Modeling vegetation and carbon dynamics of managed grasslands at the global scale with LPJmL 3.6

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Abstract. Grassland management directly affects the carbon fluxes of large areas and is thus an important factor for the global carbon budget. Nonetheless, this aspect has been largely ignored or underrepresented in global carbon cycle models. We introduce three different management schemes for the managed grassland implementation of the DGVM LPJmL that facilitate a better representation of actual management systems globally. We describe the model implementation and evaluate model performance against European data. We demonstrate the importance of accounting for differences in grassland management by assessing maximum livestock grazing densities as well as the impacts of grazing, grazing intensities and mowing systems on soil carbon stocks. Grazing leads to soil carbon losses in polar or arid regions even at moderate livestock densities ($<$ 0.4 LSU ha^{-1}) but not in temperate regions even at much higher densities (0.4 to 1.2 LSU ha^{-1}). Applying LPJmL with the new grassland management options enables assessments of global meat production and its impact on the terrestrial biogeochemical cycles, but requires a global data set on current grassland management.

1 Introduction

Pastures and rangelands cover 25 % of the Earth's ice-free land surface (FAOSTAT, 2016) and 68 % of the agricultural area (Steinfeld et al., 2006). Their extent remains relatively stable over time with an increase from 3100 Mio ha in 1960 to 3400 Mio ha in 1995 and until now (FAOSTAT, 2016). The productivity of grasslands depends on climatic and soil conditions, as well as on the amount and frequency of biomass removal by mowing or herbivores (wild animals or livestock) (Pachzelt et al., 2013). There are high uncertainties with respect to the management of grasslands. Estimates for the extent of grazing area are only available for recent years and vary between 4700 Mio ha (Erb et al., 2007) and 3400 Mio ha (FAOSTAT, 2016). Even in a recent study by Erb et al. (2016b), the uncertainty in the grazing area is given as ± 40 % in comparison to the average. Con-

sidering livestock density and fertilization as management intensity factors, less than 10 % of the grassland area are estimated to be under *high*, about 65 % under *medium* and 25 % under *low* grazing intensity (Erb et al., 2016b). A better separation of grassland management into areas with grazing or mowing on the global scale has been identified as a major challenge for better assessments of land management (Erb et al., 2016b) partly because of conflicting definitions of landuse (Erb et al., 2007;

5   Ramankutty et al., 2008).

1.1   Characteristics of managed grasslands

Agricultural area that is covered predominantly by grasses or other herbaceous forage plants for a duration of at least 5 years is classified as 'permanent pastures' or 'managed grassland' (European Commission, 2004; Ramankutty et al., 2008). We use the term 'managed grassland' for these open landscape ecosystems with herbaceous vegetation which is mown or grazed

10 by animals. We do not further distinguish (semi-)natural grasslands, as the distinction of the management intensity or the proportion between livestock and wild animals is mostly difficult (Ramankutty et al., 2008). Managed grassland differ from natural vegetation or cropland in the use of biomass to feed livestock mostly without additional irrigation or fertilization.

There are two mechanisms how management affects the vegetation composition of managed grasslands: 1. the establishment of plants that can be directly influenced by sowing of highly productive and nutritious grasses and 2. livestock grazing, as

15 animals prefer some species which may then disappear under high grazing pressure (Brown and Stuth, 1993; Sharp et al., 2014). Both mechanisms are intentionally used in European livestock systems to maximize herbage digestibility by sowing suitable forage cultivars and frequent grazing (Soussana et al., 2004).

The management of grasslands plays an important role in global carbon and water cycles (Herrero et al., 2016). The frequency of biomass removal and its fate (complete removal as feed to other locations or partially remaining in the form of

20 manure on the plot) have effects on the productivity of the grass itself and on the carbon and water budget of the grassland (Soussana et al., 2004; Herrero et al., 2016).

The form of harvesting and the amount of herbaceous biomass that is harvested are central elements of grassland management. For intensive grazing in Europe (about 2 LSU ha^{-1}), Soussana et al. (2004) report a harvest fraction of 60 % of the above-ground dry matter production and less for lower livestock densities. The digestible part of the ingested carbon (up to

25 75 %) is respired shortly after intake (Soussana et al., 2004). 25 ± 40 % (mean $\pm$ one standard deviation) of the carbon intake is non-digestable and returned to the grassland in the form of excreta (Soussana et al., 2004). Thus, management includes also the possibility to apply manure which is either directly dropped by livestock or spread by machinery. From the excreta that livestock directly release on grassland, globally only a small fraction is recovered for use outside the grassland ecosystem (Sheldrick et al., 2003) although local differences may be substantial. From the excreta produced in a stable, about 44 % (10

30 to 50 %) of the solid manure is allocated to pastures in developed countries whereas this portion is below 10 % in developing countries (Liu et al., 2010; Bouwman et al., 2002; Smil, 1999).

Mismanagement, on the other hand, can have deteriorating impacts. Overgrazing or trampling play a role especially in arid areas or under high livestock density (Dlamini et al., 2016). Mismanagement also plays a role in the increase in desertification and is the main reason of soil degradation of 15 % in the drylands in Sub-Saharan Africa (Kiage, 2013).

1.2 Representation of managed grasslands in DGVMs

Modeling grassland dynamics has a long tradition and a multitude of approaches (Chang et al., 2013, and references therein) were developed, but mostly applied at the plot scale. Dynamic Global Vegetation Models (DGVMs) provide a suitable modeling framework to also assess grassland dynamics, grassland productivity, and the impact on the biogeochemical cycles under different grassland management schemes at the global scale.

When the LPJ DGVM (Lund-Potsdam-Jena, Sitch et al., 2003) was expanded by agricultural activities, forming LPJmL (Lund-Potsdam-Jena managed Land, Bondeau et al., 2007), this extension included the integration of managed grassland. It has been represented as grassland ecosystem with human management. In this version, different practices and intensities applied around the globe were not taken into account. Managed grassland harvest was depending solely on grass productivity, disregarding the type of management (mowing or grazing, fertilization or irrigation) or the grass demand by livestock.

An implementation of management techniques into a DGVM was presented for the Organizing Carbon and Hydrology in Dynamic Ecosystems model (ORCHIDEE, Chang et al., 2013) coupled with the plot-scale pasture model PaSim (Vuichard et al., 2007). It includes mowing and grazing at the European scale and a global application is missing so far.

1.3 Approach

We here extend the representation of managed grasslands in LPJmL by explicitly describing four different management options of herbaceous vegetation with the presence of livestock or the use of harvested grass as livestock feed. The annual sum of grass biomass which is removed from managed grasslands is referred to as harvest or yield. We define management options by combining different biomass removal frequencies and amounts as well as the conversion of grass biomass to manure for grazing systems, resulting in the implementation of three new management options. These new management options are designed to cover the range of different possible management schemes with respect to their characteristics in productivity, as well as in carbon and water dynamics. Besides a default management option D similar to that in (Bondeau et al., 2007), we add the following three grassland management options:

M an intensive mowing scheme as e.g. applied for the production of hay,

G_D a continuous grazing system with flexible livestock densities, and

G_R a rotation grazing system, in which ruminants of flexible densities are moved between individual paddocks in regular intervals.

With this implementation, we aim to facilitate a much better representation of the diversity in grassland management at the global scale in model simulations of agricultural productivity and biogeochemical cycles. Given the lack of reference data for large-scale grassland harvest, we compare the data with a European data set (Smit et al., 2008) to evaluate model performance. We demonstrate the importance of accounting for grassland management for biogeochemical simulations by analyzing the management effects on Net Primary Productivity (NPP) and soil carbon stocks and for the simulations of agricultural productivity by assessing maximum harvest rates and the associated livestock densities for all simulation units (grid cells).

2 Methods

In this section we describe the data sources (2.1), an overview of the modeling concept (2.2), the representation of grass growth in LPJmL (2.3), the implementation of management options (2.4), the configuration of the model simulations (2.5) and the methodology of the analysis (2.6).

2.1 Data sources

Climate data for model simulations include monthly temperature and cloudiness from the Climate Research Unit's (CRU) time series (TS) 3.1 data (Mitchell and Jones, 2005) and monthly gridded precipitation from the Global Precipitation Climatology Centre's (GPCC, version 5) (Rudolf et al., 2010). Monthly climate data are interpolated by the model internally to daily values by linear interpolation for temperature and cloudiness and by an internal weather generator (Gerten et al., 2004) for precipitation using the number of wet days as described by New et al. (2000). Global annual values for atmospheric CO_2 concentration are used from the Mauna Loa station (NOAA/ESRL, www.esrl.noaa.gov/gmd/ccgg/trends/). Thermal and hydraulic characteristics of the soils are derived from the Harmonized World Soil Database (version 1.2) (2012). These data were first aggregated to $0.5°$ resolution and classified according to the USDA soil texture classification (http://edis.ifas.ufl.edu/ss169) (Schaphoff et al., 2013).

For the evaluation of simulated yield potentials, average yield data for European subnational entities for the year 2000 were kindly provided by Smit et al. (2008). Simulation results were averaged over the corresponding geographical units and for the years 1995 to 2004 and aggregated to the subnational units. For the spatial aggregation, we computed area-weighted means per spatial unit, using the pasture area per grid cell as given by (Fader et al., 2010) as weights.

2.2 Overview of modeling concepts in LPJmL

LPJmL simulates carbon and water cycles as well as vegetation growth dynamics depending on daily weather conditions and soil texture. Simulations in this study are conducted on a regular grid at $0.5° \times 0.5°$, but as the model is essentially a point model, it can be run at any spatial resolution provided by the input data. The soil depth of 3 m is divided into 5 soil layers of 0.2, 0.3, 0.5, 1 and 1 m thickness. The model calculates carbon fluxes (gross primary production, auto- and heterotrophic respiration) and the respective changes in carbon pools (leaves, sapwood, heartwood, roots, storage organs, litter and soil), as well as water fluxes (interception, percolation, evaporation, transpiration, snowmelt, runoff) (Gerten et al., 2004; Rost et al., 2008). Closed mass balances across all fluxes and pools are ensured for carbon and water while carbon and water pools adjust dynamically according to the in- and outgoing fluxes. Photosynthesis is simulated following a simplified Farquhar model approach for global simulations (Farquhar et al., 1980; Collatz et al., 1991, 1992; Haxeltine and Prentice, 1996a, b). After the implementation of agricultural land by Bondeau et al. (2007), grid cells are separated into different spatial units, called *stands*, with their specific carbon, water and energy budgets. Plant growth, vegetation dynamics and the associated water and carbon dynamics are simulated for representative average individuals of different plant functional types (PFTs). Natural PFTs grow on the same stand, competing for light and water (Sitch et al., 2003). Crops, on the other hand, are simulated on individual stands

assuming mono-cultures. While managed grassland is simulated on separate stands as well, vegetation can still consist of up to two herbaceous PFTs (one C_3 and one C_4 herbaceous PFT) which compete for resources.

2.2.1 Natural vegetation

Natural vegetation is represented in LPJmL at the biome level by nine PFTs (Sitch et al., 2003). Processes of carbon assim-
5 ilation and water consumption are parameterized on the leaf level and scaled to the simulation unit. Carbon assimilation by photosynthesis, water fluxes and plant and soil respiration are computed at daily time steps, whereas the allocation to the vegetation carbon pools is updated at annual time steps. Intra-annual dynamics of leaf area and, thus, light interception, are computed by scaling the leaf biomass with a phenology-dependent factor. Litterfall of leaves from vegetation upon mortality or from tissue turnover accumulates in above- and below-ground litter pools. Decomposition from these litter pools feeds into
10 soil carbon pools with fast (10-year turnover) and slow (100-year turnover) decomposition rates. Soil and litter decomposition is controlled by soil moisture and soil temperature. All soil processes are computed on a daily basis. For further details see Schaphoff et al. (2013). Carbon and water dynamics are linked so that the effects of changing temperatures, water availability and CO_2 concentrations are accounted for (Gerten et al., 2004, 2007). Physiological and structural plant traits of each PFT determine its water requirements and consumption.

15   Competition between PFTs due to differences in their performance under given climate conditions can lead to changes in vegetation composition. Changes in the PFT distribution in turn affect the productivity of individual PFTs in subsequent time steps, leading to changes in carbon and water fluxes. These fluxes are also impacted by the dynamics of the input data (weather data, soil), accounting for long-term climate trends, interannual climate variability and the impact of extreme events.

2.2.2 Agro-ecosystems

20 Plant growth and agricultural production on cropland is represented by 12 crop functional types (CFTs) as described in Bondeau et al. (2007) and Müller and Robertson (2014). Crops can be simulated as irrigated or fully rainfed production systems (Rost et al., 2008; Jägermeyr et al., 2015), each system dedicated to its own stand and with its own water budget so that irrigation water is not transferred to rainfed cropland. CFTs do not represent one specific cultivar, instead parameters that represent characteristics of a specific crop variety are internally selected depending on the local climate conditions for each CFT
25 (Bondeau et al., 2007).

    In contrast to PFTs in the natural vegetation, the allocation of assimilated carbon is simulated on a daily basis to better account for environmental impacts during different stages of crop growth and to better account for the actual growing period of annual crops. During fallow periods, crop stands are merged into a setaside stand, where soil properties (carbon, water) are mixed according to their spatial extent. Irrigated agricultural land is kept on a separate setaside stand to avoid irrigation water
30 transfer to rainfed stands upon the next cultivation cycle. Newly sown crops are planted on stands that are initialized to the conditions of the setaside stand on that particular day.

2.3 Managed grassland

2.3.1 Overall setting

Managed grasslands are implemented as agricultural stands. Establishment of herbaceous PFTs on managed grassland stands follows similar rules to those for natural vegetation, but woody PFTs (trees) are not allowed to establish. The herbaceous C_3

5 and C_4 PFTs can grow together and compete for light and water. Typically, just one PFT is present on managed grassland stands because the overlap of their bioclimatic limits is quite narrow.

The main difference of managed grasslands to natural grasslands is the occurrence of harvest events, i.e. removal of leaves by mowing or grazing. We here describe the implementation of three explicit management options as well as a default setting, which can be used in the absence of explicit knowledge on management regimes or available input data sets.

10 ### 2.3.2 Parametrization of daily allocation

Flexible harvest schemes on managed grasslands require that the allocation of assimilated carbon (B_I) occurs on a daily basis as for crops (Section 2.2.2), rather than on an annual basis as in the implementation of natural vegetation (Section 2.2.1). Partitioning of assimilated carbon B_I to leaves and roots is assumed to converge towards an optimal leaf to root biomass ratio (PFT-specific parameter $lr_p = 0.75$). Under dry conditions plants allocate an increased amount of carbon to roots, lr_p is scaled

15 to the actual ratio lr with a measure of water stress (actual ratio of plant water supply to atmospheric water demand).

On days with positive net primary productivity (NPP), i.e. when more carbon is assimilated than needed for maintenance respiration, the biomass increment B_I is positive and allocated to the leaf carbon pool (L) and the root carbon pool (R) by calculating their increments (L_I, R_I) (Eqs. 1 and 2).

$$L_I = \min\left(B_I, \max\left(\frac{B_I + R - L/lr}{1 + 1/lr}, 0 \right) \right) , \tag{1}$$

$$R_I = B_I - L_I . \tag{2}$$

When maintenance respiration outweighs carbon assimilation, NPP is negative. In this case total plant biomass is reduced. No reallocation from leaves to roots or vice versa is assumed, but the negative biomass increment B_I is divided between leaves and roots proportionally to their biomass and both compartments are reduced by the increments (L_I, R_I).

After a harvest event, leaf carbon is reduced, affecting the ratio of leaf to root mass. Carbon allocation in the following

25 period will try to reestablish the optimal leaf to root mass ratio lr_p. Accounting for the reduced leaf area after harvest events, photosynthetic capacity and light interception are reduced as well so that harvest of leaf carbon induces a feedback on photosynthesis. Following the calculations as in Bondeau et al. (2007), the actual leaf carbon L and the specific leaf area (SLA, Eq. 3 with leaf longevity $\alpha_{leaf} = 1$) is used to update leaf area index (LAI, Eq. 4) and foliage projected coverage (FPC, Eq. 5 with Lambert-Beer parameter $k_b = 0.5$). With FPC, also the fraction of absorbed photosynthetic active radiation (fAPAR, Eq. 6
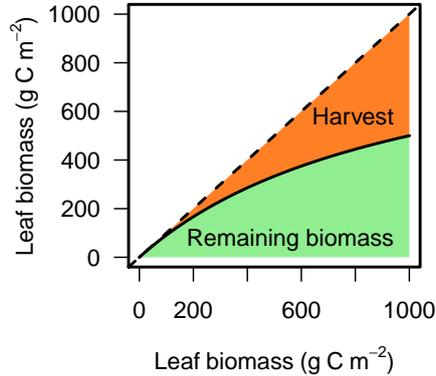
Figure 1. Partitioning of leaf carbon into harvested fraction (between solid and dashed lines) and remaining fraction (below solid line) depending on leaf carbon content before harvest (x-axis).

with the number of plant individuals $N_{ind} = 1$) is changed describing the part of radiation that is absorbed for photosynthesis.

$$
\begin{aligned}
\text{SLA} &= 2 \cdot 10^{-4} \cdot \exp(6.15 - 0.46 \cdot \log(\alpha_{leaf} \cdot 12)) \\
&= 0.0298894 \tag{3} \\
\text{LAI} &= L \cdot \text{SLA} \tag{4} \\
\text{FPC} &= N_{ind} \cdot (1 - \exp(-k_b \cdot \text{LAI})) \tag{5} \\
\text{fAPAR} &= \text{FPC} \tag{6}
\end{aligned}
$$

2.4 Implementation of grassland managment options

Pastures are managed through mowing, grazing or a combination of both, depending on the grassland productivity as well as on many other factors such as the availability of labor force. Mowing and grazing by livestock are often used in many combinations. Grazing with low densities of livestock over longer time periods or even the entire vegetation period is often combined with a few cuts and sometimes with more frequent mowing events. It is also possible that grasslands with high livestock densities are grazed for short time periods, cut a few times, but rarely mowed. To avoid the implementation of a huge set of possible combinations of grazing with different livestock densities and mowing frequencies, we decided to choose 4 basic regimes. In absence of grazing animals, option D (for default) represents frequent and option M few mowing events. Without mowing, options G_D and G_R distinguish between permanent low density and rotational high density grazing. The following paragraphs provide detailed descriptions of the management options (Tab. 1) with respect to harvest frequency, livestock density, and parameters. For a discussion on parameter choices, we refer to section 4.2.

Table 1. Characteristics of grassland management options.

	D	M	G_D	G_R
Harvest				
– frequency	biomass dependent	fixed	daily	daily
– period	last day of month	twice per year	during vegetation period	few days followed by recovery period
Soil feedback via				
– roots & stubble	yes	yes	yes	yes
– manure	no	no	yes	yes
Livestock density	none	none	0.5 LSU ha^{-1}	1.2 LSU ha^{-1}

2.4.1 Frequent mowing without grazing – Default option D

For the default option D no specific assumptions on grassland management are necessary. Its main purpose is to provide a generic accounting for biomass removal for livestock feed. Under the harvest scheme D, harvesting is possible at the end of each month (H_{day}), provided that the leaf biomass increment over all herbaceous PFTs since the last harvest event is positive.

5   Leaf biomass removal is based on harvest index H_{frac} (-) (Fig. 1), which is calculated internally via a Michaelis-Menten function using the leaf carbon L and half saturation constant $H_p = 1000$ (gC m^{-2}). In unproductive systems, only a small fraction of total leaf biomass is removed, increasing with overall leaf biomass. At a leaf biomass of 1000 gC m^{-2}, half of the leaf carbon is harvested and removed entirely from the plot.

2.4.2 Few mowing events without grazing – Option M

10   The mowing option M represents a common mowing regime with two mowing events per year. Harvest events are scheduled six months apart, scheduled on June 1st and December 1st so that the regular mowing frequency works identical on both hemispheres.

    Each individual harvest event is only realized when the leaf carbon content exceeds the threshold amount of 25 gC m^{-2}. Leaf carbon above the threshold is harvested and removed entirely like for option D. After mowing, the remaining carbon

15 content of the leaves is thus 25 gC m^{-2} which does not necessarily correspond to a specific leaf height. LAI is computed from the reduced leaf carbon according to Eq. 4. We acknowledge that there may be more mowing events than two in productive systems or with different timing, but assume no variation in mowing events for simplicity.

2.4.3 Daily grazing without mowing – Option G_D

When temperatures are sufficiently high to enable grass growth, i.e. above 5 °C, a fixed portion of the leaf carbon L is removed

20 each day per grazing livestock unit (LSU) which is corresponding to a cow of 650 kg liveweight (Chesterton et al., 2006, based on EC definitions). The stocking density can be specified per grid cell or is set to a default value of $S_D = 0.5$ LSU ha^{-1}. To

avoid permanent damage to the managed grassland, grazing is allowed only when a minimum threshold of 5 gC m^{-2} of leaf carbon is present, assuming that the livestock is removed or fed externally during these low biomass periods.

Daily intake of carbon is varying between grazing animals and seasons and it was necessary to find a value that represents the demand for grass carbon for one livestock unit independent from the corresponding production system, i.e. independent from the amount of additional feed from other sources. Cordova et al. (1978) propose to estimate daily intake corresponding to the metabolic body weight (MBW = liveweight$^{0.75}$); in this case MBW $= 129 (= 650^{0.75})$ for the chosen LSU. The daily intake varies between 18 and 41 gC day^{-1} MBW^{-1} (40 to 90 gDM day^{-1} MBW^{-1}) which gives a range of the daily intake as 2300 to 5200 gC day^{-1} LSU^{-1}. For livestock in organic farming, Kristensen et al. (2011) give estimates for feed intake and the portion of pasture feed that result in 2100 gC day^{-1} LSU^{-1} on average (minimum 780 and maximum 3450 gC day^{-1} LSU^{-1}). We assume the daily demand at 4000 gC LSU^{-1} day^{-1} (corresponding to 8.9 kg DM LSU^{-1} day^{-1}) assuming that high productive livestock requires a certain portion of grass feed along with concentrates from other sources.

The carbon from grazed biomass is incorporated into the animals, transferred to the soil carbon pool as well as mineralized to CO$_2$. The portion of the grass intake that is remaining on the grassland as manure of 25 % (Soussana et al., 2014) is incorporated into the fast soil carbon pool.

2.4.4 Rotational grazing without mowing – Option G_R

An alternative grazing management type represents a rotational system of grazing on several paddocks for a short duration and includes longer recovery periods after the grazing phase. For the implementation of this system in a grid-cell-based model, we define a number of rules on the subdivision of the grassland stand into a number of paddocks:

1. We simulate one of the paddocks and assume that the overall carbon and water budget of the other paddocks is similar, but with a temporal delay. The length of one rotation includes the grazing period at the beginning and the following recovery period.

2. The rotation period begins when the leaf carbon is above a threshold value of 40 gC m^{-2} (based on recommendations e.g. in Williams and Hall, 1994; Undersander et al., 2002; Blanchet et al., 2003, see also section 4.2). The length of the rotation period R_L in days is determined by the division of the current leaf carbon by the daily demand of the given livestock and restricting this number to a maximum value of 50 days (usually between 20 and 35 days). The stocking density can be specified per grid cell or is set to a default value of $S_R = 1.2$ LSU ha^{-1} and the daily demand of 4000 gC LSU^{-1} day^{-1} is the same as for option G_D.

3. For the determination of the number of paddocks, the rotation length R_L is chosen between an upper limit of $uR_L = 50$ days and a lower limit of $lR_L = 1$ day. The maximum number of paddocks is $P_{max} = 16$.

4. The grazing period on one paddock ends when a minimum threshold of the remaining leaf carbon $L = 5$ gC m^{-2} is reached which should represent a stubble height of 5 cm. Similar to option G_D, the removed carbon is divided into a harvest flux (incorporation into animal body and animal respiration) and a manure application to the soil pool which is

subject to mineralization there. The portion of the grass intake that is remaining on the grassland as manure (which is incorporated into the fast soil carbon pool) of 25 % (Soussana et al., 2004).

2.5 Set up of model runs

The model runs on $0.5° \times 0.5°$ spatial resolution and with a daily time step. Spinup and transient runs are conducted using
5 interpolated monthly climate data (section 2.1) from 1901 until 2009. Model simulations are based on a spin-up run of 5000 years with natural vegetation using monthly input (section 2.1) from 1901 until 1930 in repetitive loops. This spinup simulation is needed to bring potential natural vegetation composition into a dynamic equilibrium and then the corresponding soil carbon pools. Long simulation cycles are necessary, especially because of the simulated permafrost dynamics where processes are slow and soil carbon stocks are large (Schaphoff et al., 2013). After the 5000-year spinup, a 390-year spinup is conducted to
10 account for land-use change since 1700 that disturbs the dynamic soil carbon equilibrium as under potential natural vegetation and constitutes the starting conditions for the simulations conducted here.

As information on the global distribution of grassland management activities is lacking (Erb et al., 2016b), our simulations are designed to assess the effects of the different management options in all grid cells irrespective of actual land cover. After the spinup simulations, we thus ignore actual land-use patterns here and simulate only managed grasslands in all grid cells.
15 The other land-use types do not matter in this analysis after the spinup, as we only consider local carbon and water dynamics to study the effects of the introduced grassland management options. We conducted a separate transient simulation run for each of the options. For option G_D, additional simulations were conducted with livestock densities between 0 and 2 LSU ha^{-1} in 0.2 increments.

2.6 Analysis of model results

20 ### 2.6.1 Classification according to average climatic conditions

In order to relate grass growth, harvest and soil carbon to the climatic conditions under which they develop, we compute average climate conditions. Temperature and annual precipitation per grid cell are averaged over the years 1998 to 2002. We classify climatic conditions in 8 bioclimatic regions (Fig. 2 a) for a better visualization of where these climatic conditions prevail (Fig. 2 b). For the analysis of the relationship between climatic conditions and grassland dynamics, we use a much finer
25 classification, but that is difficult to visualize on a map. Under current conditions, precipitation is below 1000 mm a^{-1} in almost all grid cells with average temperatures below -5°C (bioclimatic region 1). Precipitation values above 2000 mm a^{-1} only occur with temperatures between -5 to 10°C or above 15°C corresponding to bioclimatic regions 2 and 3 (Fig. 2 a). Grid cells of bioclimatic region 2 are located along mountain ridges or near coasts whereas those of bioclimatic region 3 are located in the tropics (Fig. 2 b). High precipitation values mostly occur at low or at high average temperatures but rarely with temperatures
30 between 10 and 15°C so that a kind of bimodal patterns appear (Fig.2 a for average precipitation above 2500 mm a^{-1}. For the analysis in this paper, temperature and precipitation values are divided into bins of equal length (0.5°C for temperature
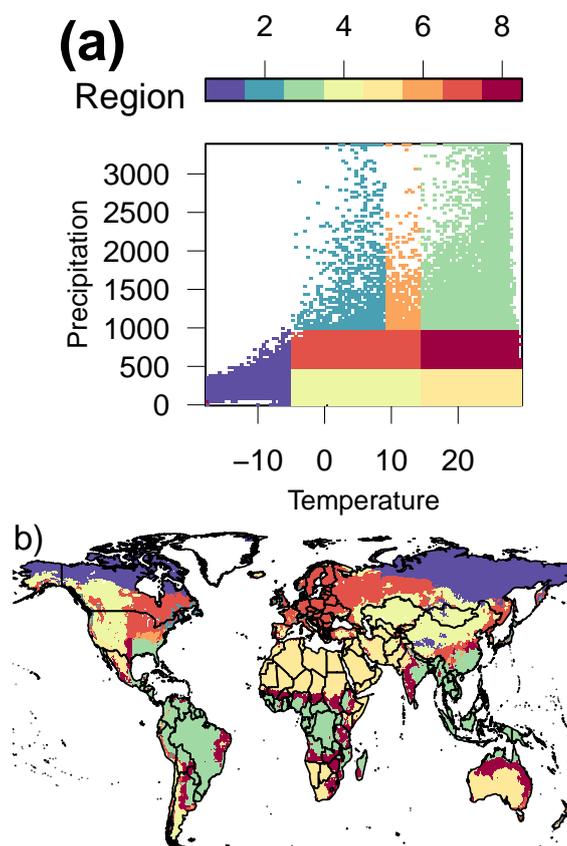
Figure 2. Temperature and precipitation values (a) averaged over the years 1998 to 2002. Global distribution of bioclimatic regions defined by temperature and precipitation averages (b) where each grid cell is colored depending on the bioclimatic region that it falls into.

and 30 mm a^{-1} for precipitation). For climate-related analyses, simulation results such as harvest or soil carbon are averaged within each bin and plotted against the temperature and precipitation axes.

2.6.2 Determination of maximum harvest under G_D

For management option G_D, we use simulations with different livestock densities to estimate the maximum annual harvest
5   potential for each grid cell. The livestock density under which this maximum harvest potential is achieved is referred to as LSU_{max}. Note that LSU_{max} is not necessarily the livestock density that can be sufficiently fed by grazing throughout the entire year, as there may be periods with insufficient grass supply (e.g. winter). The maximization of harvest potentials under LSU_{max} livestock densities can also lead to reductions in soil carbon stocks. In order to take into account the effect on soil carbon, the carbon accumulated in the soil of each run is compared to soil carbon under option M, which has a rather moderate
10   impact on soil carbon stocks compared to grassland without harvest.

2.6.3 Evaluation of correspondence using Taylor diagrams

We compare observational and simulated grassland yield data by using Taylor diagrams. These allow to display three different metrics in a single diagram: the correlation coefficient of the spatial patterns, the centered Root Mean Square Deviation (RMDS) and the variance of the data sets (Taylor, 2001). As the reference data have not temporal dimension, the correlation
5   and variance is constrained here to spatial patterns only, whereas the Taylor diagram in theory allows to assess both temporal and spatial patterns simultaneously. In Taylor diagrams, the correlation coefficient is represented by the angle, the RSMD by the distance to the location of the observational data and the variance by the distance to the origin. For details on the geometrical relationship of these three metrics see Taylor (2001). The observational data set is depicted as a point on the x-axis (perfect correlation with itself) at the value that corresponds to its variance (distance to origin of plot). Complete agreement
10 of a simulation result with the observational data set would be expressed by the same variance as the observational data set, a RMSD of 0 and a correlation coefficient of 1.

3 Results

We present simulation results for the implemented management options and compare these to a European grass harvest data set with sub-national resolution (Smit et al., 2008). For the option with daily grazing G_D, we also analyze the effect of different
15 livestock densities on harvested biomass, NPP, and total soil carbon of the 3 m soil column. All results are presented as 5-year averages around the year 2000 (1998-2002). Variability around the mean values are presented as $\pm$ one standard deviation $(x \pm y)$.

3.1 Global grassland biomass

3.1.1 Frequent mowing without grazing – Default option D

20 Grass harvest (Fig. 3 a) and NPP (Fig. 3 b) for the option D reflect the global pattern of productivity. In savannas and low productive areas (NPP below 200 gC m^{-2}), the grass yield is on average 33 gC m^{-2} a^{-1} ($\pm$ 36 gC m^{-2} a^{-1} standard deviation) and about 46 % of the NPP. Medium productivity (NPP between 200 and 600 gC m^{-2} a^{-1}) results in harvest values of 280 $\pm$ 110 gC m^{-2} a^{-1} which are on average 72 % of the NPP. In areas with high productivity (above 800 gC m^{-2} a^{-1}, corresponding mostly to bioclimatic region 3 in Fig. 2), harvest values are substantially higher (820 $\pm$ 90 gC m^{-2} a^{-1}) and
25 correspond to 80 to 93 % of the NPP (25 and 75 % quantiles).

Soil carbon content (Fig. 3 c) deviates from this pattern with values of 5.2 $\pm$ 0.9 kgC m^{-2} in high productive regions but highest values in cold climates in northern latitudes or the Tibetan plateau. There, total soil carbon may reach values between 65 to 85 kgC m^{-2} although productivity is usually quite low (NPP values of 180 $\pm$ 50 gC m^{-2} a^{-1}). Harvest on these carbon rich soils is relatively low (100 $\pm$ 49 gC m^{-2} a^{-1}) and about 48 to 56 % of the NPP.
30 Climatic conditions are of major importance for the presented results so that we aggregate them according to temperature and precipitation values (as described in section 2.6.1). For option D, high productivity and harvest results under annual mean
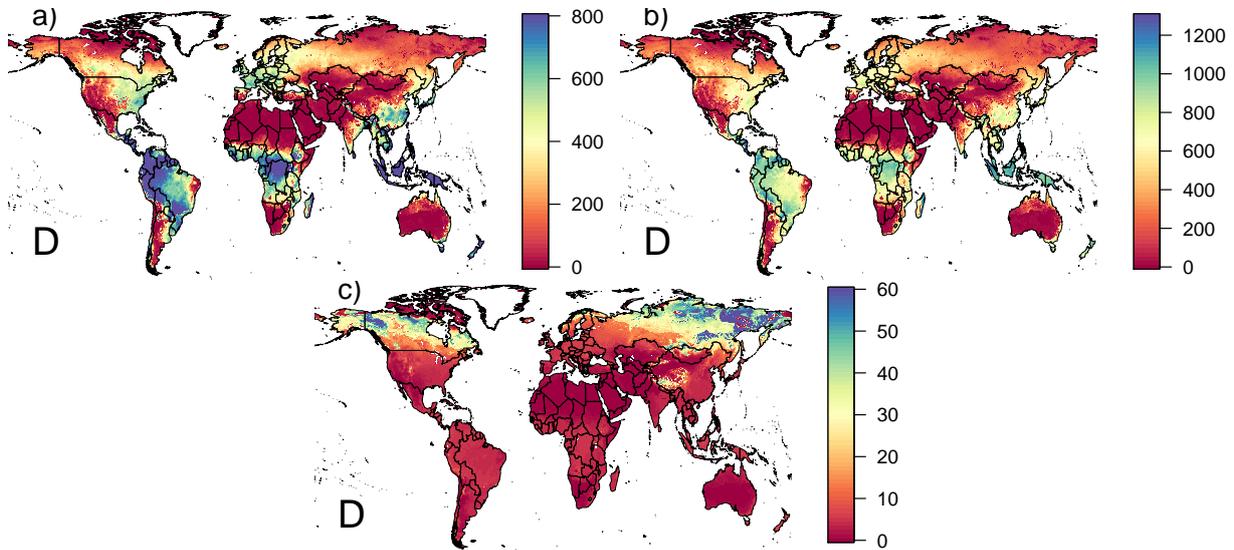
Figure 3. Simulation results for option D averaged over 1998 to 2002, a) grass harvest (gC m^{-2}), b) NPP (gC m^{-2}) and c) soil carbon (kgC m^{-2}).
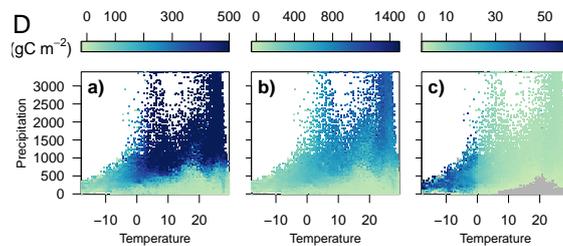
Figure 4. Simulation results for option D averaged over the years 1998 to 2002; averaged a) grass harvest (gC m^{-2} a^{-1}), b) NPP (gC m^{-2} a^{-1}), and c) soil carbon (kgC m^{-2}) per annual mean temperature ($^\circ$C) and precipitation (mm a^{-1}) values.

temperatures above 15 $^\circ$C and annual precipitation above 1000 mm (Fig. 4 a, b) corresponding nearly to tropical conditions (compare bioclimatic region 3 in Fig. 2). For this region, soil carbon (Fig. 4 c) is rather low (about 6 to 8 kgC m^{-2}). Although productivity increases further with temperature when precipitation is above 500 mm (Fig. 4 b), average grass yield and soil carbon under these conditions are not substantially different (Fig. 4 a, c). Carbon rich soils occur only under polar conditions
5   at annual mean temperatures below -5 $^\circ$C (Fig. 4 c).

3.1.2 Few mowing events without grazing – Option M

When mowing is prescribed twice per year for option M, harvest is mostly reduced by 20 to 30 % (Fig. 5 a) in comparison to option D (Fig. 3 a) but in low productive regions in the boreal north or in Sub-Saharan Africa, harvest amounts can be substantially increased in relative terms (up to 200 % increase). Considering the climatic conditions (Fig. 6 a), we find that harvest
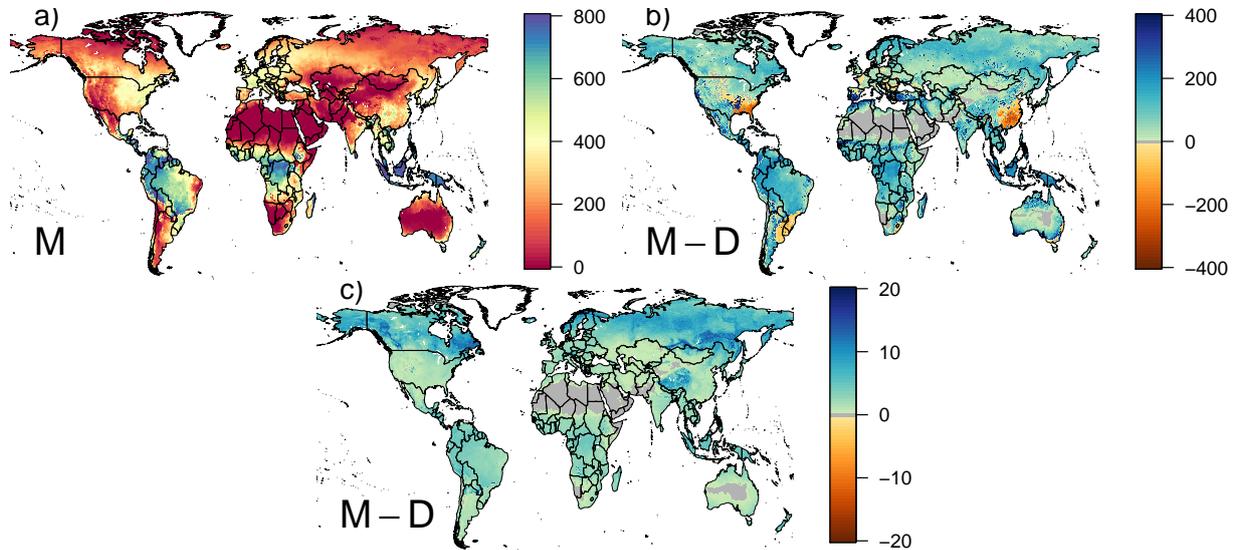
Figure 5. Simulation results for option M averaged over 1998 to 2002, a) grass harvest (gC m^{-2} a^{-1}), b) NPP difference to option D (gC m^{-2} a^{-1}) and c) soil carbon difference to option D (kgC m^{-2}).
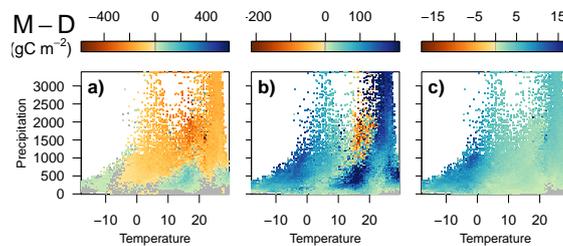
Figure 6. Difference of simulation results for option M to those for option D averaged over the years 1998 to 2002; averaged a) grass harvest (gC m^{-2} a^{-1}), b) NPP (gC m^{-2} a^{-1}), and c) soil carbon (kgC m^{-2}) per annual mean temperature ($^{\circ}$C) and precipitation (mm a^{-1}) values.

differences between options M and D are negative in regions with annual mean temperatures above -5 $^{\circ}$C and precipitation above 500 mm a^{-1}. Positive harvest differences occur where annual mean temperatures are very low ($<$ -5 $^{\circ}$C) or where annual precipitation is low (below 500 mm a^{-1}).

Net primary productivity is higher for option M (Fig. 6 b) than for option D for the majority of grid cells (87 %) with an increase of more than 100 gC m^{-2} a^{-1} for one third of the cells. These high increases of NPP occur under low annual mean temperatures ($<$ 0 $^{\circ}$C) and precipitation above
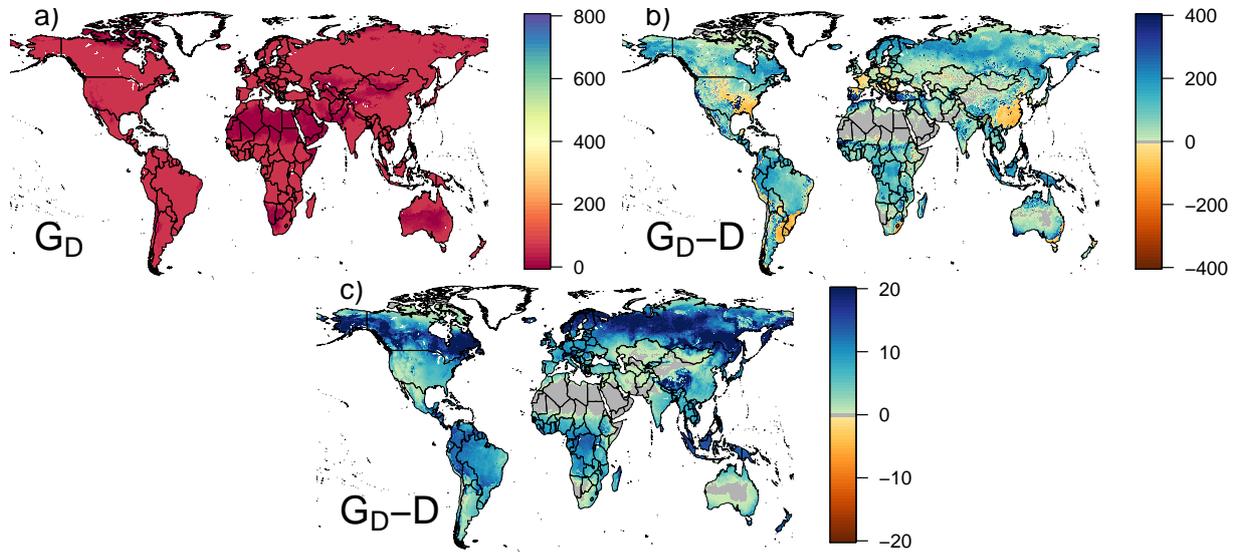
Figure 7. Simulation results for option G_D averaged over 1998 to 2002, a) grass harvest (gC m^{-2} a^{-1}), b) NPP difference to option D (gC m^{-2} a^{-1}) and c) soil carbon difference to option D (kgC m^{-2}).
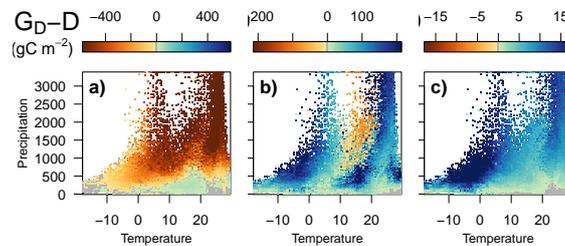
Figure 8. Difference of simulation results for option G_D to those for option D averaged over the years 1998 to 2002; averaged a) grass harvest (gC m^{-2} a^{-1}), b) NPP (gC m^{-2} a^{-1}), and c) soil carbon (kgC m^{-2}) per annual mean temperature ($^\circ$C) and precipitation (mm a^{-1}) values.

500 mm a^{-1} (Fig. 6 b) or higher annual mean temperatures (between 10 and 20 $^\circ$C) and above precipitation of 300 mm a^{-1}. When NPP is low (< 400 gC m^{-2} a^{-1}), grass yield is about 30 to 45 % of the NPP and this share increases with NPP to about 60 % for highly productive areas in the tropics. In regions with low NPP (Fig. 5 b), the grass yield is about 40 to 45 % of the NPP and scales linearly with NPP whereas in higher productive areas the share of harvested carbon is mostly 55 %.

5 Soil carbon for option M is slightly higher for almost all grid cells than for option D (3.5 ± 3 kgC m^{-2}, Fig. 5 c). The increase is especially higher in regions with annual mean temperatures below 0 $^\circ$C and precipitation above 1000 mm a^{-1} (10.5 ± 2.7 kgC m^{-2}, Fig. 6 c) which corresponds to most of the boreal regions.
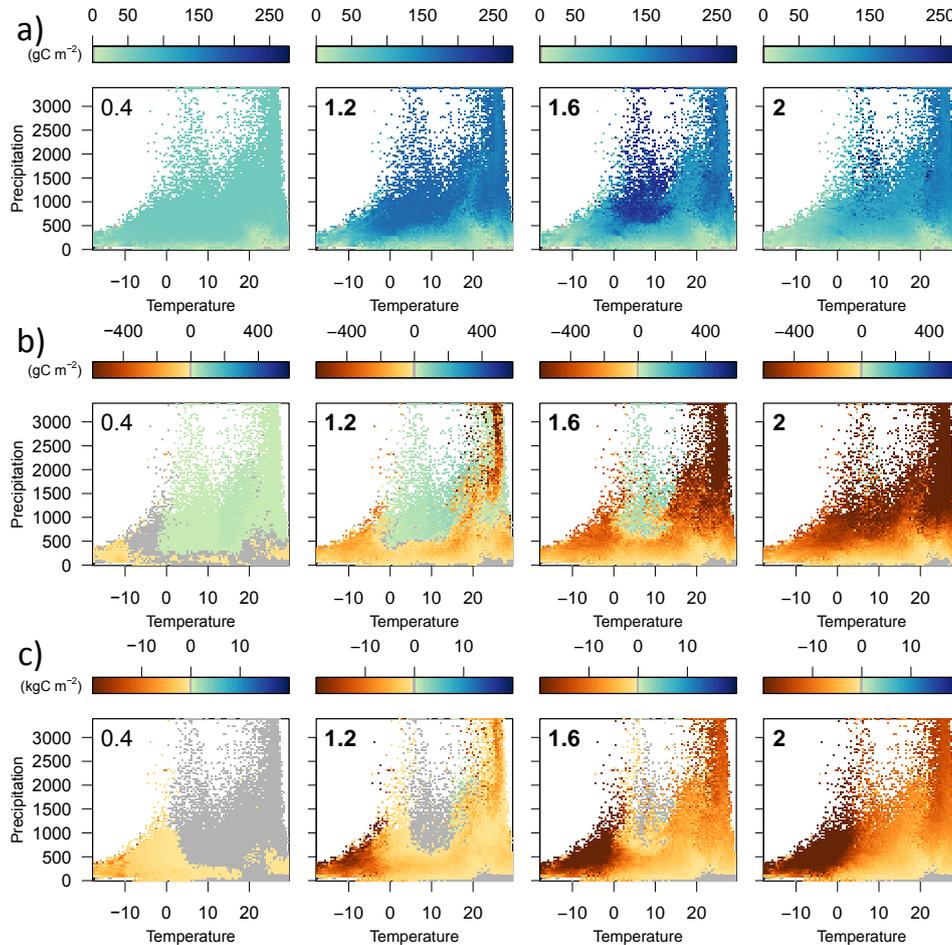
Figure 9. Difference of simulation results for option G_D with livestock densities of 0.4, 1.2, 1.6 and 2 LSU ha^{-1} to those for option G_D with livestock density 0 LSU ha^{-1} averaged over the years 1998 to 2002; averaged a) grass harvest (gC m^{-2} a^{-1}), b) NPP (gC m^{-2} a^{-1}), and c) soil carbon (kgC m^{-2}) per annual mean temperature ($^\circ$C) and precipitation (mm a^{-1}) values.

3.1.3 Daily grazing without mowing – Option G_D

For the standard application of option G_D, a livestock density of 0.5 LSU ha^{-1} is assumed so that grass harvest (Fig. 7 a) seems quite uniform and much lower for more productive regions than for options D or M. This is, because the prescribed livestock density and the assumed static intake rate per day and LSU ha^{-1} pre-define a maximum harvest rate that can be fulfilled in many regions. This underutilized harvest potential is quite large for tropical regions with annual mean temperatures above 20°C and precipitation above 1000 mm a^{-1} (Fig. 8 a). In drier areas with annual mean temperatures between 10 and 20°C, harvest is low (48 $\pm$ 23 gC m^{-2} a^{-1}) but about 14 gC m^{-2} a^{-1} higher on average than for option D.

The difference in harvest has implications on the productivity itself. NPP is mostly increased in comparison to option D by 8 to 60 % (Fig. 7, b). Although harvest is lower for all regions with precipitation above 500 mm a^{-1} (Fig. 8 a), the average NPP is also reduced in regions with annual mean temperatures between 10 and 20 °C (Fig. 8 b). This is the case in the south of China and in the south of Brazil (Fig. 7 b).

5 Soil carbon for option G_D is on average twice as high as for option D (20.3 $\pm$ 20 kgC m^{-2} Fig. 7 c, in comparison to 11.9 $\pm$ 16.9 kgC m^{-2}, Fig. 3 c) since this option includes a flux of the harvested carbon (grazed biomass) into the soil in form of manure. When decomposition rates are low (annual mean temperatures below 0 °C), soil carbon increases by 13.2 $\pm$ 8.4 kgC m^{-2} (Fig. 8 c) in comparison to option D.

Variation of the livestock density has a distinct effect on carbon stocks and fluxes. With increasing density from 0 to 10 2 LSU ha^{-1}, the harvested biomass (Fig. 9 a) first increases (48 $\pm$ 19 gC m^{-2} a^{-1} at 0.4 LSU ha^{-1} until 111 $\pm$ 65 gC m^{-2} a^{-1} at 1.2 LSU ha^{-1}) and then only increases further in regions with annual mean temperatures between 0 and 10 °C and precipitation above 1000 mm a^{-1} (from 173 $\pm$ 16 gC m^{-2} a^{-1} at 1.2 LSU ha^{-1} to 208 $\pm$ 51 gC m^{-2} a^{-1} at 1.6 LSU ha^{-1}). Under even higher grazing pressure, yields decrease everywhere to an average of 79 $\pm$ 56 gC m^{-2} a^{-1} at 2 LSU ha^{-1}.

Increasing livestock densities also affects NPP in both directions (Fig. 9 b). Areas with medium-range annual mean temper-15 atures (between 0 and 10 °C) and sufficient precipitation (above 1000 mm a^{-1}) are quite productive without grazing animals (736 $\pm$ 140 gC m^{-2} a^{-1}) and even moderately increase in NPP until 1.2 LSU ha^{-1} (gain of 35 $\pm$ 36 gC m^{-2} a^{-1}). For trop-ical regions with annual mean temperatures above 20 °C and precipitation above 1500 mm a^{-1}, the productivity is negatively affected above 1.0 LSU ha^{-1} (on average 260 gC m^{-2} a^{-1} less for 1.2 LSU ha^{-1} until 840 gC m^{-2} a^{-1} for 2 LSU ha^{-1}).

Soil carbon is decreasing with increasing livestock density (globally from 21.3 $\pm$ 22.8 kgC m^{-2} at 0 LSU ha^{-1} to 10.8 $\pm$ 20 15.5 kgC m^{-2} at 2 LSU ha^{-1}). Loss of soil carbon is especially high for regions with annual mean temperatures below 0 °C (Fig. 9 c) with decreases of 2.5 $\pm$ 2.8 kgC m^{-2} at 0.4 LSU ha^{-1} to 19.9 $\pm$ 8.2 kgC m^{-2} at 2 LSU ha^{-1}. The region in which NPP is mostly affected (annual mean temperatures above 20 °C and precipitation above 1500 mm a^{-1}), soil carbon is reduced less (11.8 $\pm$ 2.9 kgC m^{-2} at 2 LSU ha^{-1}). Interestingly, soil carbon is not or only marginally reduced (0.5 $\pm$ 1.4 kgC m^{-2} for 1.2 LSU ha^{-1} and 3.9 $\pm$ 6.4 kgC m^{-2} for 1.6 LSU ha^{-1}) for medium-range annual mean temperatures (0 to 10 °C) and 25 sufficient precipitation (above 1000 mm a^{-1}) in which NPP increased under livestock densities of up to 1.6 LSU ha^{-1}.

3.1.4 Rotational grazing without mowing – Option G_R

Option G_R is usually used with a livestock density of 1.2 LSU ha^{-1}, i.e., more than doubled livestock densities than assumed for G_D. Thus, harvest values in productive areas are higher than G_D with maximum values of 170 gC m^{-2} a^{-1} (Fig. 10 a) but with very similar NPP (Fig. 10 b) as in G_D (Fig. 7 b). The spatial pattern of grass harvest is comparable and largely uniform 30 for both grazing options (compare Fig. 10 a and 7 a) but the area on which the required supply for the given livestock density is reached is smaller for option G_R than for G_D (42 % instead of 67 %). Under favorable growth conditions with annual mean temperatures above 20 °C and precipitation above 1000 mm a^{-1}, harvest is much lower than for option D (Fig. 11 a) but the given demand can be fulfilled for all grid cells. In drier areas with annual mean temperatures between 10 and 20 °C, harvest is low (78 $\pm$ 58 gC m^{-2} a^{-1}) but about 44 gC m^{-2} a^{-1} higher on average than for option D.
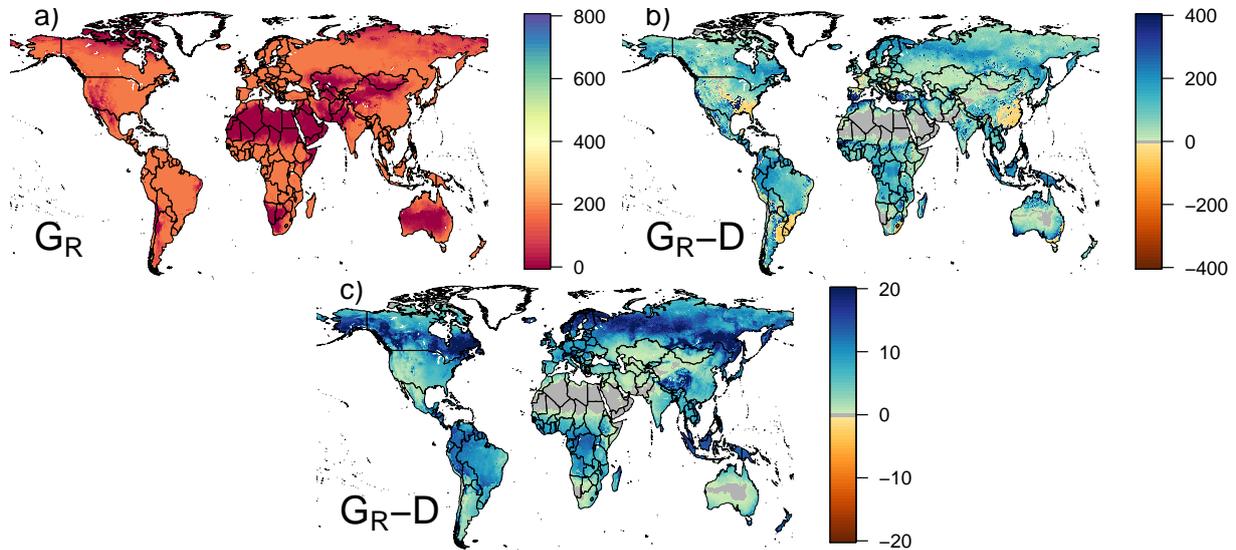
Figure 10. Simulation results for option G_R averaged over 1998 to 2002, a) grass harvest (gC m^{-2} a^{-1}), b) NPP difference to option D (gC m^{-2} a^{-1}) and c) soil carbon difference to option D (kgC m^{-2}).
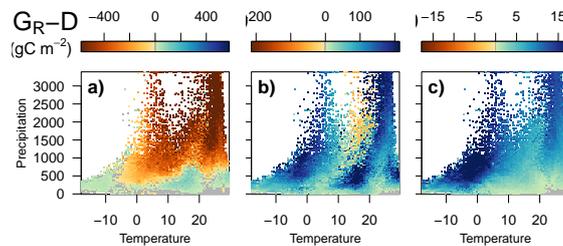
Figure 11. Difference of simulation results for option G_R to those for option D averaged over the years 1998 to 2002; averaged a) grass harvest (gC m^{-2} a^{-1}), b) NPP (gC m^{-2} a^{-1}), and c) soil carbon (kgC m^{-2}) per annual mean temperature ($^\circ$C) and precipitation (mm a^{-1}) values.

The effect of harvest on productivity is similar as for option G_D. NPP is mostly increased in comparison to option D namely by 24 to 138 gC m^{-2} a^{-1} or 11 to 63 % (Fig. 10 b). As for option G_D, harvest is lower for all regions with precipitation above 500 mm a^{-1} (Fig. 11 a) and average NPP is reduced in regions with annual mean temperatures between 10 and 20 $^\circ$C (Fig. 11 b).

5   Soil carbon for option G_R is on average a bit lower than for option G_D (19.8 ± 21 kgC m^{-2}, Fig. 10 c) because this option prescribes a higher livestock density but it results in similarly higher soil carbon content in comparison to option D because of the additional carbon flux via manure application. The soil carbon increase in regions with low annual mean temperatures (below 0 $^\circ$C) is with 11.4 ± 6.4 kgC m^{-2} (Fig. 11 c) a bit lower than for option G_D (compare Fig. 8 c).

3.2 Comparison to data

We use estimates of grassland harvest rates from Smit et al. (2008) to evaluate simulated grass harvest at the European scale. These data were provided for European administrative units (NUTS-2 level) or country-level, when more detailed data were not available (Fig. 12 a). We compare these data to our simulation results for option G_D and varying livestock densities. For each regional average, the simulation experiment with the maximum harvest value was chosen (see section 2.6.2, Fig. 12 b) which corresponds mostly to LSU ha^{-1} in the medium ranges. Clearly, the pattern differs from the reported yield estimates (Fig. 12 a), although they are in the right order of magnitude. Additionally, those livestock densities of the tested range (0 to 2 LSU ha^{-1}) that lead to harvest fluxes closest to the reported values were selected per region (Fig. 12 c) so that the livestock densities can be inferred that lead to the observed harvest values. Harvest on intensively managed grassland e.g. in the Netherlands, United Kingdom or Ireland with values above 450 gC m^{-2} a^{-1} are underestimated by our results. These intensity levels are reached e.g. by fertilization or irrigation and not explicitly accounted for in the simulations. We assume the same limitations as in the natural vegetation by the reduction of simulated leaf level photosynthesis to 50 % in the upscaling to canopy level even though intensively managed agricultural stands are not necessarily subject to such limitations (Haxeltine and Prentice, 1996b).

Results of all presented simulations are compared to the estimates by Smit et al. (2008) within the Taylor diagrams (Fig. 13, see section 2.6.3) represented by different symbols. Regarding the four basic options (Fig. 13 a) it is obvious that both options with biomass removal without feedback to the soil carbon (D, M) have low correlations, high standard deviations and RMSD values (Fig. 13a, red and blue dots). They produce non-homogeneous distributions without correlation to the observations. The grazing options (G_D, G_R) with constant default values for the livestock densities (Fig. 13 a, orange and cyan dots) lead to homogeneous grass harvest patterns and thus underestimate the variance and display even lower correlations. Although simulations with the four basic options result in grass harvest values in the same order of magnitude as reported by regional statistics, the spatial heterogeneity cannot be captured when using homogeneous default settings.

Variation of the livestock density in option G_D (dots in Fig. 13 b) results in better representation of the standard deviation for higher values of LSU ha^{-1} but correlations remain below 0.5 (highest value of 0.41 for 1.6 LSU ha^{-1}). For the maximum harvest per geographical region, the correlation coefficient is 0.43 and the variance is low (standard deviation of 33 gC m^{-2} a^{-1}, blue star in Fig. 13 b). Choosing the LSU ha^{-1} value such that the simulated grass harvest gets nearest to the reported value results in a correlation coefficient of 0.8 and an increase in the overall variance to 65 gC m^{-2} a^{-1} (Fig. 13, purple star).

3.3 Sustainable potentials

In order to derive harvest potentials for livestock grazing at the global scale, simulation results with option G_D and livestock densities between 0 and 2 LSU ha^{-1} were analyzed (see section 2.6.2). First, the livestock density value LSU$_{max}$ was determined for each grid cell for which the maximum harvest was simulated (Fig. 14). High values can be found in temperate regions in Europe and the US mainly corresponding to bioclimatic region 7 (see Fig. 2). Arid regions (precipitation below 500 mm a^{-1}) show low values but large livestock densities are feasible e.g. in Australia or in northern Russia. This is the case for regions e.g. with strong seasonality in temperature or precipitation and a distinct but short vegetation period. There, the
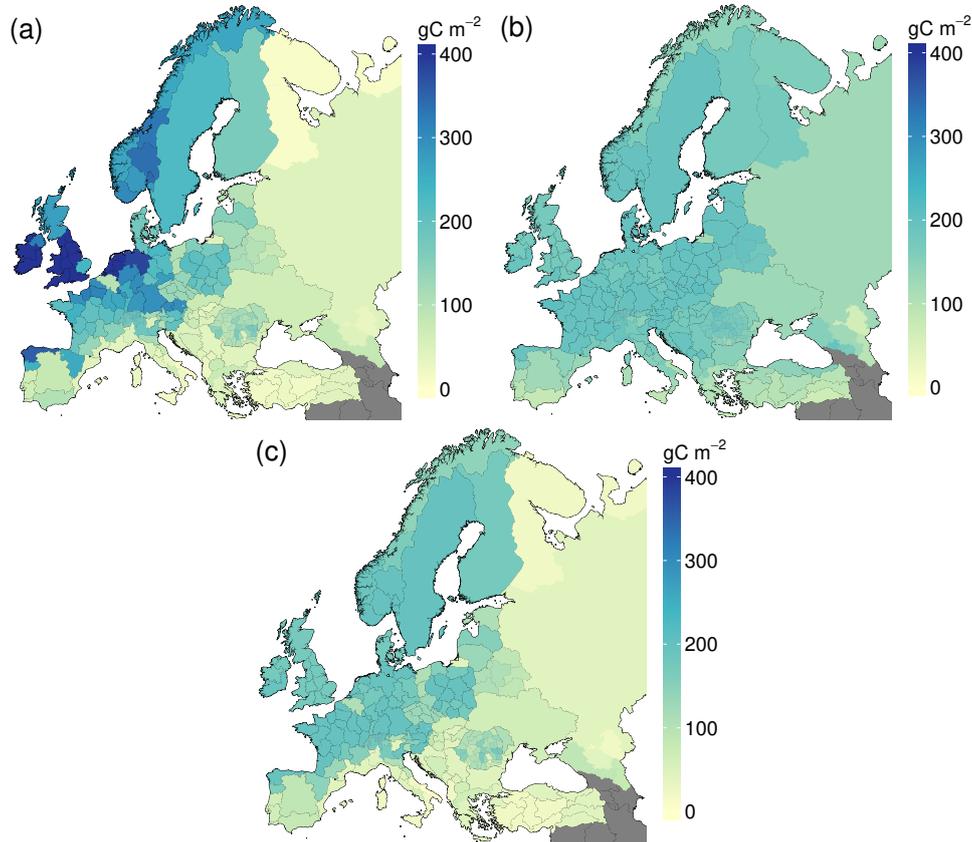
Figure 12. Average grassland harvest for European geographical regions (in gC m^{-2} a^{-1}); (a) as given by Smit et al. (2008), (b) maximum grass harvest (gC m^{-2} a^{-1}) as simulated by option G_D with varying livestock densities and (c) simulated grass harvest (gC m^{-2} a^{-1}) as simulated with option G_D with the livestock density that produces harvest values closest to observed values.

detected LSU$_{max}$ results in the highest yield but livestock at this stocking density cannot be sustained throughout the year by the pasture area, because the daily feed demand cannot be met during the less productive periods. Also, negative impacts, such as possible reductions in NPP or soil carbon, are neglected when determining LSU$_{max}$ only for maximizing the yield.

The global distribution of LSU$_{max}$ gives the highest share of more than 20 % of the grid cells for 1.2 LSU ha^{-1} (Fig. 15).
5 LSU$_{max}$ is between 1 and 1.4 LSU ha^{-1} for 56 % of the cells. The harvest achieved in grid cells with LSU$_{max}$ = 1.2 LSU ha^{-1} is 151 ± 43 gC m^{-2} a^{-1}, which is well below the actual demand of 175 gC m^{-2} a^{-1} under this livestock density. The gap between demand and simulated yield is even higher for low productive regions. In 6 % of the cells, no livestock can be fed by grazing, and in the 2.5 and 3.7 % for which 0.2 or 0.4 LSU ha^{-1} are derived as LSU$_{max}$, average yield is 11.3 and 33 gC m^{-2} a^{-1} instead of the 29.2 or 58.4 gC m^{-2} a^{-1} required by the grazing animals. These regions – belonging to rather
10 arid or cold climates (Fig. 14) – are suitable for some grass production but only during a short vegetation period. This can be underlined when deriving the distribution of LSU$_{max}$ only for Sub-Saharan Africa (AFR) or Europe (EUR) separately (red
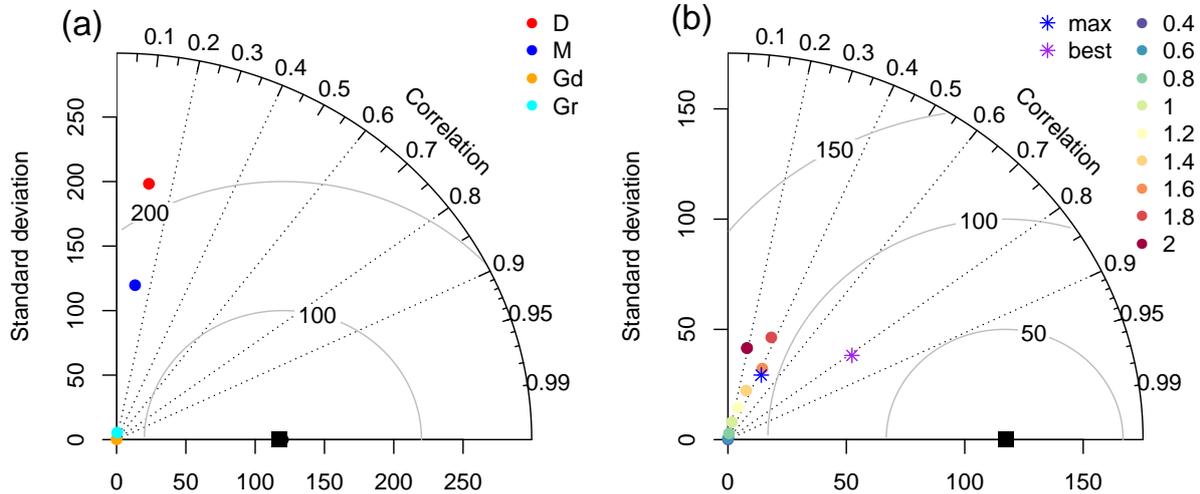
Figure 13. Taylor diagrams of simulated European grass harvest (gC m^{-2} a^{-1}) aggregated to administrative units and evaluated using estimates from Smit et al. (2008) for all grassland management options (a) and for option G_D with varying livestock densities (b). Stars in (b) denote values for the maximum harvest (blue) and values closest to those given by Smit et al. (2008) (purple) (compare distributions in Figs. 12 b, c). Perfect match to the estimates would mean that the simulated data points (colored circles) are at the location of the black box on the x-axis, having a standard deviation of 112 gC m^{-2} (distance to origin) and a correlation of 1 (angle) as well as a centered RMSD of zero (gray contour lines).
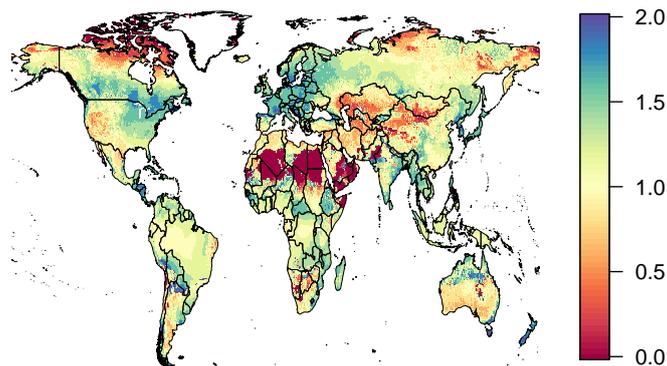
Figure 14. Distribution of livestock densities that result in maximum harvest (LSU$_{max}$ in LSU ha^{-1}) with harvest option G_D averaged over the years 1998 to 2002.

and blue bars in Fig. 15). In AFR, about 11 % of the grid cells cannot feed any livestock and LSU$_{max}$ livestock densities above 1.2 LSU ha^{-1} are found for 34 % of the cells which is similar to the global pattern (32 %) but much lower than European distributions of LSU$_{max}$ (67 %). In grid cells with LSU$_{max}$ of 1.8 LSU ha^{-1}, grass harvest is globally 232 ± 72gC m^{-2} a^{-1}, only 135 ± 102gC m^{-2} a^{-1} for AFR and 261 ± 12gC m^{-2} a^{-1} for EUR. For one third of the European grid cells (32.5 %)
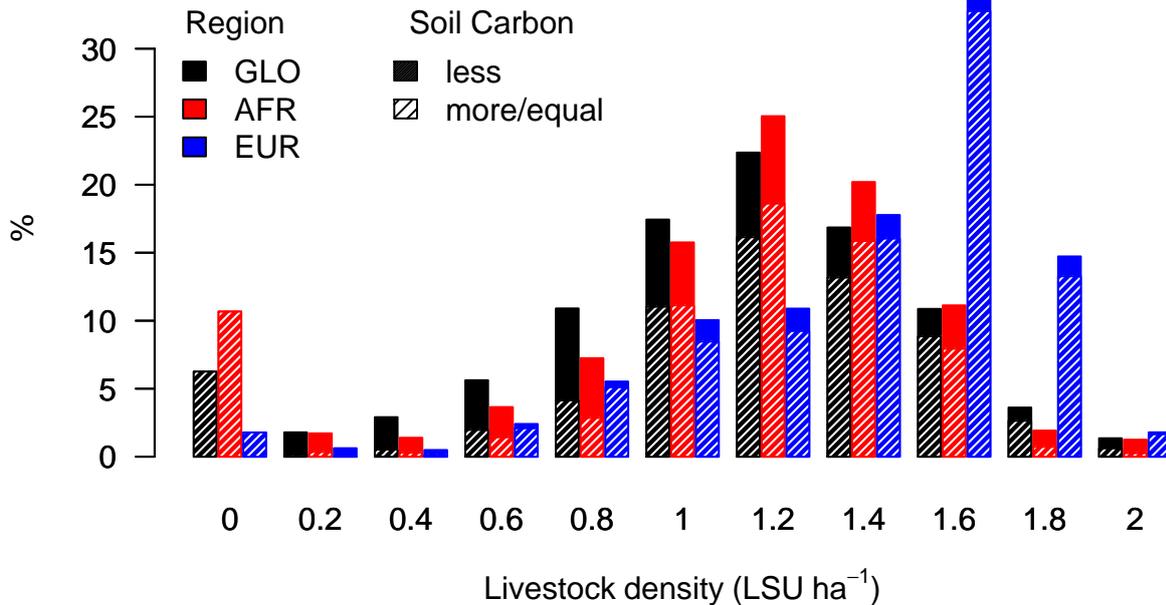
Figure 15. Distribution of livestock densities under which harvest with option G_D is maximal (LSU_{max}, section 2.6.2) as percentage of the area in the respective regions. Colors denote global values (GLO) as well as regional (EUR for Europe and AFR for Sub-Saharan Africa). The hatched sections of the bars depict the area in which maximum harvest is achieved without soil carbon loss in comparison to results under the mowing option M.

LSU_{max} is calculated as 1.6 LSU ha^{-1} with grass harvest of 233 ± 7 gC m^{-2} a^{-1} which is very close to the given demand of 234 gC m^{-2} a^{-1} at this livestock density.

In the assessment of sustainable production potentials, we also account for negative impacts of grassland management, by considering the soil carbon losses. For each of the grid cells, the soil carbon content under the derived LSU_{max} is compared to soil carbon for option M (see section 2.6.2). The bars in Fig. 15 are hatched for those grid cells, in which the difference of both soil carbon values is positive, i.e. there is no additional loss of soil carbon compared to option M. Globally, only 65 % of the area falls into this category, whereas this is the case for 70 % in AFR and 91 % in EUR. Especially in low productive regions with LSU_{max} values below 1 LSU ha^{-1}, most of the grid cells have lower soil carbon content under G_D than under M when the LSU_{max} livestock density is chosen (e.g. 91, 82 or 65 % of the grid cells with LSU_{max} of 0.2, 0.4 or 0.6 LSU ha^{-1}). In Argentina, 48 % have LSU_{max} values between 0.6 and 1 LSU ha^{-1} and 58 % of these areas are subject to soil carbon loss in comparison to the simulation with option M. Although the difference in soil carbon is negative for low LSU_{max} also in Sub-Saharan Africa and Europe (80 % in AFR and 98 % in EUR for $\text{LSU}_{max} = 0.2$ LSU ha^{-1}), this relation is quite different for higher LSU_{max}. For the cells with a LSU_{max} of 1 LSU ha^{-1}, one third in AFR and only 16 % in EUR show lower soil carbon

content than under option M. 11 % of the area in AFR have maximum harvest at livestock densities of 1.6 LSU ha^{-1} and 7.9 % of the African area sees no carbon loss in comparison to option M in this LSU$_{max}$ category. For EUR, these fractions are much larger in this category with 34 % and 33 % respectively. Thus, the potential of high grassland yields and high livestock densities in Europe without diminishing soil carbon content is much higher than for most parts of the world.

4   Discussion

4.1   Major findings & model performance

Grassland management has a strong impact on the carbon cycle, i.e. it alters yields and productivity (NPP) as well as carbon stocks in vegetation and soil. We find that increasing densities of grazing livestock can lead to both positive and negative changes in NPP and soil carbon content depending on the climatic conditions, which is in agreement with various field studies: Negative impacts of overgrazing on both productivity and soil carbon are reported in many studies (e.g. Schuman et al., 1999; Reeder and Schuman, 2002). The potential to re-establish soil sequestration by grazing management (reduction of herd sizes or exclusion of livestock) was reported from a study in China (Wang et al., 2011).

Especially in temperate and humid regions, simulated yield, productivity as well as soil carbon can increase even under moderate to high grazing livestock densities (Fig. 9). In temperate regions in the US (Conant et al., 2001) as well as in Europe (Soussana et al., 2004, 2010), carbon sequestration was measured for moderate grazing and soil improving techniques such as moderate fertilization. In Europe, the soil carbon sequestration potential was estimated to be higher for cut than for grazed grassland from a 2-year study (Soussana et al., 2007, 2010) which we could not reproduce with the current mowing option M, but assume that this is due to the simplifying assumptions made (no variation in timing and number of harvest events). In boreal regions, simulated soil carbon reduction with increasing grazing pressure is stronger than the NPP decline. Here, carbon rich soils with more than 60 kgC m^{-2} develop only without grazing animals under low NPP and respiration.

In arid regions of the US, productivity and soil carbon content increased under light grazing (Schuman et al., 1999; Reeder and Schuman, 2002) due to an acceleration of carbon turnover. We could reproduce these dynamics by simulations with option G_D and livestock densities below 0.4 LSU ha^{-1} (compare bioclimatic region 4 in Fig. 9). Even a more diverse plant community and denser rooting system were observed under these conditions (LeCain et al., 2002; Reeder and Schuman, 2002).

In tropical regions, grazing even with low livestock densities and poor as well as soil-improving management was observed to decrease soil carbon in the Amazon (Fearnside and Barbosa, 1998) and in Argentina (Abril and Bucher, 1999). In comparison to temperate regions, simulated carbon stocks under option G_D are much lower in tropical regions (< 10 kgC m^{-2}) at low livestock densities and show a much higher reduction in NPP under increasing stocking densities (Fig. 9b).

We find that the representation of the feedbacks between primary productivity, respiration, carbon turnover and soil dynamics as implemented in LPJmL, allows for simulating the effects of grass harvesting options as reported in the literature.

The newly implemented options therefore allow for an assessment of different pasture management options as well as for accounting for these important dynamics in global simulations of biogeochemical cycles or agricultural productivity. The comparison with the European grassland productivity (Smit et al., 2008) showed good agreement when considering non-homogeneous

livestock densities supporting the relevance of grassland management. They can be applied for evaluating potentials for sustainable intensification or deriving suitable pasture areas for livestock production under current and future climatic conditions.

4.2 Uncertainties & assumptions

Implementing grassland management options into a DGVM requires some assumptions and parameter value choices. We
5 discuss these in comparison to other approaches.

Mowing is a harvest technique applied mostly in Europe on pasture and productive grassland often in combination with grazing before or after the mowing event. We assume two cuts per year and the removal of all leaf carbon above a threshold of 25 gC m^{-2}. This simplifying approach is easily applied and captures the difference to productivity-dependent harvesting (default option D) and the grazing regimes. The choice of the cutting dates as 1st of June and 1st of December takes into
10 account a spring and winter cut for both hemispheres. For simplicity we stick to this regular scheme and only allow for skipping mowing events if not enough leaf biomass is available. For Germany, phenological data are collected by the German Weather Service (Kaspar et al., 2014) also for haymaking dates which give beginning of June for the first cut (average day of year 157 $\pm$ 12 days). Usually, the spring cut is triggered by a threshold amount of biomass build up before the flowering. This threshold is given e.g. as 1700 kg DM ha^{-1} (= 77 gC m^{-2}) in recommendations for pastures in temperate regions (IKC, 1993) but it is
15 hardly possible to derive a common rule for a global application from literature values. Also information on conditions for a second mowing is scarce with estimates such as leaf biomass accumulation of 3000 kg DM ha^{-1} (= 135 gC m^{-2}) or day of year 222 ($\pm$ 20 days) in the German phenological database. For the reduction of frost damage (IKC, 1993), it is recommended to mow not too late in fall (e.g. after the 1st of October in the northern hemisphere). Thus, our choice for a spring cut in the northern and southern hemisphere and an additional cut where enough leaf biomass is present represent the affirmed practices
20 for mowing. The poor timing of the winter cut, which is typically simulated too late in comparison to observational data (Kaspar et al., 2014) is acceptable as long as grass quality is not considered, as leaf carbon does not change much during the cold period of the year (very low photosynthesis and maintenance respiration). The biomass residual of 25 gC m^{-2} is lower than the parameter chosen for the ORCHIDEE model (150 g DM m^{-2} = 67.5 gC m^{-2}, Chang et al., 2013).

Although differences in livestock grazing exist between systems globally, the major differences to other treatments can
25 be expressed by the chosen options G_D and G_R and the ability to vary livestock densities. Livestock is either reared inhouse and gets additional feed from cropland or is present on the pasture daily or for a short time period. Here, the focus lies on the grassland treatment and not directly on the development and feed security of the livestock itself. This can be addressed with the presented modeling approach with the stocking density specifying the maximum removal of leaf carbon and the grazing period specifying the timing and duration of leaf carbon removal. The threshold for the beginning of grazing
30 is chosen differently for the continuous grazing with 5 gC m^{-2} and rotational grazing with 40 gC m^{-2} which represents management on pasture of different productivity. For rotational grazing, some estimates can be found in recommendations by IKC (1993) with about 700 kg DM ha^{-1} (= 30 gC m^{-2}) or Blanchet et al. (2003) with a minimum of 4 inches of grass with 250 lb DM acre^{-1} inch^{-1} (= 40 gC m^{-2}). Williams and Hall (1994) do not give a minimum but optimal grass height of 7 inches and 300 lb DM acre^{-1} inch^{-1} (= 84 gC m^{-2}) and Undersander et al. (2002) recommend the beginning of the grazing

period at 4 to 8 inches of grass (= 40 to 48 gC m^{-2}). The end of the grazing period with 5 gC m^{-2} is chosen a bit lower than other modeling studies (e.g. for the ORCHIDEE model: 300 kg DM ha^{-1} = 13.5 gC m^{-2}, Chang et al., 2013).

Assumptions are necessary also with respect to the specification of the spatial distribution of management activities (Chang et al., 2013; Sandor et al., accepted). Here, we chose to analyze scenarios with spatially homogeneous management varia-
5   tions. With the current uncertainties in livestock density distributions (Kruska et al., 2003), management intensity and even distribution of pasture areas (Portmann et al., 2010) a global assessment of the current role of grassland management for bio-geochemical cycles is not feasible. Recently, a global dataset of grassland management was derived by combining regional data on livestock and its feed demand with satellite data and model simulations (Chang et al., 2016). Although this dataset might be of great importance for improving managed grassland assessments, Chang et al. (2016) also state that their method results in
10   biomass production deficits in some areas caused by uncertainties in production system settings, pasture area distributions and in the mapping of regional averages to gridded data. Thus, further research and harmonization of these approaches are needed.

4.3   Further development

The implementation of the four basic harvesting schemes on managed grassland is a starting point for a variety of possible further developments, applications and extensions. In order to reflect the actual contribution of managed grasslands to global
15   biogeochemical fluxes, improvements of global datasets (such as Chang et al., 2016) on livestock densities and management settings are needed. The intensity of the grassland management with fertilization and irrigation could be included as well corresponding to the intensity level that was established in Fader et al. (2010). This would enable to better capture highly pro-ductive regions in the United Kingdom or the Netherlands and to assess pathways to conventional or sustainable intensification management. It also seems sensible to establish combined harvesting schemes with cutting and grazing events in LPJmL when
20   appropriate information about the application of such schemes is available. Such information would enable improvements of the current implementation as well by e.g. deriving mowing events depending on grass biomass or growing degree days.

The role of heterogeneity in livestock distributions and grazing activities is currently not considered in the model. In the cur-rent implementation, the grass leaf biomass is reduced by a certain amount each day (paragraph 2.4.3). Ideally, the modeling approach should capture the roaming of the livestock by reducing some plants completely, covering some with manure, tram-
25   pling others and undisturbed growth of the remaining. An improvement of a globally applicable approach could distinguish the frequency of leaf biomass removal depending on the livestock density and prolong the interval from daily to weekly or monthly time periods.

Implementing more realistic grassland management options in DGVMs would help to improve analyses of future changes in the biogeochemistry of grasslands and their implications for sustainable land management. While we have focused on carbon,
30   the importance of differences in grassland management options still needs to be assessed for water and eventually nitrogen dynamics. Human interference in the carbon balance of grasslands worldwide can have non-linear effects which might not be captured correctly when only considering it as a human appropriation of NPP (HANPP, Erb et al., 2009). The HANPP concept is based on the assumption that carbon sequestration of natural vegetation is reduced by human activities (Erb et al., 2016a). However, our results show that in grasslands under light to moderate grazing, the feedback on productivity may lead not only to

higher carbon sequestration but also higher storage of carbon in the soil for a longer period. Especially with increasing livestock densities, we find a substantial feedback on NPP and soil carbon stocks. As such, these effects should be accounted for when assessing human impacts on the carbon dynamics on pasture areas. Applying an approach as we introduced and applied in this study would allow to disentangle the effects of climatic changes and changes in management on grassland which would help

5 to reduce uncertainties and would allow for assessing options for adaptation to climate change.

Whereas our implementation of grassland management options is a necessary first step that establishes a major improvement in modeling capacities, the list of Kipling et al. (2016) suggests a range of further improvement strategies for grassland modeling and climate change impact assessments with these. It remains to be tested which of these suggestions are suitable for an implementation in a global-scale model and how sensitive modeling results are to these changes.

10 ## 5   Conclusions

The presented simulation results of the implementation of grassland management in the DGVM LPJmL can be used to better investigate the effect of different management practices on the global terrestrial carbon budget. 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.

15   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.

20 ## 6   Code availability

The code of the model LPJmL is available upon request for review purposes and for collaboration projects. Information on model versions and the download procedure can be found here https://www.pik-potsdam.de/research/projects/activities/ biosphere-water-modelling/lpjml/versions.

7   Data availability

25 Simulation results and the code for the analysis are available upon request.

Author contributions. SR, JH, and CM designed the model improvement which was implemented by SR, JH and JtR. PAL, LB, ebp, IW and ABo contributed to parameter specification and design of the experiments. SR performed model simulations and analysis. SR wrote the manuscript with contributions from all co-authors.

Competing interests.   We declare non competing interests.

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