are still heavily under-researched in terms of global distributions of grazing livestock and wild herbivores and the implications of overgrazing in boreal and polar regions. With the model extension presented, the DGVM LPJmL can also contribute to the assessment of the ecological 'hoofprint' of livestock. Here, simulations of potential grass yields and the effects on soil carbon stocks may help to frame guidelines for sustainable grassland management and to better understand the implications of livestock production and climate mitigation targets.'

- *Fig. 3: Suggestion: The colour scale of figure 3 is a divergent colour scale but should be changed into a sequential colour scale, as in Fig. 12. Sequential colour scale might be easier to interpret, are color-blind & black/white print friendly, and fits to the grass harvest, NPP and soil carbon variables, which are sequential variables. However, the divergent colour scales in Figs. 5 b-c, 7 b-c, 10 b-c are OK since differences in NPP and soil carbon between options are divergent variables.*
  We will change the color scale for all maps showing absolute values (now figures 3, 5a, 7a, 10a, 14).

- *Fig 4: Incoherence of scales: Fig. 4 a) scale for grass harvest is from 0 to 500 gCm-2 while Fig. 3 a) scale is 0-800 gCm-2.*

This incoherence is caused by the averaging of values shown in Fig. 4a. The scales are chosen to be representative for comparable variables (e.g. Figs. 5b, 7b and 10b or 5c, 7c and 10c) and deviating values are given in the text (e.g. page 12 line 24). To compute values shown in the climate response plots, these are averaged for same temperature and precipitation bins.

Editorial comments

- *P3L21: ": : : to that in (Bondeau et al., 2007), ..." should be ": : : to that in Bondeau et al. (2007), ..."*
  Right, done.
- *P3L29: Suggestion (not sure): "...we compare the data with..." should be ": : : we compare the simulations with..."?*
  Right, done using the term 'simulation results'.
- *P17L7: Seems there is a space missing between "manure." and "When".*
  Right, done.

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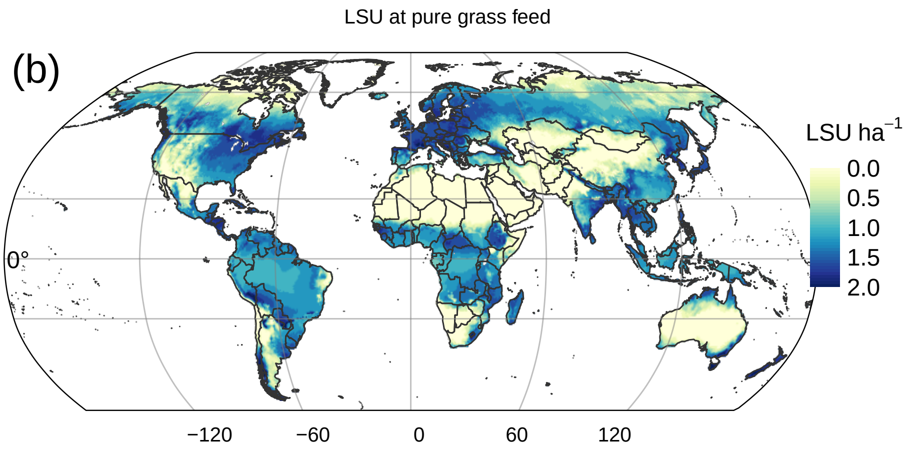

Fig. 1. Distribution of maximum livestock densities that can be fed purely on the local grass harvest (LSU$_{feed}$ in LSU~ha^{-1}) under harvest option G$_D$ averaged over the years 1998 to 2002.

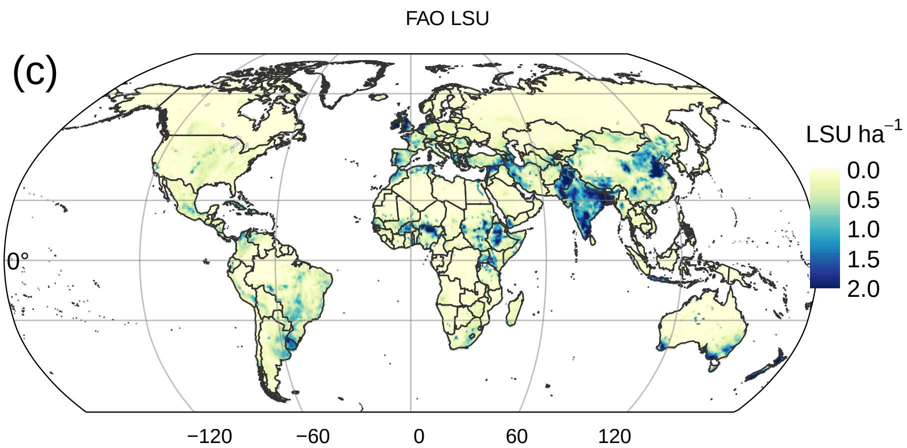

Fig. 2. Distribution of ruminant livestock densities as reported by FAO (LSU$_{fao}$ in LSU~ha^{-1}).