Supplementary Information

## Text S1. Parameter settings in ORCHIDEE-GM

ORCHIDEE-GM was applied to simulate GHG budgets and ecosystem carbon stocks under climate, $CO_2$ and management changes for Europe. Its structure and rather generic forcing fields, in principle, also allow global gridded simulations. But an extension of the model to regions outside Europe requires first a calibration of plant traits and parameters. The $Vc_{max}25$ = 55 μmol m$^{-2}$ s$^{-1}$ and $SLA_{max}$ = 0.048 m$^2$ per g C in ORCHIDEE-GM were previously derived from observations and indirectly evaluated against eddy-flux tower measurements of GPP for temperate C3 grasslands in Europe (Chang et al., 2013, 2015b). The global TRY database gives SLA values for C4 grasses, of 0.0192 m$^2$ g$^{-1}$ dry matter (0.0403 m$^2$ per g C with a mean leaf carbon content per dry matter of 47.61%; Kattge et al., 2011). Thus, we have set the value of $SLA_{max}$ = 0.044 m$^2$ per g C for C4 grasses in ORCHIDEE-GM to fit the mean value from the TRY estimate, as we did previously for C3 grasses (Chang et al., 2013). The parameter $Vc_{max}$25 cannot be directly measured, but it is usually derived from A/$C_i$ curves in C3 or C4 photosynthesis models (C3: Farquhar et al., 1980; C4: Collatz et al., 1992) where A is the leaf-scale net $CO_2$ assimilation rate and $C_i$ the partial pressure of $CO_2$ in leaf intercellular spaces. C3 grasses usually have higher $Vc_{max}$25 than C4 species. For example, a range of 43 – 131 μmol m$^{-2}$ s$^{-1}$ for $Vc_{max}$25 of C3 grasses, and of 15 – 26 μmol m$^{-2}$ s$^{-1}$ for C4 grasses was derived from an observation-constrained photosynthesis model by Feng and Dietze (2013). Verheijen et al. (2013) further collected data from the literature showing a $Vc_{max}$25 range of 24 – 118 μmol m$^{-2}$ s$^{-1}$ for C3 grasses (15 observations) and 22 – 46 μmol m$^{-2}$ s$^{-1}$ for C4 grasses (28 observations). Based on these estimates, we decided to keep the value of $Vc_{max}$25 = 55 μmol m$^{-2}$ s$^{-1}$ previously calibrated in Europe for all C3 grasses, and to set $Vc_{max}$25 = 25 μmol m$^{-2}$ s$^{-1}$ for C4 grasses. These values may not reflect differences in nitrogen, and phosphorus availability between locations, nor adaptation or species changes within a C3 or C4 grassland, but they are within the range of observations made under different conditions, and consistent with values used by other terrestrial ecosystem models (Table S1).

## Text S2. Domestic ruminant stocking density

FAOSTAT (2014) provides annual country-averaged statistical data for dairy cows, beef cattle, sheep and goats of livestock numbers (with the units in head). The gridded livestock of the world (GLW) (Wint and Robinson 2007) uses environmental variables to spatially distribute national data down to grid-level. Recently, an improved database using sub-national data (Gridded Livestock of the World v2.0, Robinson et al., 2014) has been generated, and was first corrected to match the polygon values of the observed data and then to match the FAOSTAT country values in 2006.

Feed requirements for an animal may differ significantly for different species across countries. For facilitating cross-country comparison by taking into account all categories of livestock, FAO (2003) presents the conversion factors for major livestock categories that take into account "feed requirements" for the animal. However, the conversion factors provided by FAO (2003) only contain values for 11 regions of the world, and cannot represent the within-regional (country-specific) variation. To obtain a more consistent and realistic ruminant stocking density, livestock species in GLW v2.0 are converted here to livestock unit (LU) based on the calculation of metabolisable energy (ME) requirement for each country (see Supporting Information of Chang et al., 2015b for details). In this study, ME requirement, the amount of energy (MJ $day^{-1}$) an animal needs for maintenance and for activities such as lactation, and pregnancy, were calculated following the IPCC Tier 2 algorithms (IPCC, 2006 Vol 4, Chapter 10, Eqs. 10.3 to 10.13). One LU is defined as an average adult dairy cow producing 3000 kg milk annually, with live body weight of 600 kg (Eurostat, 2013; with ME requirement of ca. 85 MJ $day^{-1}$, and with dry matter intake of ca. 18 kg daily, calculated in Supporting Information Text S1 of Chang et al., 2015b). The conversion factor (F) for livestock category *i* (i.e., cattle, sheep or goats) in country *j* is calculated as:

$$F_{i,j} = \frac{ME_{head,i,j}}{ME_{LU}} \qquad \text{(S1)}$$

where $ME_{LU}$ is the ME requirement by one LU; and $ME_{head,i,j}$ is the ME requirement per head of livestock category *i* in country *j*, given by:

$$ME_{head,i,j} = \frac{ME_{i,j}}{N_{i,j}} \qquad \text{(S2)}$$

where $N_{i,j}$ is the total number (in head from FAOSTAT) of animals in livestock category *i* in country *j*; $ME_{i,j}$ is the total ME requirement of livestock category *i* in country *j*, which includes the ME of animals for different production types (i.e., animals producing milk, slaughtered for meat, or animals neither producing milk nor slaughtered for meat; see Supporting Information Text S1 of Chang et al., 2015a for details). To be consistent with the country-level livestock data used by GLW v2.0, statistical data (FAOSTAT, 2014) for the reference year 2006 were used to calculate the conversion factors.

After conversion to LU, the livestock densities from GLW v2.0 were aggregated to total ruminant density. For each grid-cell *k* in country *j*, the total ruminant density for the reference year 2006 ($D_{ref,k}$; including cattle, sheep and goats) can be calculated as:

$$D_{ref,k} = \sum (D_{i,k} \times F_{i,j}) \qquad \text{(S3)}$$

where $D_{i,k}$ is the density of livestock category *i* in grid-cell *k* from GLW v2.0 dataset. To be consistent with the spatial resolution of climate forcings used to drive global vegetation models, the total ruminant density ($D_{ref,k}$) was aggregated from the original resolution (about 1 × 1 km at the Equator) to $0.5^{o} \times 0.5^{o}$ (about 50 × 50 km at the Equator) considering suitable areas in livestock production systems (Robinson et al., 2011), and was then converted to the unit of LU per hectare of land area in each grid-cell (Fig. S3).

**Text S3. Historic changes of domestic ruminant stocking density (1901-2012)**

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

$$D_{m,k} = D_{ref,k} \times I_{m,j} \qquad \text{(S4)}$$

where $I_{m,j}$ is the ME index for country $j$ in year $m$, and given by:

$$I_{m,j} = \frac{ME_{m,j}}{ME_{ref,j}} \qquad \text{(S5)}$$

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

For the period 1900-1960, regional livestock numbers by 10-year interval derived from Mitchell (1993, 1998a,b) were scaled in 1961 to match the FAOSTAT data (data processed by Dr. Kees Klein Goldewijk, and given for 17 world regions with the numbers of cattle, sheep and goats; available in the HYDE database: http://themasites.pbl.nl/tridion/en/themasites/hyde/landusedata/livestock/index-2.html). The 17 world regions were designated for global change research, as defined by Kreileman et al. (1998). Linear interpolation is applied to calculate the regional livestock numbers of each year. Assuming the meat (carcass weight) and milk yield for the period of 1900-1960 are the same as that for 1961 from FAOSTAT (2014), the ME index ($I_{m,j}$) is then simply extended to 1900-1960 through:

$$I_{m,j} = I_{1961,j} \times \frac{ME_{m,j}}{ME_{1961,j}} \qquad \text{(S6)}$$

where $I_{1961,j}$ is the ME index for country $j$ in the year 1961; $ME_{m,q}$ and $ME_{1961,q}$ are the total ME requirement by all ruminants for region $q$ in year $m$ and 1961 respectively.

**Text S4. Grazing-ruminant density and its historic change**

Spatial statistical information on grazing-ruminant 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 density in grid-cell $k$ in year $m$ ($D_{grazing,m,k}$) as:

$$D_{grazing,m,k} = \frac{D_{m,k}}{f_{grass,m,k}} \quad \text{(S7)}$$

where $D_{m,k}$ is the total ruminant density in unit of LU per hectare of land area; 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. Figure S4 shows an example map of grazing-ruminant density for 2000. 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 for the density map given the fact that too low grazing-ruminant density is not economical in practice.

The historic land-cover change maps were based on GLC2000 land-cover data (Bartholomé and Belward, 2005; Eva et al., 2004) as reference map for the year 2000. To be used by global vegetation models like ORCHIDEE-GM, GLC2000 land-cover data were aggregated to 0.5$^{o}$ × 0.5$^{o}$, and grouped into plant functional types (PFT) using the reclassification method from Poulter et al. (2011). The fraction of cropland in the PFT map was further constrained by the cropland and pasture area of 2000 in the HYDE 3.1 dataset (Klein Goldewijk et al., 2011). The above processes produced a reference GLC2000-based PFT map for the year 2000. The land-use changes derived from Hurtt et al. (2011) were applied to this reference PFT map to constrain the land-cover changes of forest, grassland (combining pasture and natural grassland), and cropland during the period 1901-2005. As a result, a set of historic PFT maps suitable for global vegetation models were established distinguishing global land-cover changes for the period of 1901-2005. However, note that management types of grassland (e.g., mown, grazed or unmanaged) are not separated in these historic PFT maps and will be distinguished in Text S6.

**Text S5. Fertilizer application over grassland**

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, where gridded mineral fertilizer and manure-N application rate for European grasslands in the European Union (EU-27) was estimated by the CAPRI model (see Leip et al., 2011, 2014) based on combined information from official and harmonized data sources such as Eurostat, FAOstat and OECD, and spatially dis-aggregated using the methodology described in Leip et al. (2008). In order to establish the gridded fertilizer application rate for other world regions, we use the animal manure-N fertilizers on grasslands for 17 world regions at 1995 derived from various sources (e.g., IFA, 1999; FAO/IFA/IFDC, 1999; FAO/IFA, 2001) and synthesized by Bouwman et al. (2002a; also see Table S3 for detail). Note that animal manure-N was estimated as all excretion from cattle, pigs, and poultry, except that part excreted during grazing, use of manure as fuel, and storage losses of $NH_3$ (Bouwman et al., 2002a).

To downscale the total amount of regional N fertilizer to grid-level (except for OECD Europe and Eastern Europe where gridded data are available), the rules suggested by Bouwman et al. (2002b) are used, namely: animal manure application to grasslands is assumed to occur in mixed farming systems that are defined as grasslands occurring in grid-cells where the arable land coverage exceeds 35% in developed countries and 15% in developing countries. Here, the grasslands that satisfy the above rules are cited as manure-suitable grassland. In addition, assuming higher ruminant density produces more manure, we calculate the manure-N application rate for each grid-cell $k$ in year 1995 ($F_{manure,1995,k}$) as:

$$F_{manure,1995,k} = R_q \times D_{1995,k} \qquad \text{(S8)}$$

where $D_{1995,k}$ is the domestic ruminant density (from the maps established in Text S1) in grid-cell k where manure-suitable grassland exists in 1995; and $R_q$ is the manure-N application rate per LU for region $q$, and given by:

$$R_q = \frac{Manure_q}{N_q} \qquad \text{(S9)}$$

where $Manure_q$ is the total amount of manure-N fertilizer in region $q$ from Bouwman et al., (2002a, b); $N_q$ is the total ruminant numbers in region $q$ in 1995, which can be calculated by:

$$N_q = \sum (D_{1995,k,q} \times A_{k,q}) \qquad \text{(S10)}$$

where $D_{1995,k,q}$ is the ruminant density (from the maps established in Text S2) of grid cell $k$ in region $q$; and $A_{k,q}$ is the land area of grid cell $k$ in region $q$.

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 fertilized areas are given indicating that not all the grassland is fertilized. Thus to apply the mean N fertilizer application rate on grassland areas similar to that from FAO/IFA/IFDC/IPI/PPI (2002), we set a threshold of domestic ruminant density for each country. The total grassland area with ruminant density over the threshold (Table S4) will be similar to the fertilized area given by FAO/IFA/IFDC/IPI/PPI (2002). However, note that the regional total amount of mineral-N fertilizer aggregated from country-scale data in FAO/IFA/IFDC/IPI/PPI (2002) is much lower than the values given in Bouwman et al. (2002a; see Table S3 for detail).

**Text S6. Historic changes in fertilizer application over grassland (1901-2012)**

Given the assumption that higher ruminant density produces more manure (Text S4), the manure fertilizer application rate is assumed to change along with changes in ruminant density. It is calculated as:

$$F_{manure,m,k} = F_{manure,1995,k} \times \frac{D_{m,k}}{D_{1995,k}} \qquad \text{(S11)}$$

where $F_{manure,m,k}$ and $F_{manure,1995,k}$ is the manure N application rate for grid-cell $k$ in year $m$ and 1995 respectively; $D_{m,k}$ and $D_{1995,k}$ are the domestic ruminant density (from the maps established in Text S1) in grid-cell k in year m and 1995 respectively.

The temporal evolution of gridded mineral-N fertilization for the EU-27 has been described by Chang et al. (2015c) for the period 1901-2010. For the other 13 countries, the country-scale total nitrogenous fertilizer consumption data (TNF; derived from FAOSTAT, 2014; available for the period 1961-2002) were used to extrapolate the mineral-N application rate. For Azerbaijan and Belarus, where FAOSTAT only provide data for 1992-2002, the variation of nitrogenous fertilizer consumption by the former USSR is used for the period 1961-1991. The rate of mineral-N application for grid-cell $k$ in year $m$ in country $j$ ($F_{mineral,m,k,j}$) changes along with the variation of country-scale TNF, and is calculated as:

$$F_{mineral,m,k} = F_{mineral,2000,k} \times \frac{TNF_{m,j}}{TNF_{2000,j}} \quad \text{(S12)}$$

where $F_{mineral,2000,k}$ is the mineral-N application rate for grid-cell $k$ in year 2000, which is given by FAO/IFA/IFDC/IPI/PPI (2002); $TNF_{m,j}$ and $TNF_{2000,j}$ are the country-scale total nitrogenous fertilizer consumption in country $j$ in year $m$ and 2000 respectively. The mineral-N fertilization rate after 2002 is taken as constant and the same as that in 2002. For the period 1901-1960, the same set of rules as applied for the EU-27 (see section ‘Simulation set-up’ in Chang et al., 2015c for details) are used: 1) no mineral-N fertilizer was applied over grassland before 1950; and 2) For the period 1951-1961, the rate of application is assumed to increase linearly from zero to the level of 1961.

**Text S7. Wild animals over unmanaged grassland**

In prehistoric times, wild animals were distributed all over the world. Now, along with the development of civilization and especially the population growth after the industrial revolution, the habitats of wild animals have been mostly cultivated as cropland and pasture. Nowadays, wild animals can only exist on sparsely populated land (e.g., high latitude region such as Siberia, and Amazonian forest) or reserves (e.g., reserves in African savanna). Significant population of wild herbivores living on grassland can only be found in North America, Scandinavia, the former USSR and Africa (Bouwman et al., 1997). Nevertheless, wild herbivores are estimated to eat 3% -10% of the consumable Net Primary Productivity (NPP) where they exist (Warneck, 1988). They thus contribute to the GHG balance of grassland. Gridded maps of wild herbivore density are not available, therefore population data for larger herbivores were derived from the literature and collected by Bouwman et al. (1997; also see Table S2 for details). The populations of these larger herbivores were first converted to LU (according to the metabolisable energy (ME) requirement calculated based on mean weight; Table S2), and then distributed to suitable grassland based on grassland aboveground (consumable) NPP simulated from ORCHIDEE-GM. Here the suitable grassland in each grid-cell is defined by a set of rules. For North America, Scandinavia, and the former USSR where moose and reindeer are major wild herbivores, the suitable grassland is that in the grid-cell where: 1) grassland fraction is over 10%; 2) the fraction of unmanaged (extensive) grassland is over 70%; 3) forest fraction is over 40%; and 4) human population density is lower than 50 people km$^{-2}$. For Africa where bovids are mainly grazing on savanna, the suitable grassland is grassland in the grid-cell where: 1) grassland fraction is over 20%; 2) the fraction of unmanaged (extensive) grassland is over 50%; and 3) human population density is lower than 50 people km$^{-2}$. The wild herbivore density for grid-cell $k$ ($D_{wild,k}$) is calculated as:

$$D_{wild,k} = F_{wild,k} \times (ANPP_{suit,k} \times A_{suit,k}) \qquad \text{(S13)}$$

where $ANPP_{suit,k}$ is the aboveground NPP of unmanaged (extensive) grassland simulated by ORCHIDEE-GM averaged for the period of 1971-1990; $A_{suit,k}$ is the corresponding suitable grassland area of grid cell $k$ in the historic land-cover change maps (Text S3); and $F_{wild,k}$ is the factor for wild herbivore density given by:

$$F_{wild,k} = \frac{N_{wild,q}}{\sum (ANPP_{suit,k,q} \times A_{suit,k,q})} \qquad \text{(S14)}$$

where $N_{wild,q}$ is the population of larger herbivores in region $q$. For Africa, median population of bovids (300 million head) was used for density distribution, given the estimated population range (100 – 500 million head; Van Soest et al., 1994; McDowell 1976; Table S2). The resultant wild herbivore density (Fig. S5) is assumed to be constant during the period of 1901-2012 because no population data were available.

**Text S8. Specific grazing strategy for wild animals**

Unlike domestic ruminants fed by harvested forage, crop products and/or by-products during the non-growing season, wild herbivores stay on grassland all year round. To simulate the grazing performance of wild herbivores, a specific grazing strategy was introduced in ORCHIDEE-GM v3.1. We assumed that: 1) during growing season when grass biomass is sufficient to support grazing, wild herbivores will eat the same amount of fresh grass biomass as domestic ruminants (e.g., with daily ME requirement of ca. 85 MJ LU$^{-1}$ day$^{-1}$ and intake of 18 kg DM LU$^{-1}$ day$^{-1}$); 2) during the non-growing season when grass biomass is insufficient to support grazing, wild herbivores will eat dead grass instead (with daily intake of 10 kg DM $LU^{-1}$ $day^{-1}$ given the unpalatability of dead grass). The dead grass is defined as fresh litter from grass biomass only, excluding the litter from excreta of grazing animals.

ORCHIDEE-GM v3.1 simulated a total annual consumption by wild herbivores of 166 – 726 million tonnes dry matter (DM) of the 8372 million tonnes DM in aboveground NPP (consumable NPP) over suitable grassland (Table S5), which comprises 2% - 11% of the consumable NPP, similar to the range given by Warneck (1988). The fraction of consumption in consumable NPP varied from 1% in the former USSR to 9% in Scandinavia indicating the different significance of wild herbivores on grassland.

**Supplementary Tables and Figures**

Table S1. The maximum rate of rubisco carboxylation activity at a reference temperature of 25°C ($Vc_{max}25$, μmol $m^{-2}$ $s^{-1}$) used in the models and the values from observation-based estimates.

| | $Vc_{max}25$ (μmol $m^{-2}$ $s^{-1}$) | | |
|---|---|---|---|
| **Model** | C3 grass | C4 grass | Reference |
| ORCHIDEE-GM | 55 | 25 | Chang et al., 2013; this study |
| Yale Interactive terrestrial Biosphere model (YIB) | 43 | 24 | Yue and Unger, 2015 |
| PEcAn/ED model | 58 | 21 | Dietze et al., 2014 |
| ACCESS-CABLE | 60 | 10 | Kowalczyk et al., 2013 |
| Soil-plant-atmosphere (SPA) model | 73.6 | 47 | Whitley et al., 2011; data colleted from Zeppel et al., 2008; Ghannoum et al., 2005 |
| **Observation based estimate** | | | |
| | 43.21-130.48 | 15.22-25.57 | Feng and Dietze, 2013 |
| | 24.4-118.4 | 21.7-46.3 | Verheijen et al., 2013; data collected from Domingues et al., 2010; Kattge et al., 2009; Niinemets, 1999, 2001 |

Table S2. The population of wild herbivores in the world[a].

| Wild Herbivores | North America | Scandinavia | Former USSR | Africa | Source | Mean weight (kg)[b] | ME requirement (MJ $day^{-1}$)[c] |
|---|---|---|---|---|---|---|---|
| Moose (Million head) | 0.9 | 0.6 | 1 | | Drew and Baskin, 1989 | 350 | 50 |
| Reindeer (Million head) | 16.5 | 0.8 | 2.7 | | Drew and Baskin, 1989 | 90 | 13 |
| Bovids (Million head) | | | | 100-500 | Van Soest et al., 1994; McDowell 1976 | 125 | 18 |
| Total (Million LU) | 3.1 | 0.5 | 1 | 21-106 | | 600 | 85 |

[a] Data were derived from literature and collected by Bouwman et al. (1997).

[b] The mean weight of wild herbivores were derived from Crutzen et al. (1986). For mean weight of Bovids in Africa, the weight of wildebeest was used.

[c] The metabolisable energy (ME) requirement of 1 LU was calculated following the IPCC Tier 2 algorithms (IPCC, 2006 Vol 4, Chapter 10, Eqns 10.3 to 10.13), and described in Text S1. The ME requirement for 1 head of Moose, Reindeer and Bovids was simply calculated based on their metabolic body weight (i.e., $(\text{mean weight})^{0.75}$) and the ratio between their metabolic body weight and that for 1 LU, given the facts that: 1) net energy (NE) for maintenance (NEm) is the major part of total ME, and calculated based on the metabolic body weight; 2) Some other parts of ME, such as NE for activity, for pregnancy, and for draft power (looking for food), are directly correlated to NEm.

Table S3. Animal manure-N and mineral-N fertilizers on grasslands for 17 world regions at 1995 synthesized by Bouwman et al. (2002a), and the mineral-N fertilizers on grasslands at 1999/2000 derived from FAO/IFA/IFDC/IPI/PPI (2002).

| Region Name | Animal manure-N (1000 tonne) | Mineral-N (1000 tonne) | Mineral-N (1000 tonne; FAO/IFA/IFDC/IPI/PPI, 2002) |
|---|---:|---:|---:|
| Canada | 207 | 0 | 0 |
| USA | 1583 | 0 | 0 |
| Central America | 351 | 25 | 3 |
| South America | 1051 | 12 | 77 |
| Northern Africa | 34 | 0 | 17 |
| Western Africa | 137 | 0 | 0 |
| Eastern Africa | 148 | 0 | 0 |
| Southern Africa | 78 | 31 | 26 |
| OECD Europe | 3085 | 3074 | 2616 |
| Eastern Europe | 737 | 210 | 46 |
| Former USSR | 2389 | 760 | 135 |
| Middle East | 167 | 17 | 0 |
| South Asia | 425 | 0 | 0 |
| East asia | 1404 | 0 | 0 |
| South East Asia | 477 | 0 | 0 |
| Oceania | 52 | 175 | 75 |
| Japan | 59 | 27 | 102 |
| World | 12386 | 4331 | 3097 |

Table S4. Fertilized area, average mineral-N fertilizer application rate, total mineral-N fertilizer used over grassland, the threshold of ruminant density and the corresponding grassland area for the 13 non-EU countries. Fertilized area, average mineral-N fertilizer application rate, and the total mineral-N fertilizer for 1999/2000 were derived from FAO/IFA/IFDC/IPI/PPI (2002). The threshold of ruminant density was chosen to make total fertilized grassland area be similar to the fertilized area given by FAO/IFA/IFDC/IPI/PPI (2002).

| Name | Fertilized area (1000 ha) | Fertilized rate (kg N $ha^{-1}$) | Total N fertilizer (1000 tonne) | Threshold (LU $ha^{-1}$) | Fertilized Area above threshold (1000 ha) |
|---|---:|---:|---:|---:|---:|
| Australia | 30000 | 2.5 | 75.0 | 0.10 | 29730 |
| Azerbaijan | 54 | 6.0 | 0.3 | 0.31 | 141 |
| Belarus | 2405 | 40.0 | 96.2 | 0.15 | 2743 |
| Chile | 900 | 45.0 | 40.5 | 0.29 | 916 |
| Dominican Republic | 13 | 80.0 | 1.0 | 0.70 | 152 |
| Japan | 965 | 106.0 | 102.3 | 0.36 | 1023 |
| Mexico | 20 | 80.0 | 1.6 | 0.63 | 113 |
| Morocco | 341 | 51.0 | 17.4 | 0.23 | 365 |
| Norway | 145 | 100.0 | 15.0 | 0.22 | 153 |
| South Africa | 1750 | 15.0 | 26.3 | 0.24 | 1901 |
| Switzerland | 360 | 45.0 | 16.0 | 0.23 | 381 |
| Uruguay | 650 | 10.0 | 6.5 | 0.66 | 694 |
| Venezuela | 600 | 50.0 | 30.0 | 0.75 | 701 |

Table S5. The consumable NPP for wild herbivores and actual consumption simulated by ORCHIDEE-GM.

| | North America | Scandinavia | Former USSR | Africa | World total |
|---|---|---|---|---|---|
| Consumable ANPP (Million tonne DM) | 922 | 37 | 1032 | 6381 | 8372 |
| Total consumption (Million tonne DM) | 20 | 3 | 6 | 136 - 696* | 166 - 726 |
| Portion | 2% | 9% | 1% | 2% - 11% | 2% - 9% |

* The values for Africa come from the range of the Bovids population given in Table S2.

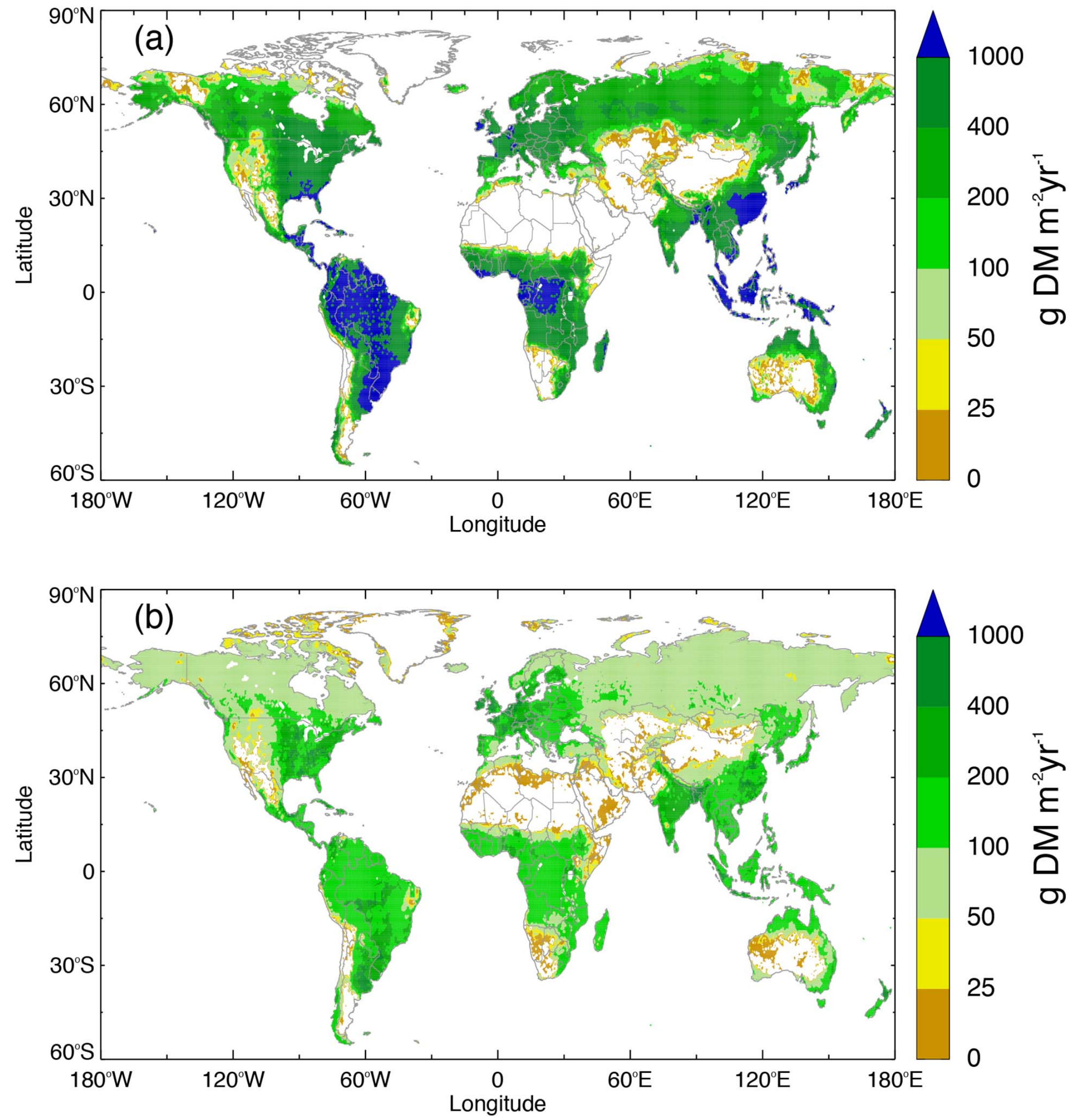


Figure S1. (a) The potential harvested biomass from mown grassland and (b) the potential biomass consumption over grazed grassland, simulated by ORCHIDEE-GM. Data were averaged for the period 1991-2010. The historic gridded grazing-ruminant density used as input to ORCHIDEE-GM v3.1 was described in Text S4. It is noteworthy that a minimum grazing-ruminant density of 0.2 LU $ha^{-1}$ was set to drive the model given the fact that too low grazing-ruminant density is not economical in practice.

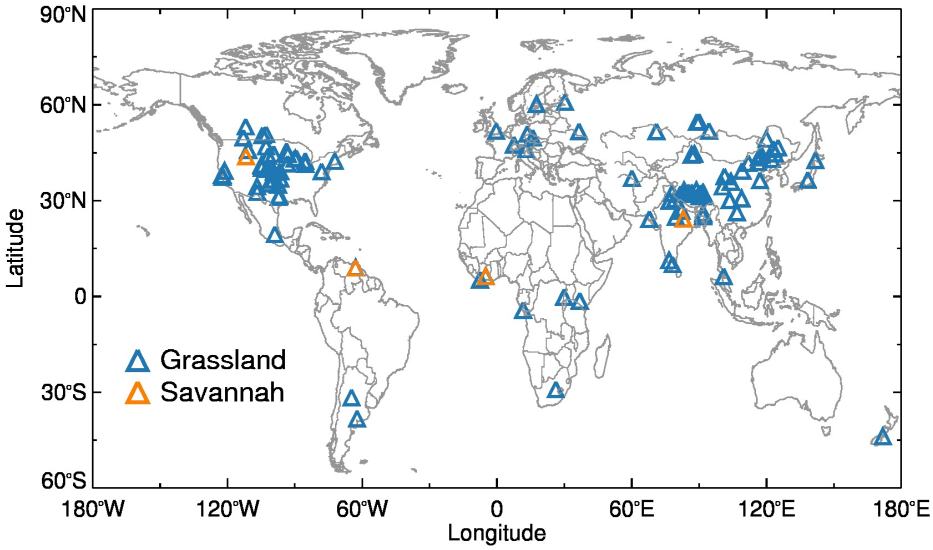


Figure S2. Spatial distribution of grassland NPP observations. In total, 214 NPP observations from 113 sites all over the world (including grassland, and savanna) are used in this study.

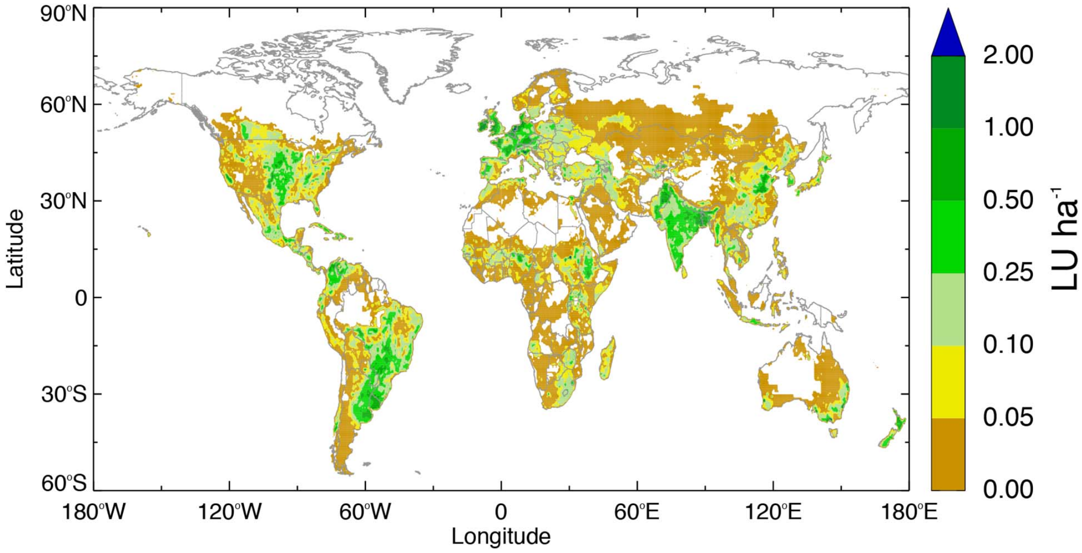


Figure S3. Domestic ruminant density of the world for 2006. Density data was derived from the Gridded Livestock of the World v2.0 (GLW v2.0; data on ruminants including cattle, sheep and goats were used; Robinson et al., 2014), converted to livestock unit (LU), and aggregated to the resolution of $0.5^o \times 0.5^o$ (see Text S2 for details).

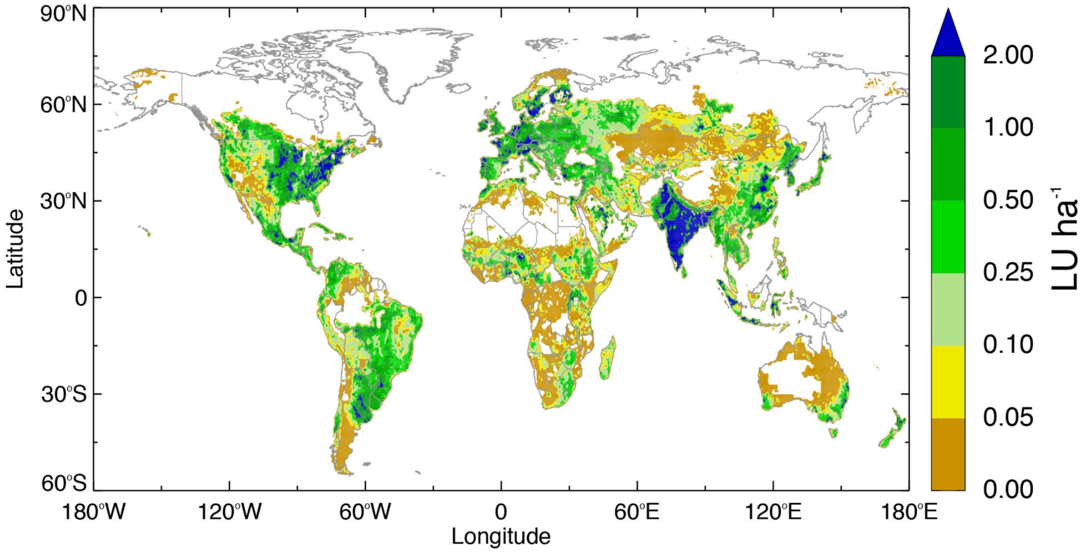


Figure S4. Grazing-ruminant density of the world for 2000. Grazing-ruminant density was calculated based on the domestic ruminant density (Text S2 and S3) and the grassland area from the historic land-cover change maps (see Text S4 for detail).

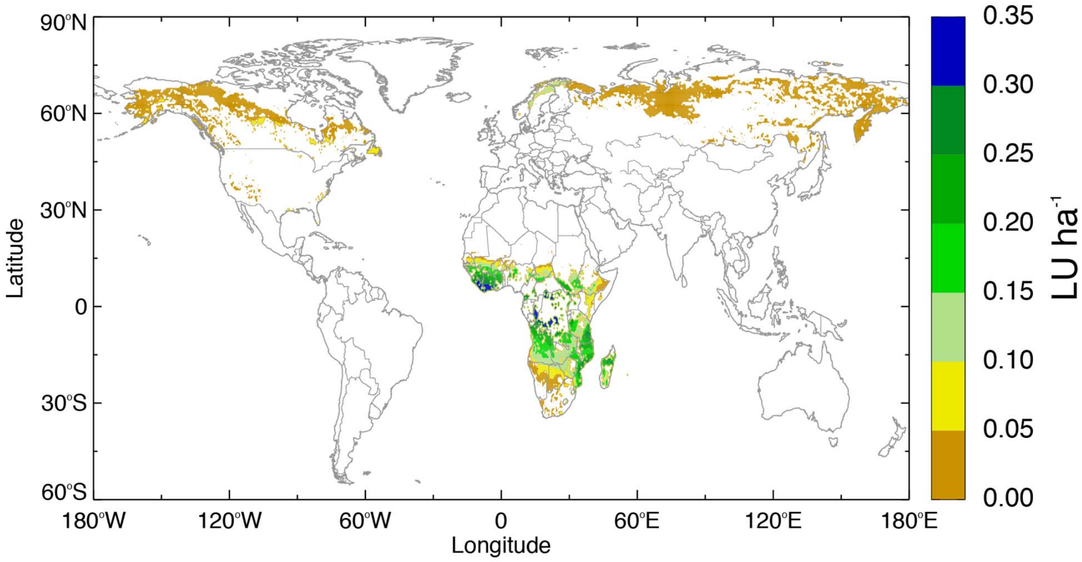


Figure S5. Wild herbivore density across the world. Original data from literature were collected by Bouwman et al. (1997), and shown in Table S2.