***Interactive comment on* "Combining livestock production information in a process based vegetation model to reconstruct the history of grassland management" *by* J. Chang et al.**

Anonymous Referee #2

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General comments: This study attempted to reconstruct the history of grassland management by integrating grazing-ruminant stocking density maps, wild-herbivores population density maps, nitrogen fertilizer application maps as well as nitrogen deposition maps to develop grassland management intensity maps. This land use information is very important to global change studies and very interesting as well. The attempt of integrating those scattered data in various scales is valuable even though the methods might be over-simplified. The manuscript, however, poorly delivered this information. I think the title of this manuscript delivered interesting and clear information about the study, but the main text lost focus that were specified in the title and the abstract. The method sections (in both the main text and the SI) are very confusing and could be more organized. Some descriptions on modeling or calculation were unnecessarily complicated, and some assumptions for extrapolating data need to be checked carefully. Overall, the current version requires major revisions before considered for publication.

[Response] We thank the reviewer for the valuable comments. Please find our detailed responses below each comment in blue. The corresponding major modifications in the revised manuscript were attached as Appendix A1-A3, Figure A1 and Table A1.

[Comment 1] (1) 'Results' and 'Discussion' of the current version made this manuscript read like evaluating the performance of the updated version of ORCHIDEE-GM model that includes livestock data to estimate global grass biomass. The model is a key piece in this study, which generates the NPP and GPP, but it seems the goal of this study is actually 'combining livestock production' and 'to reconstruct the history of grassland management'. If so, the main text should be reorganized. The evaluation-related sections could be combined.

[Response] Thanks for the suggestions. In order to stick to the goal of this study, we have revised the manuscript through 1) reorganizing section 2.4 - 2.6 to present the procedures of reconstructing grassland management intensity maps more clearly; 2) combining method sections on model evaluation to one subsection 2.7; 3) the model evaluation sections (section 3.2, 3.4 – 3.6 in the previous manuscript); and 4) shortening the discussion on model evaluation (section 4.3).

[Comment 2] (2) The model-related descriptions in the 'Material and Methods' section are not clear. At page 4 line 28-32, it is not clear what was updated in the model v3.1. Only bug-corrections? Are there any updates in modeling ecological processes or management activities?

[Response] In the version 3.1 of ORCHIDEE-GM, we made the adjustment of its parameters for the C4 grassland biome (Sect. 2.2), and implemented a specific strategy for wild animal grazing (Sect. 2.3). Furthermore, in the revised manuscript, version 3.1 has been updated with ORCHIDEE Trunk.rev2425 (a recent version of ORCHIDEE). The above information has been added in the section 2.1 of the revised manuscript.

[Comment 3] (3) At page 5 line 22-25, the author listed the input data, but the output was never clearly described in the manuscript. This information may be described in previous publications, but it would be good to briefly describe in this manuscript. Line 12-15 at page 7 reads like descriptions of output, but confusing. I think this part is very important as it is related to how the authors defined and quantified 'management intensity', so it needs to be clearly presented.

[Response] We have reorganized the sections in the revised manuscript to clarify the model input (section 2.4), simulation set-up (section 2.5), and the procedures for reconstructing management intensity history (section 2.6). Moreover, we have added a new flowchart (Fig. A1) illustrating the procedures for reconstructing management intensity history, and a table listing all variables shown in the method section (including abbreviation, units, related equations, and data sources). We believe that the flowchart and the revised section 2.4-2.6 presented the reconstruction of the grassland management intensity maps in a more comprehensive way than before.

[Comment 4] (4) Does '. . . not use a land-cover map in the simulations, but rather consider that grasslands are distributed all over the world' mean the areas that are not characterized as grassland in a land-cover map have zero grass productivities in your productivity maps?

[Response] During post-processing, the grids with zero grassland in the land-cover maps ($A_{grass,m,k} = 0$) will be masked, thus will have zero grass productivities in the productivity maps as shown in Fig. 2 in the previous manuscript. This clarification has been added in the section 2.5 'Simulation set-up' of the revised manuscript.

[Comment 5] (5) Line 14-15 at page 8, how the Ygrazed is calculated from Dgrazing,m,k? I think this is a key step of this study and should be described clearly. [Variables, equations and data conversions] There are many equations and data conversions in this manuscript. The authors should define variables clearly and present units for important variables (e.g. D in text S2), so that the readers can easily follow the ideas of producing those data sets. Or, a table listing those variables and associated data sources might be helpful.

[Response] Thanks for your suggestion. We added the description about how the model calculates the Y_{grazed} and Y_{mown} in the revised manuscript to clarify this key step (as Appendix A1). We also added a new table listing all variables shown in method section, including abbreviation, units, related equations, and data sources (Table A1).

[Comment 6] (6) I think the assumption at Line 4-5 at page SI_3 might be wrong as the ratio of the total ruminant density between years can be calculated based on the assumptions in text S2. I could be wrong, but I think the authors should carefully check the conversion and should not make too many assumptions arbitrarily as this might affect the results significantly. A brief interpretation of my thoughts: see the supplement for equations and calculations.

[Response] Thank you for the comment. Yes, you are right about the calculation. We should calculate the gridded ruminant density ($D_{m,k}$) variation and gridded grass biomass use ($GBU_{m,k}$) based on the category-specific variation of metabolisable energy (ME) requirement in the country rather than the changes in country-scale total ME requirement. Thus we have modified all related calculations

(including $D_{m,k}$, $D_{grazing,m,k}$, and $GBU_{m,k}$), re-run all simulations, and re-calculate gridded management intensity history based on modified calculation. In the revised manuscript, the calculations of $D_{m,k}$ and $GBU_{m,k}$ have been changed as Appendix A2 and Appendix A3 respectively. The gridded ruminant density ($D_{grazing,m,k}$) has been re-calculated based on modified $D_{m,k}$, while the description of calculation is the same as that in the previous manuscript.

[Comment 7] (7) This point may be trivial, so it is just a suggestion. I don't think the variable of ME index (Im,j, page 8 and page SI_3) is really necessary unless the ME index has some other meanings. The assumptions seemed just to be: see the supplement. The ME index made the conversions more complicated than it should be.

[Response] Thanks for the suggestion. Yes, the ME index ($I_{m,j}$) is not necessary, and might complicate the conversions. Thus we have deleted it in the revised manuscript.

Appendix A1: Calculation of Y_{grazed} and Y_{mown} in ORCHIDEE-GM v3.1

The effective yield on grazed grassland (Y_{grazed}, unit: kg DM m^{-2} yr^{-1} from grazed grassland) depends on the grazing stocking rate (here, $D_{grazing}$) and on the environmental conditions of the grid cell (Chang et al., 2015a), and calculated as:

$$Y_{grazed,m,k} = IC \times T_{grazing,m,k} \times D_{grazing,m,k}$$

where IC is the daily intake capacity for 1 LU (~ 18 kg dry matter per day calculated in Supporting information Text S1 of Chang et al., 2015b), $T_{grazing,m,k}$ is the number of grazing days in grid cell k at year m. Due to the impact of livestock on grass growth through trampling, defoliation (i.e., biomass intake) etc., and because grassland cannot be continuously grazed during the vegetation period, thresholds of shoot biomass are set for starting, stopping and resuming grazing (Vuichard et al., 2007). The 'recovery' time required under grazing is obtained in the model using threshold (Vuichard et al., 2007; Chang et al., 2015a), which determine when grazing stops (dry biomass remaining lower than 300 kg DM ha^{-1}), or when grazing can start again (dry biomass recovered to a value above 300 kg DM ha^{-1} for at least 15 days. Under mowing, the frequency and magnitude of forage harvests in each grid cell is a function of grown biomass (Vuichard et al., 2007). $Y_{mown,m,k}$ (unit: kg DM m-2 yr-1 from mown grassland) is the annual total harvested grass biomass.

Appendix A2: Calculation of the historical changes of ruminant stocking density (D)

Domestic ruminant numbers, and therefore stocking density, are continually changing from year-to-year as reported in FAOSTAT (2014). However, GLW v2.0 only provides livestock density for the reference year (i.e., 2006). To establish the historic changes of ruminant density from 1901 to 2012, two assumptions were made: 1) the distribution of ruminant density did not change during the time-span of this study (1901 - 2012); and 2) the changes in the ruminant density of each category in grid-cell k in country j ($D_{m,j,k}$) co-varied with the changes in category-specific ME requirement in that country. Thus the total ruminant density for grid-cell k in country j in year m ($D_{m,j,k}$) is calculated as:

$$D_{m,j,k} = \sum (D_{ref,i,j,k} \times \frac{ME_{m,i,j}}{ME_{ref,i,j}})$$

where $D_{ref,i,j,k}$ is the ruminant density of category i for grid-cell k in country j in reference year (i.e., 2006); $ME_{m,i,j}$ and $ME_{ref,i,j}$ are the total ME requirement by ruminant category i for country j in year m and in the reference year 2006 respectively. The method to calculate ME requirement is given in Supporting Information Text S1 of Chang et al., 2015b. Here, the range of year m is from 1961 to 2012, since FAOSTAT (2014) provides annual country-averaged statistical data for dairy cows, beef cattle, sheep and goats of livestock numbers (with the unit in head), and meat (carcass weight) or milk yield for the period from 1961 up to the present day.

For the period 1900-1960, regional livestock numbers by 10-year interval derived from Mitchell (1993, 1998a,b) were scaled in 1961 to match the FAOSTAT data (data processed by Dr. Kees Klein

Goldewijk, and given for 17 world regions with the numbers of cattle, sheep and goats; available in the HYDE database: http://themasites.pbl.nl/tridion/en/themasites/hyde/landusedata/livestock/index-2.html). The 17 world regions were designated for global change research, as defined by Kreileman et al. (1998). Linear interpolation is applied to calculate the regional livestock numbers of each year. Assuming the meat (carcass weight) and milk yield for the period of 1900-1960 are the same as that for 1961 from FAOSTAT (2014), total ruminant density for grid-cell *k* in region *q* in year *m* ($D_{m,p,k}$) is then simply extended to 1900-1960 through:

$$D_{m,q,k} = \sum (D_{ref,i,q,k} \times \frac{ME_{m,i,q}}{ME_{ref,i,q}})$$

where $D_{ref,i,q,k}$ is the ruminant density of category i for grid-cell k in region *q* in reference year (i.e., 2006); $ME_{m,i,q}$ and $ME_{ref,i,q}$ are the total ME requirement by ruminant category i for region *q* in year m and in the reference year 2006 respectively.

Appendix A3: Calculation of the historical changes of grass biomass use (*GBU*)

Herrero et al. (2013) established a global livestock production dataset containing a high-resolution (8 km × 8 km) gridded map of grass-biomass use for the year 2000. In this study, this dataset is extrapolated onwards in time from 2000 to 2012 and backwards in time from 2000 to 1901 to constrain the grass-biomass consumption in ORCHIDEE GM v3.1 in order to establish historical changes in the spatial distribution of grassland management intensity. Assuming that grass-biomass use for grid cell *k* in country *j* and year *m* ($GBU_{m,j,k}$ in kg dry matter (DM) per year) varies proportionally with the domestic ruminants density in the same grid-cell, $GBU_{m,j,k}$ can be calculated from its value during the year 2000 given by Herrero et al. (2013), according to :

$$GBU_{m,k} = GBU_{2000,k} \times \frac{D_{m,k}}{D_{2000,k}}$$

where $D_{m.k}$ and $D_{2000,k}$ are the total ruminant stocking density for grid-cell *k* in year *m* and in year 2000 calculated by Eqn S4 and S5 in Supplementary information Text S1, which take into account the changes in category-specific ME requirement at country-scale (1961-2012) or regional-scale (1901-1960).

Figure A1 and Table A1:

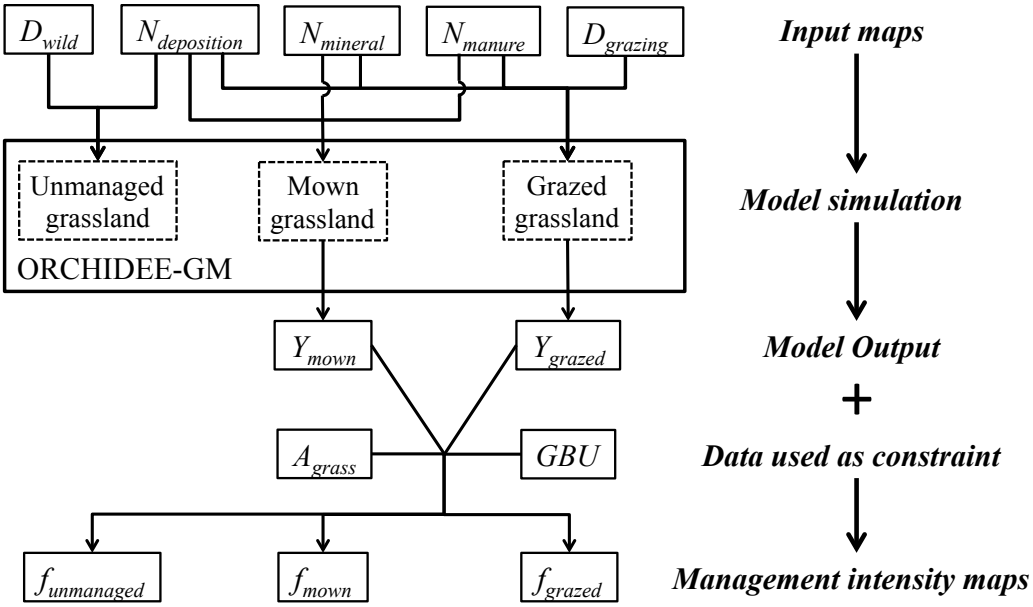

Figure A1. Illustration of the procedures for reconstructing management intensity maps. Italic texts indicate the major steps of the reconstruction. The meanings, units, related equations, and data sources of the variables (i.e., gridded maps) are shown in Table 1. $D_{grazing}$, grazing-ruminant stocking density; D_{wild}, wild herbivore density; N_{manure}, organic (manure) nitrogen fertilizer application rate; $N_{mineral}$, mineral nitrogen fertilizer application rate; $N_{deposition}$, atmospheric-nitrogen deposition rate; Y_{mown}, annual potential harvested biomass from mown grasslands; Y_{graze}, annual potential grazed biomass from grazed grasslands; GBU, grass biomass use; f_{mown}, minimum fraction of mown grassland; f_{grazed}, minimum fraction of grazed grassland; $f_{unmanaged}$, maximum fraction of unmanaged grassland.

Table A1. The abbreviations, units, related equations, and data sources of the variables shown in this study.

Abbreviations[a]	Variables	Units[b]	Related Equations	Sources
D	Domestic ruminant stocking density	LU per ha of land area	Eqns 1, 2, S3, S4, S5	Robinson et al., 2014; FAOSTAT, 2014
$D_{grazing}$	Grazing-ruminant stocking density	LU ha^{-1}	Eqns 1, 3	Robinson et al., 2014; FAOSTAT, 2014; Bartholomé and Belward, 2005; Eva et al., 2004; Poulter et al., 2011; Hurtt et al., 2011
D_{wild}	Wild herbivore density	LU ha^{-1}	Eqn S6	Synthesiezed by Bouwman et al., 1997
N_{manure}	Organic (manure) nitrogen fertilizer application rate	kg N ha^{-1} yr^{-1}	Eqns S7, S8	Synthesiezed by Bouwman et al., 2002a, b
$N_{mineral}$	Mineral nitrogen fertilizer application rate	kg N ha^{-1} yr^{-1}	Eqns S9	FAO/IFA/IFDC/IPI/PPI, 2002
$N_{deposition}$	Atmospheric-nitrogen deposition rate	kg N ha^{-1} yr^{-1}		Hauglustaine et al., 2014
GBU	Grass biomass use	kg DM yr^{-1}	Eqns 2, 4, 7	Herrero et al., 2013; FAOSTAT, 2014
Y_{mown}	Annual potential harvested biomass from mown grasslands	kg DM m^{-2} yr^{-1}	Eqns 7, 10, 11	this study
Y_{graze}	Annual potential biomass consumption over grazed grasslands	kg DM m^{-2} yr^{-1}	Eqns 3, 4, 7, 10, 11	this study
A_{grass}	Grassland area	m^2	Eqns 4, 7	Bartholomé and Belward, 2005; Eva et al., 2004; Poulter et al., 2011; Hurtt et al., 2011
f_{grass}	Grassland fraction	Percent (%)	Eqns 1	Bartholomé and Belward, 2005; Eva et al., 2004; Poulter et al., 2011; Hurtt et al., 2011
f_{mown}	Minimum fraction of mown grassland	Percent (%)	Eqns 5, 7, 8, 10, 11	this study
f_{grazed}	Minimum fraction of grazed grassland	Percent (%)	Eqns 4, 6, 7, 8, 10, 11	this study
$f_{unmanaged}$	Maximum fraction of unmanaged grassland	Percent (%)	Eqns 6, 9, 10, 11	this study

[a] the subscripts of these variables in this study: i, ruminant category; j, country; k, grid cell; m, year; q, region.

[b] if not specified, the ha^{-1} (or m^{-2}) in the units indicate per ha (or per m^2) of grassland area.