***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 #1

Received and published: 31 March 2016

The manuscript estimates globally the historical management intensity of grasslands. Thereby, authors use the process-based vegetation model ORCHIDEE-GM in combination with globally derived maps on livestock density, wild herbivory density, nitrogen fertilization and atmospheric nitrogen deposition, and grass-biomass use. Authors can show that largest fractions of managed grasslands occur in regions of high livestock density. A comparison of grassland productivity between managed and unmanaged grassland simulations shows that management has largest impact in regions of high N fertilizer applications. Authors further examined a global increase of 116% of managed grassland area (from 5.1x106 km2 in 1901 to 11x106 km2 in 2000). The topic is interesting and scientifically relevant as more research focusses on the global impact of land use but historical data on land use is rare. Nevertheless, the manuscript requires large improvements.

[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-A4, Figure A1 and Table A1.

[Comment 1] I miss a clear statement on the hypothesis or goal of this study in the introduction. While reading the manuscript, it was confusing if authors focus on global management intensity, net biome productivity (NBP) or grassland productivity (NPP). Previous studies and intentions of the study presented in this manuscript are mixed so that it is confusing which parts of this study are novel and which parts are used from previous studies. Is the presented study just an extension of the Europe-study of Chang et al. 2015a? Which challenges arise by constructing a management intensity map for the globe instead of only Europe? Are there differences in the methodology? I highly recommend (1.) providing a clear statement on the goal of this study, (2.) highlighting challenges which arise and (3.) indicating the authors' own novel contribution for achieving this goal. The results and discussion section should also be more focused, following the hypotheses or goals that should be formulated clearly in the introduction.

[Response] Thanks for the suggestion. We have rephrased the 'Introduction' section as Appendix A1. In the revised introduction, we presented the importance of grassland management intensity history (paragraph 1 and 2), pointed out the limitations of the previous studies related to grassland management and the lack of the gridded management intensity history maps (paragraph 2). Then we cited a recent study that provides a starting point to the reconstruction in this study (paragraph 3). In the last paragraph of introduction, we presented the goal, and the structure of this study.

This study is beyond an extension of the Europe-study. We pointed out the limitation of previous study (paragraph 2) to emphasize the necessary of gridded information on management intensity and the long-term history (1901-2012), which does not exist before and is the challenge and novelty of this study.

In the revised manuscript, we reorganized the structure to better focus on the major goal of this study as reconstructing the history of grassland management intensity. Given the fact that the gridded grassland management intensity maps are productivity-dependent, we still give a specific attention to the evaluation of modeled productivity against both a new set of site-level NPP measurements, and satellite-based models of NPP and Gross Primary Productivity (GPP). The evaluation part has been combined and shortened in the revised manuscript.

[Comment 2] Besides the motivation of this study, the methods section requires large clarification in a similar way. For the model description the authors write about applications of recent model versions (v1 and v2.1) and state that they use version 3.1 of ORCHIDEE-GM. However, I would expect (especially for readers who are not familiar with ORCHIDEE and ORCHIDEE-GM) to get basic information on the model (i.e. most important modelled processes, time step, spatial scale, important input and output of the model).

[Response] In section 2.1 of the revised manuscript, we have added some more basic information of ORCHIDEE and ORCHIDEE-GM (as Appendix A2) including 1) the major processes and output of ORCHIDEE and their time step, and 2) the processes and output of the management module and the time step. The spatial scale is presented in the previous manuscript as "from site-level to global scale". The important input of the model in this study was presented in the section 2.4 'Model input' of the revised manuscript.

[Comment 3] Concerning the model parameters in section 2.2, only 2 parameters are mentioned. Information on where to find the other parameters of the model and their values should be provided. Moreover, this paragraph occurs a second time in the supplement (which is just redundant information). The text S1 in the supplement is, however, written much better and more concise than in the main manuscript.

[Response] Original section 2.2 in the previous manuscript and Text S1 has been combined as the section 2.2 in the revised manuscript. In addition, the reference on the other model parameterization was added as "All other parameters of ORCHIDEE model are kept consistent with that in Trunk.rev2425. The parameter settings for grassland management module are in consistent with that in ORCHIDEE-GM v1 (Chang et al., 2013) and v2.1 (Chang et al., 2015ab)".

[Comment 4] This applies also for the other text paragraphs in the manuscript of section 2.3 and their corresponding text in the supplement. Partly, introductory information occurs in the supplementary paragraph while it is needed in the paragraph of the main manuscript. In turn, technical information occurs in the main manuscript which is hard to understand without reading the supplementary text first.

[Response] Original section 2.3 in the previous manuscript has been separated to 2 sections: 2.4 Model input; and 2.5 Simulation set-up. The paragraphs have been rephrased with introductory information and only necessary technical information (as Appendix A3), and the corresponding text in the supplementary information is reorganized and rephrased too.

[Comment 5] Following sections 2.4 and 2.5, it's difficult to understand which maps provide input for ORCHIDEE-GM simulations and which maps are combined with simulation output of ORCHIDEE-

GM. In total, the entire methods section needs large improvements, i.e. clear, concise and comprehensive statements in order to be able to reproduce the results of this study.

[Response] In the revised manuscript, we have added a new flowchart (Fig. A1) illustrating the procedures for reconstructing the 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 6] Regarding the manuscript language and style, I highly recommend to shorten the manuscript and to be more concise and precise, but still comprehensive. The entire manuscript is too long. Sentences are too long to fluently read the manuscript, some paragraphs are too technical. There are grammar and spelling mistakes. References should be double-checked (e.g., page 4, line 12).

[Response] In the revised manuscript, we have reorganized the manuscript through 1) rephrasing section 2.4 'Model input' with only introductory information and necessary technical information; 2) combining the previous section 2.5 'Modelled productivity', 2.6 'Datasets for model evaluation' and section 2.7 'Model-data agreement matrics' as section 2.7 'Model evaluation' in the revised manuscript, 3) combining the model evaluation sections (section 3.2, 3.4 – 3.6 in the previous manuscript), and 4) shortening the discussion on productivity evaluation (section 4.3). However, we were not able to significantly reduce the size of this manuscript, because the comprehensive explanations of the critical material, key methods and results are necessary to help readers understanding the reconstruction of management intensity history in this study.

Thanks for the suggestions. We have corrected the grammar and spelling mistake and double-checked the reference in the revised manuscript. For example, the reference for PaSim model has been corrected as Riedo et al., 1998; Vuichard et al., 2007a,b; Graux et al., 2011. We have shortened or separated some long sentences to present them more clearly.

[Comment 7] The last sentences of the abstract (page 2, lines 13-21) are confusingly written and hard to understand without reading the entire article.

[Response] Given the reason that "the gridded grassland management intensity maps are model-dependent because they depend on modelled productivity", we gave a specific attention to the evaluation of modelled productivity in this study. We have deleted some detail information, and rephrased the last sentences of the abstract as Appendix A4.

Appendix A1: Revised introduction

The rising concentrations of greenhouse gases (GHGs), such as carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) are driving climate change, through increased radiative forcing (IPCC, 2013). It is estimated that over the whole globe, livestock production (including crop-based and pasture-based) currently accounts for 37% of the anthropogenic CH4 (Martin et al., 2010) and 65% of the anthropogenic N2O emissions (FAO, 2006). Grassland ecosystems support most of the world's livestock production, thus contributing indirectly a significant share of global CH4 and N2O emissions. For CO2 fluxes however, grassland can be either a sink or a source with respect to the atmosphere. The net annual carbon storage of managed grassland ecosystems in Europe was found to be correlated with carbon removed by grazing and/or mowing (Soussana et al., 2007). Thus, knowledge of management type (grazed or mown) and intensity (intensive or extensive) is crucial for simulating the carbon stocks and GHG fluxes of grasslands.

For European grasslands, Chang et al. (2015a) constructed management intensity maps over the period 1961-2010 based on i) national-scale livestock numbers from statistics (FAOstat, 2013), ii) static sub-continental grass-fed fraction of each type of animal (Bouwman et al., 2005), and iii) the grass-fed livestock numbers supported by the net primary productivity (NPP) of the ORCHIDEE-GM model. That study estimated an acceleration of soil carbon accumulation over the period 1991- 2010. The increasing soil carbon accumulation rate was attributed separately to climate change, CO2 trends, nitrogen addition, and land-cover and management intensity changes. The observation-driven trends of management intensity were found to be the dominant driver explaining the positive trend of NBP across Europe (36 - 43% of the total trend with all drivers; Chang et al., 2015c). That study confirmed the importance of management intensity in drawing up a grassland carbon balance. However, the national-scale fraction of intensively/extensively managed and the identical history maps between 1901-1960 in that study carried several sources of uncertainty (Chang et al., 2015a). It implies that long-term history of large-scale gridded information on grassland management intensity could be more helpful. The HYDE 3.1 land-use dataset (Klein Goldewijk et al., 2011) provides reconstructed gridded changes of pasture area over the past 12,000 years. Here, pasture represents managed grassland providing grass biomass to livestock. This reconstruction is based on population density data and country-level per capita use of pasture land derived from FAO statistics (FAO, 2008) for the post-1961 period or assumed by those authors for the pre-1960 period. It defined land used as pasture but does not provide information about management intensity. To our knowledge, global maps of grassland management intensity history are not available.

Recently, Herrero et al. (2013) garnered a global livestock data to create a dataset with gridded grass biomass use information for year 2000. In this dataset, grass used for grazing or silage is separated from grain feeds, occasional feeds and stovers (fibrous crop residues). A variety of constraints have been taken into account in creating this global dataset, including the specific metabolisable energy requirements for each animal species, and regional differences in animal diet composition, feed quality and feed availability. This grass-biomass use dataset provides a starting point for constraining the amount of carbon removed by grazing and mowing (i.e., the target intensity of grass biomass use), and is suitable for adoption by global vegetation models to account for livestock-related fluxes.

The major objective of this study is to produce global gridded maps of grassland management intensity since 1901 for global vegetation model applications. These maps combine historical NPP changes from the process-based global vegetation model ORCHIDEE-GM (Chang et al., 2013; 2015b) with gridded grass biomass use extrapolated from Herrero et al. (2013). First, ORCHIDEE-GM is calibrated to simulate the distribution of potential (maximal) harvested and grazed biomass from mown and grazed grasslands respectively. In a second step, the modelled NPP maps are used in combination with livestock data in each country since 1961 and in 18 large regions of the globe for 1901-1960 for reconstructing annual maps of grassland management intensity at a spatial resolution of 0.5° by 0.5°. The reconstructed management intensity defines the fraction of mown, grazed and unmanaged grasslands in each grid-cell. The gridded grassland management intensity maps are model-dependent because they depend on Net Primary Productivity (NPP). Thus in this study, we also give a specific attention to the evaluation of modeled productivity against both a new set of site-level NPP measurements, and satellite-based models of Gross Primary Productivity (GPP). In Sect. 2, we describe the ORCHIDEE-GM model, the adjustment of its parameters for the C4 grassland biome, model input, the method proposed to reconstruct grassland management intensity, and the data used for evaluation. The management intensity maps and the comparison between modelled and observed productivity are presented in Sect. 3 and discussed in Sect. 4. Concluding remarks are made in Sect. 5.

Appendix A2: Revised section 2.1 Model description

ORCHIDEE (ORganizing Carbon and Hydrology In Dynamic Ecosystems) is a process-based ecosystem model developed for simulating carbon fluxes, and water and energy fluxes in ecosystems, from site-level to global scale (Krinner et al., 2005; Ciais et al., 2005; Piao et al., 2007). It is composed of two main modules. The SECHIBA (soil–vegetation system and the atmosphere) parameterization computes the energy and hydrology budget on a half-hourly basis, together with photosynthesis based on enzyme kinetics (Viovy and de Noblet, 1997). These results are fed into a module of ORCHIDEE called STOMATE, which simulates C dynamics on a daily basis: gross primary production (GPP) is allocated to different organs, and then respired by the plant or by soil microorganisms when parts of the plant die. These processes determine several ecosystem state variables such as leaf area index (LAI) and canopy roughness, which are fed back into SECHIBA because they control the energy and water budgets.

ORCHIDEE-GM (Chang et al., 2013) is a version of ORCHIDEE that includes the grassland management module from PaSim (Riedo et al., 1998; Vuichard et al., 2007a,b; Graux et al., 2011), a grassland model for field-level to continental-scale applications. Accounting for the management practices such as mowing, livestock grazing and organic fertilizer application on a daily basis, ORCHIDEE-GM proved capable of simulating the dynamics of leaf area index (LAI), biomass and C fluxes of managed grasslands. ORCHIDEE-GM v1 was evaluated and some of its parameters calibrated, at 11 European grassland sites representative of a range of management practices, with eddy-covariance net ecosystem exchange (NEE) and biomass measurements. The model successfully simulated the NBP of these managed grasslands (Chang et al., 2013). At continental scale, ORCHIDEE-GM version 2.1 was applied over Europe to calculate the spatial pattern, interannual variability (IAV) and the trends of potential productivity, i.e., the productivity of an optimal management system that maximizes simulated livestock densities in each grid-cell (Chang et al., 2015b). Chang et al. (2015b) then added a parameterization of adaptive management through which farmers react to a climate-driven change of previous-year productivity. Though a full nitrogen cycle is not included in ORCHIDEE-GM, the positive effect of nitrogen fertilizers on grass photosynthesis rates, and thus on subsequent ecosystem productivity and carbon storage, are parameterized with an empirical function calibrated from literature estimates (Chang et al., 2015b). ORCHIDEE-GM v2.1 was used to simulate NBP and NBP trends over European grasslands during the last five decades at a spatial resolution of 25 km and a 30-minute time-step.

ORCHIDEE-GM v1 and v2.1 were developed based on ORCHIDEE v1.9.6. To benefit from recent developments and bug-corrections in the ORCHIDEE model, ORCHIDEE-GM is updated in this study with ORCHIDEE Trunk.rev2425 (available at: https://forge.ipsl.jussieu.fr/orchidee/browser/trunk#ORCHIDEE). We further 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). The updated model is referred to here as ORCHIDEE-GM v3.1.

Appendix A3: Revised section 2.4 Model input

ORCHIDEE-GM v3.1 was run on a global grid over the globe using the CRU+NCEP reconstructed climate data for the period 1901–2012 (http://dods.extra.cea.fr/data/p529viov/cruncep/readme.htm). The fields used as input of the model are temperature, precipitation, specific humidity, solar radiation, wind speed, pressure and long wave radiation at a 6-hourly time-step. The CRU+NCEP climate is a combination of CRU TS.3.21 0.5° × 0.5° monthly climate fields covering the period 1901–2012 (http://badc.nerc.ac.uk/view/badc.nerc.ac.uk__ATOM__dataent_1256223773328276), and the US National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR) reanalysis 1° × 1° 6-hourly climatology covering the period 1948 to the present-day (Kanamitsu *et al.,* 2002).

Other input data are: 1) yearly grazing-ruminant stocking density maps, 2) wild-herbivores population density maps, 3) nitrogen (N) fertilizer application maps including manure-N and mineral-N fertilizers, and 4) atmospheric N deposition maps. These input maps all cover the period from 1901 to 2012 and are briefly described below (also see Supplementary Information Text S1 – S4). Table 1 lists all variables shown in this section, including their abbreviations, units, related equations, and data sources.

Grazing-ruminant stocking density maps. Spatial statistical information on grazing-ruminant stocking density (i.e., stocking rates) is not available at global scale. In this study, assuming that all the ruminants in each grid-cell were grazing on the grassland within the same grid, we defined the grazing-ruminant stocking density in grid-cell k in year m ($D_{grazing,m,k}$, unit: LU per ha of grassland area) as:

$$D_{grazing,m,k} = \frac{D_{m,k}}{f_{grass,m,k}} \qquad (1)$$

where $D_{m,k}$ is the total domestic ruminant stocking density in unit of LU per hectare of land area (Supplementary Information Text S1); and $f_{grass,m,k}$ is the grassland fraction in grid-cell k in year m from a set of historic land-cover change maps (Supplementary Information Text S2). To avoid unrealistic densities of ruminant grazing over grassland (which might cause grasses die during the growing season), a maximum value of 5 LU ha^{-1} was set for the density map. In addition, a minimum grazing-ruminant density of 0.2 LU ha^{-1} was set to avoid economically implausible stocking rates. The domestic ruminant stocking density (D, unit: LU per ha of land area) for the reference year 2006 is derived from the Gridded Livestock of the World v2.0 dataset (GLW v2.0; Robinson et al., 2014). The original density of each ruminant category (including cattle, sheep and goats, unit: head) is converted to Livestock Units (LU) and aggregated to the resolution of $0.5^{o} \times 0.5^{o}$. The category-specific gridded ruminant stocking density is then back-casted from 2012 to 1901 assuming that it has changed in each grid-cell proportionally with country-scale metabolisable energy requirement (ME) from that category of ruminants (Supplementary Information Text S1). The evolution of ME requirement by each category of ruminants was calculated from FAO ruminant population statistics during the period 1961-2012 (FAOSTAT, 2013) and from Mitchell (1993, 1998a, b) during the period 1901-1960 (http://themasites.pbl.nl/tridion/en/themasites/hyde/landusedata/livestock/index-2.html) using the method given in the Supporting information Text S1 of Chang et al. (2015b). Figure S1 shows the example maps of ruminant stocking density (D) and corresponding grazing-ruminant stocking density ($D_{grazing}$) for reference year 2006.

Wild herbivore density maps. Gridded maps of wild herbivore density are not available, therefore the gridded population density of wild herbivores (D_{wild}, unit: LU per ha of grassland area) is derived from the literature data, and from Bouwman et al. (1997) (see Table S2 for detail). The population of these herbivores was first converted to LU according to the ME requirement calculated from their mean weight (Table S2), and then distributed to suitable grasslands based on grassland aboveground (consumable) NPP simulated from ORCHIDEE-GM v3.1 (Supplementary Information Text S3; Fig. S2). The wild herbivores density was assumed to remain constant during the period of 1901-2012, because no gridded worldwide wild-animals population information was available.

Nitrogen application rates from mineral fertilizers and manure. Grassland is fertilized with organic nitrogen (N) fertilizer (e.g., manure, slurry) and/or even mineral-N fertilizer, though this is not as common as it is for cropland. Gridded fertilizer application rates on grassland are not available worldwide. The only exception that we are aware of is for European grasslands. Gridded mineral fertilizer and manure nitrogen application rates for grasslands for EU-27 was estimated by the CAPRI model (Leip et al., 2011, 2014) based on information from official and harmonized data sources such as Eurostat, FAOstat and OECD, which are spatially disaggregated using the methodology described by Leip et al. (2008). For countries/region other than EU-27, the following data and methods were used (see Supplementary Information Text S4 for detail).

The amount of manure-N fertilizer for 17 world regions at 1995 was derived from various sources (e.g., IFA, 1999; FAO/IFA/IFDC, 1999; FAO/IFA, 2001) and synthesized by Bouwman et al. (2002a, b; Table S3). The regional data were downscaled to a 0.5° × 0.5° grid according to ruminant stocking density (*D*) of each grid-cell, which implies that locally higher ruminant density produces more manure. In each grid-cell, historical changes of manure-N fertilization (N_{manure}, unit: kg N per ha of grassland area per year) were assumed to follow the same evolution as the gridded total ruminant stocking density (including cattle, sheep and goats; Supplementary Information Text S1).

For mineral-N fertilizers on grassland, country-scale data of fertilized area and mean fertilization rate for 1999/2000 are available in FAO/IFA/IFDC/IPI/PPI (2002) with grassland/pasture been fertilized in 34 countries. Within the 34 countries, 21 of them belong to EU-27 where gridded fertilizer application rate is available. For the other 13 non-EU-27 countries, the national mean application rates (Table S4) are applied on grid-cells with a total ruminant stocking density above a certain threshold. The value of this threshold is determined for each country making the total grassland area of fertilized grids is identical to the national fertilized grassland area reported by FAO/IFA/IFDC/IPI/PPI (2002). The application rate of mineral-N fertilizers ($N_{mineral}$, unit: kg N per ha of grassland area per year) is extrapolated using country-scale total nitrogenous mineral fertilizers consumption data from FAOSTAT (2014) during the period 1961-2002. The mineral-N fertilization rate after 2002 is assumed to be constant as the 2002 rate. For the period 1901-1960, the same set of rules that were applied for the EU-27 (see section 'Simulation set-up' in Chang et al., 2015a for details) is used, namely: 1) no mineral-N fertilizer is applied over grasslands before 1950, and 2) for the period of 1951-1961, the rate of application is assumed to increase linearly from zero to the level of 1961 in each grid-cell.

Atmospheric-nitrogen deposition maps. The historical atmospheric N deposition maps were simulated by the LMDz-INCA-ORCHIDEE global chemistry-aerosol-climate model which couples on-line the LMDz (Laboratoire de Météorologie Dynamique, version-4) General Circulation Model, the INCA (INteraction with Chemistry and Aerosols, version-3) chemistry transport model and ORCHIDEE v9 dynamical vegetation model. A description of the model components is given by Hauglustaine et al. (2014). Hindcast simulations for the years 1850, 1960, 1970, 1980, 1990, and 2000, have been performed using anthropogenic emissions from Lamarque et al. (2010). Based on these simulations, the LMDz-INCA total nitrogen deposition fields (wet and dry; NHx and NOy) of all nitrogen-containing gas phase and aerosol species have been simulated at a spatial resolution of 1.9^{o} in latitude and 3.75^{o} in longitude. These deposition fields have been evaluated against measurements from the EMEP network over Europe (emep.int), from the NADP network over North America (http://nadp.sws.uiuc.edu/NTN) and from the EANET network over eastern Asia (http://www.eanet.cc/). They show a generally good agreement with observations (Hauglustaine et al., 2014). Linear interpolation was performed between the hindcasts years to produce temporally variable atmospheric-N deposition maps ($N_{deposition}$, unit: kg N per ha of grassland area per year).

Appendix A4: Revised part of 'Abstract'

The gridded grassland management intensity maps are model-dependent because they depend on modelled productivity. Thus we also give a specific attention to the evaluation of modelled productivity against a series of observations from site-level Net Primary Productivity (NPP) measurements to two global satellite products of Gross Primary Productivity (GPP) (MODIS-GPP and SIF data). Generally, ORCHIDEE-GM captures the spatial pattern, seasonal cycle and interannual variability of grassland productivity at global scale well, and thus appears to be appropriate for global applications.

Figure A1 and Table A1:

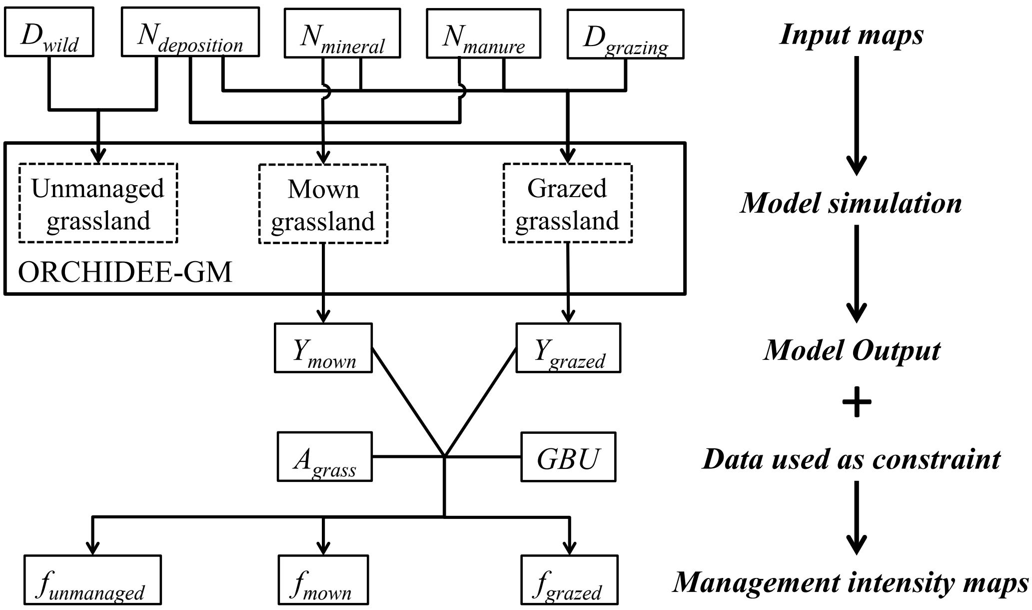

Figure A1. Illustration of the procedures for reconstructing management intensity maps. Italic texts indicate the major steps of the reconstruction. The meanings, units, related equations, and data sources of the variables (i.e., gridded maps) are shown in Table 1. $D_{grazing}$, grazing-ruminant stocking 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.