Global assessment of grassland carrying capacities and relative stocking densities of livestock

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Abstract

Although many suggest that future diets should include more plant-based proteins, animal-sourced foods are unlikely to completely disappear from our diet. Grasslands yield a notable part of the world's animal protein production, but thus far, there is no global insight into the relationship between current livestock stocking densities and the availability of grassland forage resources. This inhibits acting upon concerns over the negative effects of overgrazing in some areas and utilising the potential for increasing production in others. Previous research has examined the potential of sustainable grazing but lacks generic and observation-based methods needed to fully understand the opportunities and threats of grazing. Here we provide a novel framework and method to estimate global livestock carrying capacity and relative stocking density, i.e. the reported livestock distribution relative to the estimated carrying capacity. We first estimate the aboveground biomass that is available for grazers on grasslands and savannas based on the MODIS Net Primary Production (NPP) approach on a global scale. This information is then used to calculate reasonable livestock carrying capacities, using slopes, forest cover and animal forage requirements as restrictions. With this approach, we found that stocking rates exceed the forage provided by grasslands in northwestern Europe, midwestern United States, southern China and the African Sahel. In this study, we provide the highest resolution global datasets to date. Our results have implications for prospective global food system modelling as well as national agricultural and environmental policies. These maps and findings can assist with conservation efforts to reduce land degradation associated with overgrazing and help identify undergrazed areas for targeted sustainable intensification efforts.

Keywords: livestock, carrying capacity, aboveground biomass, relative stocking density, overgrazing, grasslands, NPP

1. Introduction

The scientific literature expresses diverse opinions on the sustainability of livestock production on the grasslands of the world. Certain studies suggest that some of the livestock production relying on natural grasslands is sustainable from the point of view of natural resources and the environment (e.g. Holechek et al., 2010; Kemp and Michalk, 2007) and that significant areas of grassland are understocked and thus have potential to increase the production of livestock and animal proteins in these areas (Fetzel et al., 2017; Monteiro et al., 2020; Rolinski et al., 2018). However, other studies state that a notable fraction of the world's grasslands host livestock populations that exceed the carrying capacity with negative effects on the environment (Alkemade et al., 2013; Reid et al., 2009). These contrasting views do not necessarily contradict each other. Instead, they reflect a situation where some grasslands are overstocked, whilst in other situations, livestock utilizes grasslands according to or below their carrying capacity.

Depending on the definition, methods and assumptions, grasslands comprise 20–47% of the world's land area (Godde et al, 2018) and 80% of agriculturally productive land (Gibson and Newman, 2019). Furthermore, they support the livelihood of around 800 million people (Suttie et al., 2005; Kemp et al., 2013). Grazing systems are diverse, ranging from nomadic pastoral activities in sub-Saharan native savannas to sedentary Dutch dairy farming on fertilized sown pastures (Godde et al., 2018). In some regions, vegetation adapted to extreme conditions and the species-rich population of the grasslands provide a buffer for the disadvantageous effects of climate change (Craine et al., 2013; Dengler et al., 2014; Tamburino et al., 2020). In fact, constitutive components of biodiversity such as pollinators are greatly dependent on these regions. However, moving away from traditional agricultural practices—such as extensive grazing and land use—jeopardizes grassland areas and their species (Estel et al., 2018; Gibson and Newman, 2019; Gossner et al., 2016).

Heavy stocking densities cause land degradation and desertification, which lead to land erosion, whereas properly managed moderate grazing can benefit the environment by providing ecosystem services, regulating the terrestrial carbon cycle and increasing the ecological resilience against natural disasters (Gibson and Newman, 2019; Lv et al., 2020). The importance of light or moderate grazing and especially rotational grazing has been extensively emphasized in the literature (Gibson and Newman, 2019; Holechek et al., 2010; Loeser et al., 2007). Nevertheless, the exact locations where grazing should or should not occur are yet to be designated. Part of the animal protein produced in grasslands is difficult and unnecessary to replace as not all the grasslands are suitable for food production other than grazing (Van Zanten et al., 2018).

As stated before, carrying capacity (CC) is important for determining proper stocking rates as it describes the maximum number of animals or animal units an area can sustainably hold (De Leeuw et al., 2019; Rees, 1996). Although the principles of the CC calculation are simple, evaluation of the available forage creates difficulties due to the year-to-year variation of grass yields and the special characteristics of different regions. Here we calculate CC values for an average year based on remotely sensed averages of aboveground biomass. CC assessments based on remote sensing have been applied so far for restricted geographical area (De Leeuw et al., 2019; Zhao et al., 2014), and the global estimations of CCs on the world's grasslands are still lacking. Nonetheless, some studies have started the task by estimating potential grazing intensities globally based on biophysical models (Fetzel et al., 2017a; Fetzel et al., 2017b; Monteiro et al., 2020; Rolinski et al., 2018). However, these models are not able to fully capture all the dynamics impacting the CC. To support that work, observation-based estimates with a higher spatial resolution are needed.

In this article, we aim to fill this gap by using remote sensing products to estimate the CC at the global scale. We do this by calculating spatially distributed aboveground biomass on the world's grasslands, using remotely sensed primary production and then defining the number of animal units that can be fed with the biomass. A second knowledge gap arises from the need to assess the stocking density relative to the primary production that is available to sustain livestock. Global assessment of the stocking density of livestock exists (Gilbert et al., 2018), but these estimates cannot directly express which areas are overstocked or understocked. The stocking density that can be sustained depends on the availability of forage biomass, which varies geographically. Here we propose that the relative stocking density (RSD), the ratio of stocking density relative to the availability of forage biomass would be an appropriate metric to compare the sustainability of stocking densities across the globe.

Thus, we expect the results to reveal areas where potential overgrazing occurs or that are dependent on imported forage, and areas where grazing intensity falls within the CC. In addition, we analyse factors that prevent the currently estimated animal densities to reach the theoretical CC boundaries and discuss why transgressing these upper boundaries is inadvisable.

2. Materials and methods

To conduct the analysis, we combined several open access global datasets together as summarised in Figure 1. The detailed description is given below. We used remote sensing estimates of MODIS (Moderate Resolution Imaging Spectroradiometer) data products to estimate the carrying capacity (CC). We first extracted MODIS Land Cover Type product (Sulla-Menashe and Friedl, 2018; Table 1) and chose classes with significant grass cover, i.e. Woody savannas, Savannas and Grasslands according to the IGBP International Geosphere–Biosphere Programme) classification system. This grassland area comprises around 46% of the world's land area (excluding Antarctica). As land cover types might vary between years, we calculated the mode value (the land cover class that occurs most often) during 2010–2018 for defining the most common land cover type.

We followed the approach described by De Leeuw et al. (2019) to calculate aboveground biomass (AB) based on the 500 m resolution MODIS Net Primary Productivity (NPP) product (Running and Zhao, 2019; Table 1). First, we calculated the mean NPP during 2001–2019 and used a carbon conversion factor of 0.47 (Eggleston et al., 2006) to convert the original NPP values expressed as kg C m^{-2} yr^{-1} to biomass. Since plants store part of their NPP in above ground biomass, we used the following formula (Eq. 1) developed for the grasslands (Hui and Jackson, 2006) to derive the fraction of the NPP (f_{ANPP}) allocated aboveground biomass:

(1) $f_{ANPP} = 0.171 + 0.0129\ MAT$ (Hui and Jackson, 2006)

where MAT is the Mean Annual Temperature in °C. MAT for 1970–2000 was derived from WorldClim version 2 (Fick and Hijmans, 2017) and resampled to 500 m resolution.

Trees in savannas and woody savannas compete with grass and reduce its productivity. We reviewed the literature related to the effect of the tree canopy cover on the ground cover and the NPP of sub-canopy vegetation (De Leeuw and Tothill, 1990; Le Brocque et al., 2008; Lloyd et al., 2008; White et al., 2000). These studies revealed that an increase in the tree canopy cover results in a non-linear reduction in the sub-canopy cover, which reaches zero at tree canopy covers above 40–50%. Based on this, we developed the following transfer function to translate the tree canopy cover into the fraction of NPP that is allocated to the sub-canopy.

(2) $TreeCoverMultiplier = -2.5x^2 - 0.75x + 1,$

$x \in \{0, 0.5\}, y \in \{1, 0\}$,

where *TreeCoverMultiplier* refers to sub-canopy biomass and *x* refers to the percentage of the pixel area covered by the tree canopy. Here we used forest coverage data provided by Global Forest Change (Hansen et al., 2013; Table 1). Based on the function, we utilized the five tree canopy classes when reclassifying the original values and deriving the aboveground biomass of the understory (Figure 1). After the reclassification, the data was resampled to the resolution of the MODIS products. Thus, the final modified forest coverage data expresses the feed efficiency number for each forest pixel. The spatial extent of the forest coverage data (180°W, 180°E, 60°S, 80°N) also determined the spatial extent of the study.

We further reduced this aboveground biomass by a slope steepness factor (see De Leeuw et al., 2019) to account for the risk erosion and avoid land degradation (Holechek et al., 2010). Data for the global representation of slope steepness at 250 m resolution was provided by ISRIC World Soil Information (Table 1). This was derived in SAGA GIS from the SRTM DEM using the method proposed by Wood (1996). We first reclassified the slopes following the recommendations by George and Lyle (2009) and then resampled the data to the same resolution with the MODIS products (Figure 1). Thus, the modified slope map (*SlopesMultiplier* in Eq. 3) expresses the feed efficiency number for each pixel.

Given the above, the formula for available aboveground biomass (AB) available for grazing animals is (Eq. 3):

(3) $AB = NPP * fANPP * TreeCoverMultiplier * SlopesMultiplier$

After calculating AB, we estimated the CC in animal units (AU). Following the definition of Holechek et al. (2010), the AU corresponds to 455 kg, with a daily forage intake equal to 2% of its body weight. This dry matter intake is suitable for most range ruminants (Holechek et al., 2010). We then aggregated the daily dry matter intake for a year. The available aboveground biomass (AB) divided by the forage requirements of the AU yields the CC (Eq. 4):

(4) $Carrying\ capacity = \frac{AB}{weight_{AU} * intake_{daily} * 365}$

where weight equals 455 kg and daily intake equals 0.02.

As a final step, we derived the relative stocking density (RSD) by dividing the modelled livestock density by the potential density that could be sustained while considering grass biomass availability alone. This calculation creates a ratio that varies from zero to above one. We classified the RSD into three classes:
< 0.20 low pressure,
0.20–0.65 medium pressure (falling within the range of reported Proper Use Factor (PUF) values),
> 0.65 overstocked.

These class boundaries were used for the following reasons. Livestock does not consume all aboveground biomass, as a part of it is trampled, consumed by other species or avoided because of toxicity or poor quality. Carrying capacity assessments typically use a PUF that describes the fraction of forage that can be sustainably consumed (see e.g. De Leeuw et al., 2019). We considered it inappropriate to apply a single PUF for all grassland ecosystems worldwide because PUFs vary significantly between ecosystems (Fetzel et al., 2017a). Instead, we decided to exploit the minimum (0.20) and maximum (0.65) PUF values reported in the literature (Bornard and Dubost, 1992; De Leeuw et al., 2019; Mayer et al., 2005; Neudert et al., 2013; Vallentine, 2016). Those boundary values were then used to define the RSD (Figure 1).

To examine the RSD, we first extracted the Gridded Livestock of the World (GLW 3) estimates for the year 2010 (Gilbert et al., 2018; Table 1) and converted the number of cattle, horses, sheep, goats and buffaloes to the number of animal units per unit area, following FAO (2011) and Holecheck et al. (2010). We used areal-weighted GLW products in the analysis, but also tested that dasymmetric products result in similar RSD estimates. We note that the calculation of RSD is the same as forage requirements of the GLW–modelled livestock divided by the AB.

We further masked CC and RSD maps to livestock-grazing grasslands based on Robinson et al. (2011). In the livestock-grazing system, 90% of the forage consumed by animals comes from pastures and rangelands. Thus, we can better separate mixed and industrial production systems from grazing and detect overgrazing more reliably than for all grasslands.

We used R version 3.6.1 (RStudio Team, 2019) for the analyses but processed the land cover classes, and forest coverage in the Google Earth Engine platform before pulling them into R. As the AB estimates are negative in areas where the average temperature falls below -13 °C (see Eq. 1), we excluded these values from the analyses.

Table 1 Data used in the analysis.

Data	**Time Interval**	**Resolution**	**Reference**
Land Cover Type (MCD12Q1.006)	Mode value of 2010-2018	500 m (16.2 arc-seconds)	Sulla-Menashe and Friedl (2018)
Net Primary Productivity (MOD17A3HGF)	Yearly averages of 2001-2019	500 m (16.2 arc-seconds)	Running and Zhao (2019)
Average Temperature (WorldClim v2)	Yearly averages of 1970-2000	1 km (30 arc-seconds)	Fick and Hijmans (2017)
Global Tree Cover (Global Forest Change)	Year 2000	30 m (1 arc-seconds)	Hansen et al. (2013)
Slope% map	-	250 m (8.1 arc-seconds)	Wood (1996)
Gridded Livestock of the World (GLW 3)	Year 2010	10 km (5 arc-minutes)	Gilbert et al. (2018)
Global Livestock Production systems	Year 2011	1 km (30 arc-seconds)	Robinson et al. (2011)

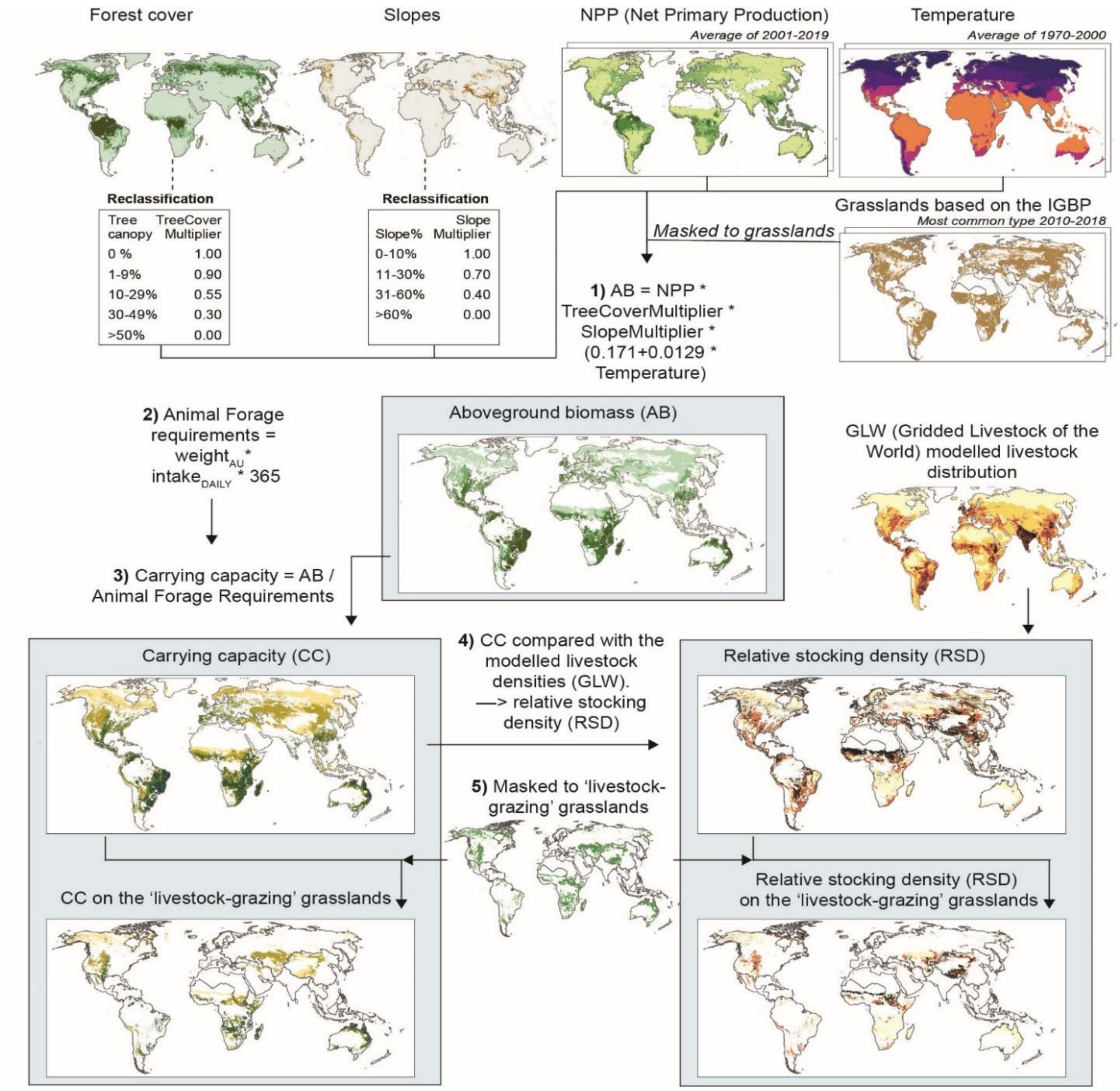

Figure 1. Flowchart of data and methods used in the analysis. Abbreviations used in the study: NPP = Net Primary Productivity, IGBP =the International Geosphere-Biosphere Programme, AB = Aboveground biomass, AU = Animal unit, CC= Carrying capacity, GLW = Gridded Livestock of the World, RSD = Relative Stocking Density.

3. Results and interpretation

3.1. Aboveground biomass and carrying capacity

The yields of the aboveground biomass are largest in low latitudes where there is also large spatial variation depending on the climatic zone. Near deserts, the AB may fall below 10 g m^{-2}, whereas the most productive grasslands in the subtropics and tropics produce biomass over 500 g m^{-2} (Figure 2a). Notably large areas of high AB can be found in the eastern parts of South America and in East Africa (Figure 2a), where the NPP values are also the highest (Supplementary Figure S1). Our results in these areas are well in line with existing local studies and field observations, such as Fidelis et al. (2013), who collected samples of AB in South America and found that biomass can yield over 500 g m^{-2} on tropical wet grasslands. Consequently, Cox and Waithaka (1989) collected samples from tropical grasslands in Kenya that even yielded biomass of 1000 g m^{-2}.

Due to the low NPP values and dense tree canopy, the northernmost areas of the globe are incapable of maintaining the high stocking densities from the CC perspective. Consequently, the mountainous areas especially in Central-Asia diminish the grazing possibilities (Figure 2b). In these areas, our results also align with more local studies (e.g. Yang et al., 2009; Zhao et al., 2014) that integrated field survey data and MODIS datasets to derive AB estimates. The average potential CC per area is highest on grasslands in South America and Oceania, followed by Central America and Middle and South Africa (Figure 2c). Grasslands of Eastern Europe and Central Asia yield the lowest CC estimates. These areas mainly follow the IGBP classes 'woody savannas' and 'savannas'.

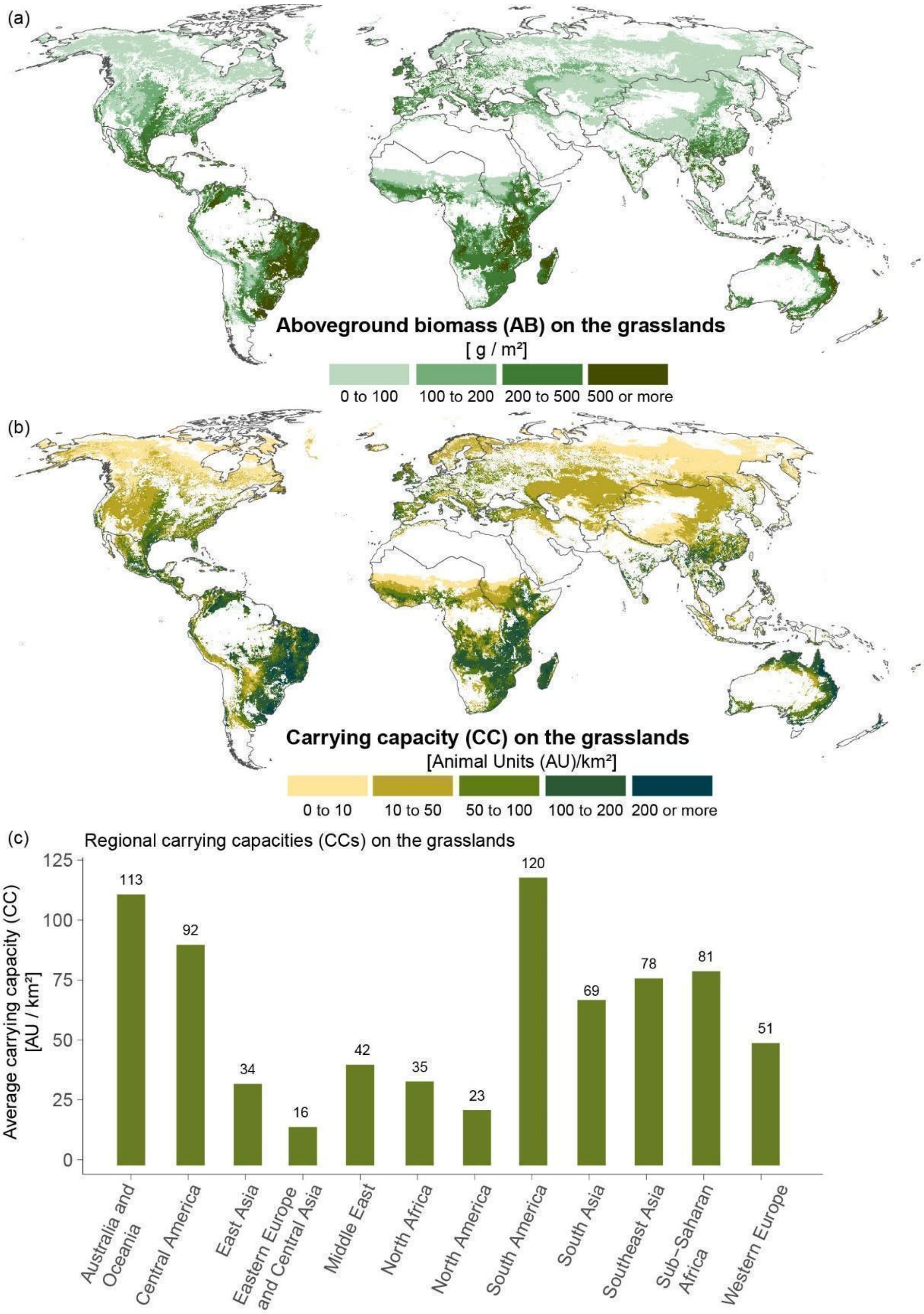

Figure 2. (a) Aboveground biomass and (b) carrying capacities on grasslands. (c) regional average values. Note the spatial extent (180°W, 180°E, 60°S, 80°N).

3.2. Relative stocking densities (RSD)

On average, animal densities, as estimated by Gilbert et al. (2018), already concentrate in areas where the NPP and consequently the CC values are high. However, some of these regions are already overgrazed (e.g. Gaitán et al., 2018) or affected by degradation (Bai et al., 2008). Slightly more than half of the GLW3-modelled livestock population (nearly 2 billion AUs; see Supplementary Figure S2) is located in the areas we consider here as grasslands. This means that a considerable proportion of the livestock production (e.g. in India) is located outside of our study area (Figure 3, Supplementary Figure S2).

Our results show (Figure 3) that most parts of the world's grasslands fall within low or medium pressure categories of RSD (see the Methods section). This observation might lead to the conclusion that there is potential to increase livestock density and production. However, caution is needed, as grass biomass availability is only one factor impacting the CC of animal production.

In the arid and semi-arid zones, livestock populations are controlled by feed shortages during the long dry season and strong year-to-year variation in biomass production (Vetter, 2005). Temperate zone grasslands are dominated by C3 grasses, while tropical grasslands are dominated by C4 grasses that have lower nutritional value and are poorly digested by ruminants (Barbehenn et al., 2004). In addition, animal diseases (e.g. tsetse in southern Africa), poisonous plants and the distance from water limit the grazing possibilities in tropical grasslands (Holechek et al., 2010). In Arctic and temperate continental grasslands, feed shortage or difficulty to access forage during long winter periods control livestock populations (Hui and Jackson, 2006; Suttie et al., 2005). Moreover, conservation areas and the local wildlife populations require untouched land with lower grazing density than our results imply. Due to these constraints, the potential to increase livestock grazing is lower than suggested by the RSD map (Figure 3). Given all the above, exceeding the upper boundaries of the CC can be extremely harmful, and increasing the stocking densities even in the medium pressure regions might lead to land degradation. At the same time, other unaccounted factors may support higher grazing rates in certain regions than those introduced in our study.

Most parts of Southern Africa, Central Asia and Australia fall within the 'low pressure' RSD category (Figure 3). This implies that in these regions, livestock does not consume all the available biomass. Similar findings exist in various studies (Fetzel et al., 2017a; Monteiro et al., 2020; Rolinski et al., 2018; see Supplementary Figures S3–S5), suggesting that there may be potential for larger grazing densities. The results between the studies are consistent, especially in Central Africa, but divergent in South Asia. However, previous studies did not focus on RSD. In addition, the divergent results may be explained by different methods (see the Discussion section).

The RSD falls within the 'overstocked' class (i.e. exceeding grassland CC) in large parts of the Sahel region, southern China and northwestern Europe (Figure 3). It should be noted that in regions such as the Sahel, livestock migrates seasonally between rainy and dry season pastures (Dixon et al., 2019; Yi et al., 2008), which has an impact on grazing pressures. Nonetheless, overgrazing clearly occurs in many of these regions, such as in the Three-River Headwaters region in China (Zhang et al., 2014).

Although the existing livestock leaves some of the biomass untouched ('low pressure' category) in the northernmost areas of the globe, those areas have limited potential for increased grazing due to low biomass availability. Nonetheless, higher animal densities can be sustained in regions where livestock is not only fed with locally produced grass but also externally acquired forages, crop grains, crop residue leftovers or other feed supplements. In reality, intensive livestock production utilizes other feed resources produced elsewhere (Naylor et al., 2005). This enables concentrating production on areas where the NPP is low and grazing animals may exist in areas unsuitable from the CC perspective. Large dairy industries in Saudi Arabia, Syria and Jordan provide examples of this (Alqaisi et al., 2010). Thus, areas where the forage demand of the livestock exceeds the AB are most likely dependent on the supplementary feed.

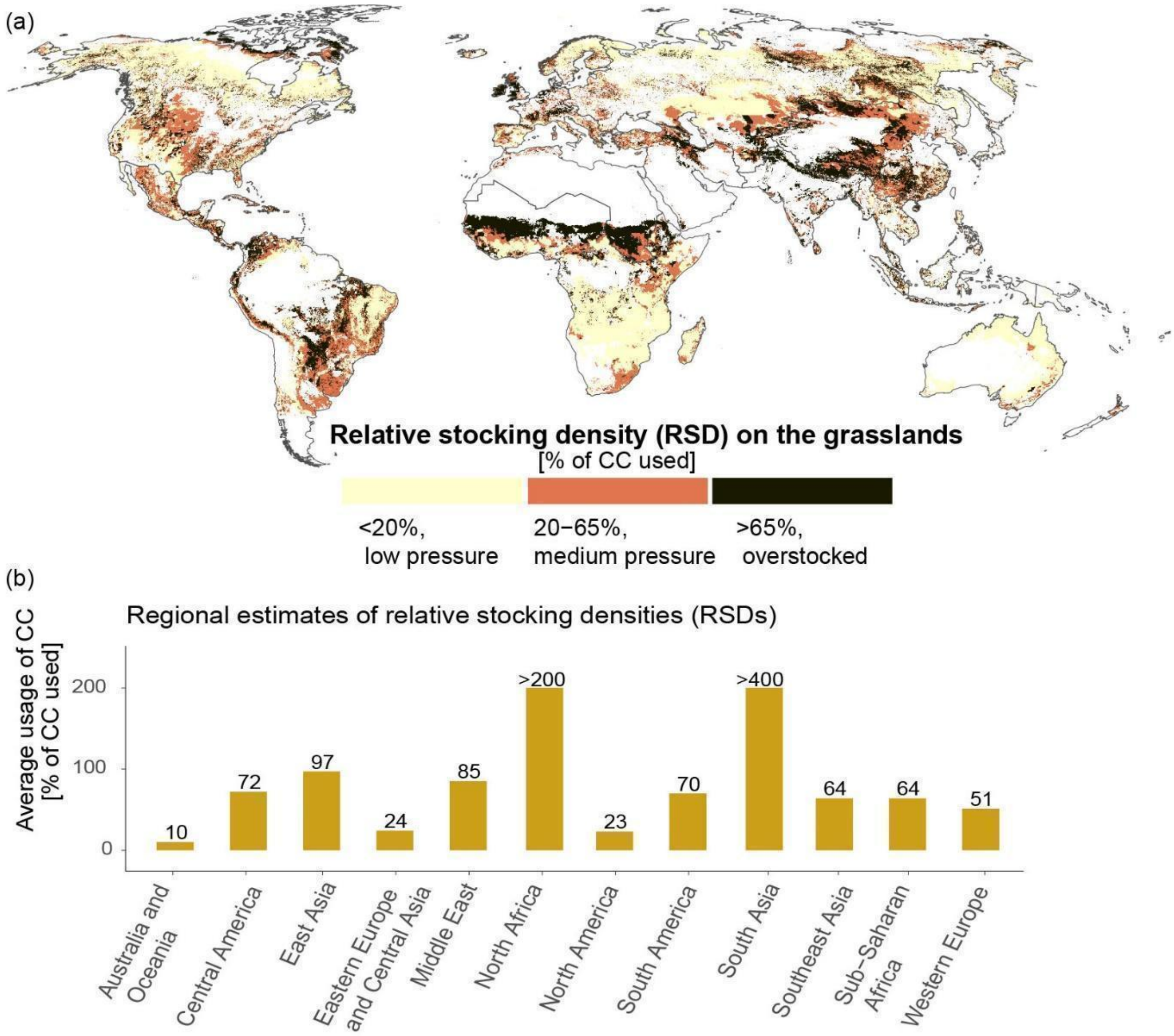

Figure 3. The relative stocking density (RSD), i.e. the ratio of carrying capacity (CC) used by the Gridded Livestock of the World (GLW) modelled livestock (industrial and grazing) on the world's grasslands (a). When calculating regional averages (b), we excluded areas where CC <1. Calculated as GLW / CC, which is the same as the forage requirements of the GLW-modelled livestock divided by the aboveground biomass (AB).

3.3. CCs and RSDs in production system 'livestock-grazing'

Our calculations cannot observe livestock consuming supplementary feed or account for all the variations in production systems ranging from extensive to intensive farming. Therefore, we estimated CCs and RSDs on grasslands, where the production system is 'livestock-grazing' (Robinson et al., 2011) as discussed in the methods section. These livestock-grazing grasslands comprise an area roughly corresponding to the IGBP land cover class 10, 'grassland', which contains broad and remote pasturage and extensive livestock production. It covers about one-third of our IGBP-based grassland area (classes 8, 9 and 10) and approximately 240 million AUs inhabit these areas according to the GLW estimates (around 10% of total AU). Consequently, CCs on these livestock-grazing grasslands make up around one-third of the total CC of all the grasslands.

The RSD falls within the 'overstocked' class in the Sahel region and the mountains surrounding the Tibetan plateau. However, the RSDs seem generally less severe on livestock-grazing grasslands (Figure 4) compared to all grasslands (Figure 3). The availability of supplementary feed, low productivity and long distances may restrict the animal population from exceeding the ecological limits in these regions. Yet, overgrazing clearly occurs also in a livestock-grazing system where most of the forage comes from pastures and rangelands.

Our RSD map (Figure 4) shows that Central Africa and Australia fall into the 'low pressure' category. However, we disagree with Monteiro et al. (2020), who observed that grazed-only systems perform below their potential especially in arid areas. Instead, we argue that increasing stocking densities in these areas is highly questionable, as discussed in the previous chapter.

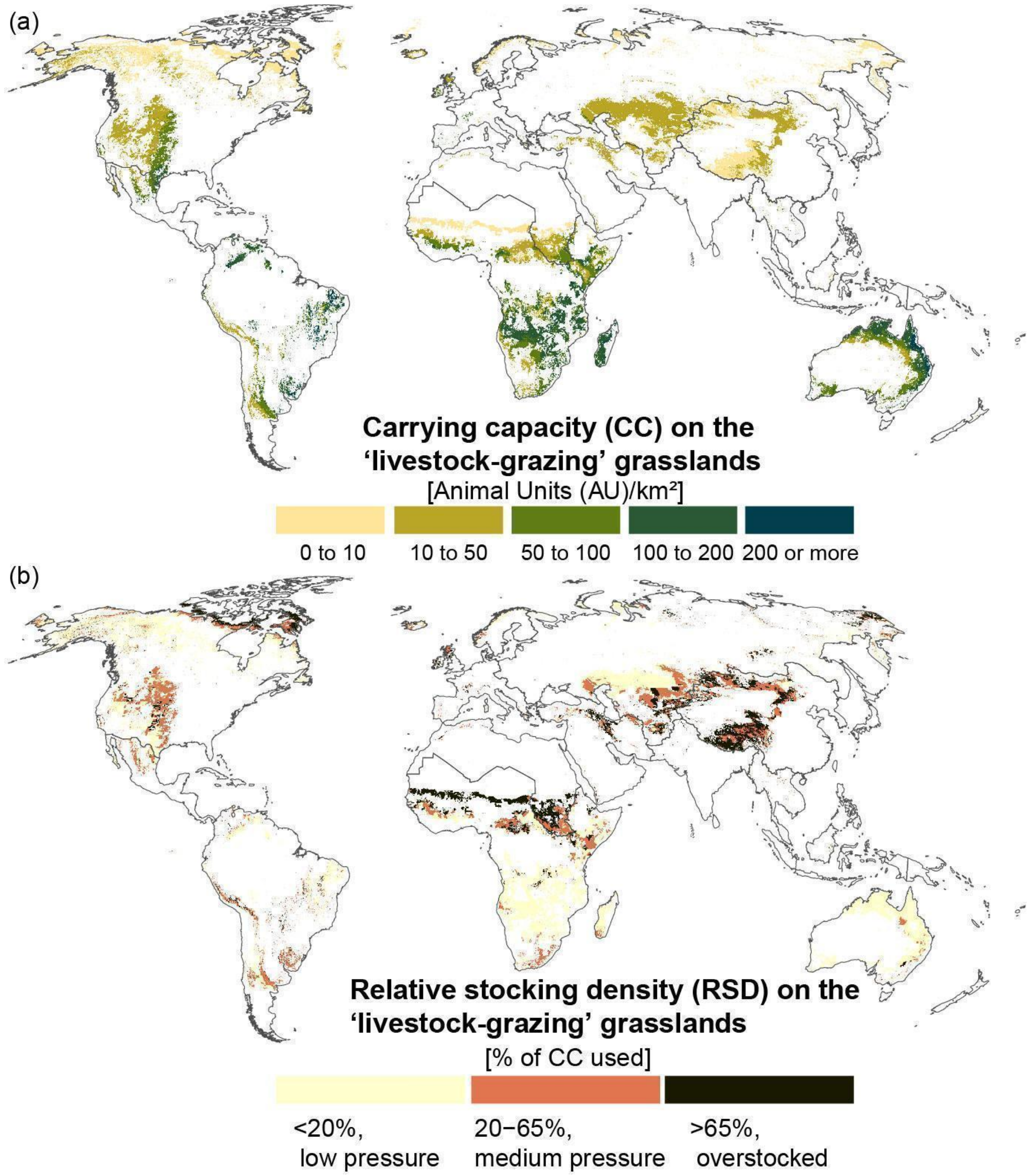

Figure 4. The carrying capacities (CC) (a) and relative stocking densities (RSD) (b) on grasslands with a production system of 'livestock grazing'. RSD is calculated as GLW/CC, which is the same as the forage requirements of the Gridded Livestock of the World (GLW) modelled livestock divided by the aboveground biomass (AB).

4. Discussion and conclusion

Grassland management will play a critical role in problems relating to the environment, food, energy and livelihood of the people. Nevertheless, definite identification of the suitable grazing areas and desirable stocking densities on the world's grasslands are yet to be reached. Various studies demand more accurate datasets related to ecological limits on the NPP of grazing lands, grassland management and livestock density (Fetzel et al., 2017a; Herrero et al., 2013; Monteiro et al., 2020; Rolinski et al., 2018). This study fills the research gap by providing estimates of AB (aboveground biomass) and CC (carrying capacity) on the world's grasslands with a high resolution (500 m). In addition, the study assesses RSD (relative stocking density) of estimated livestock distribution on grasslands and livestock-grazing grasslands to detect signs of overgrazing.

4.1 RSDs compared to stocking densities found in other studies

Existing global modelling studies express globally a larger grazing potential compared to the current grazing intensity (Fetzel et al., 2017a; Monteiro et al., 2020, Rolinski et al., 2018; see Supplementary Figures S3–S5). For the most part, our results align with Fetzel et al. (2017a; see Supplementary Figure S3), who find that the possibilities to increase grazing are limited in the Sahel and East Asia, but grazing pressures can still be increased in large parts of Sub-Saharan Africa. However, according to our results, stocking densities cannot increase in the grasslands of South America, which is opposite to the results found by Fetzel et al. (2017a).

In general, results relating to grazing pressures are slightly different between the studies. According to Irisarri et al. (2017), estimated grazing intensities reported in the literature are generally higher than those modelled by Fetzel et al. (2017a). Divergent results may be explained by different methods. Global simulation models, such as JULES and ORCHIDEE, yield different NPP estimates compared to field data or the MODIS NPP product (Chang et al., 2015; Slevin et al., 2017). In addition, the definition of grazing land notably differs since different land cover maps produce varying estimates of land cover type (Fritz et al., 2011).

Although our maps imply that Central Africa and Australia fall into the 'low pressure' RSD category, we conclude that possibilities to increase grazing are limited in these areas due to the constraints discussed throughout the paper. Instead, our findings suggest that many of the grazing lands are near or above their peak livestock, and policy interventions might be needed to prevent unsupportable livestock management. On the other hand, areas with unused capacity could be utilized for ecosystem services, carbon sinks or rewilding.

4.2. Limitations and future directions

Our approach provides a method—based on open-access global datasets—to create continuously updated estimates of AB, CC and RSD at the local and global level. Timely estimates are crucial as the herbaceous biomass of rangelands is estimated to decrease in many regions towards the 2050s (Godde et al., 2020). Combined with the increasing inter-annual variability of climate and forage, this creates notable challenges to livestock management across the world's grasslands. The optimal density of livestock will significantly change depending on the region, which may call for the re-optimization of livestock distribution. Here, we analysed the mean NPP values and the most common land cover type over a long period to obtain robust estimates of the available feed. Our results thus represent average conditions, but monthly or yearly estimations of CC would also be needed when defining proper stocking rates in a highly variable climate. While our method can be used to produce these seasonal estimates, this represents an area for future model development.

Our approach, based on the MODIS NPP product, may result in unfeasible CC estimates for individual areas, depending on their special characteristics. For example, poor feed quality or dead biomass still cannot be observed by current satellite products. The calculated AB may differ from reality especially in woody areas, whose understory forage yields depend heavily on different tree species and the forest type. The transfer function (Eq. 2) we developed for the study cannot observe this, and thus should be improved in further studies. Similarly, to match reality, different animal and plant species should be considered when calculating forage requirements.

More precise land cover and NPP maps will improve the accuracy of the results but the location of grazing lands will likely cause difficulties even in the future. Ideally, the land cover classification should not restrict the CC assessment. Instead, other restrictions—such as soil erosion or quality of the feed—should have an effect on determining suitable grazing areas for livestock.

Besides the ecological perspective, economic and social sustainability perspectives must also be considered when optimizing livestock production. Further research should detect the opportunity cost of grazing in different areas and then indicate where the sustainable intensification of grassland is feasible in the first place. This examination could result in dividing grasslands into arable and non-arable grasslands and determining where grazing livestock does not compete with crop production.

4.3. Concluding remarks

This study provides the first satellite observation-based global CC (carrying capacity) estimate of the world's grasslands. Our study provides much-needed high spatial resolution (500 m) data on AB (aboveground biomass) and CC, and a method to update these estimates regularly on a monthly and annual basis. Moreover, we assess the RSD (relative stocking density) on grasslands and livestock-grazing grasslands and discuss the reasons behind the regional differences in RSD. This information can be used in sustaining proper land management on grazing areas and rearranging the global food production in a sustainable way. These maps and findings can help identify undergrazed areas for targeted sustainable intensification efforts and assist with conservation efforts to reduce land degradation associated with overgrazing. Whilst our results imply that most parts of the world's grasslands fall within the low or medium pressure categories of RSD, we argue that grazing densities may not be increased in all of these regions. A notable share of the grasslands is currently overstocked and policy interventions might be needed to prevent unsupportable livestock management.

Dataset distribution

The code used in the analyses will be published upon publication in GitHub. The derived datasets will be published in the Zenodo repository upon publication.

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Supplementary figures

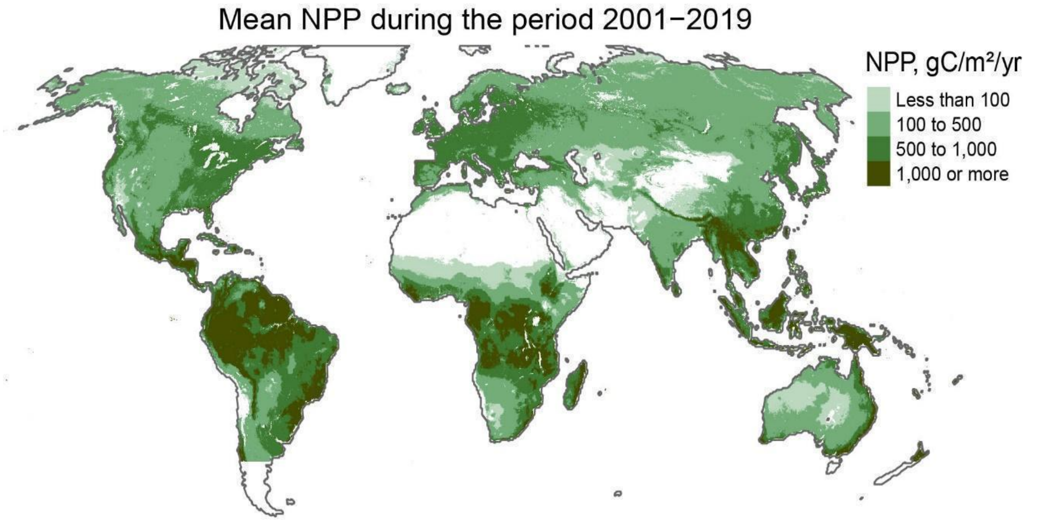

Figure S1. Mean NPP (MOD17A3HGF) of 2001-2019. Note the spatial extent (180°W, 180°E, 60°S, 80°N).

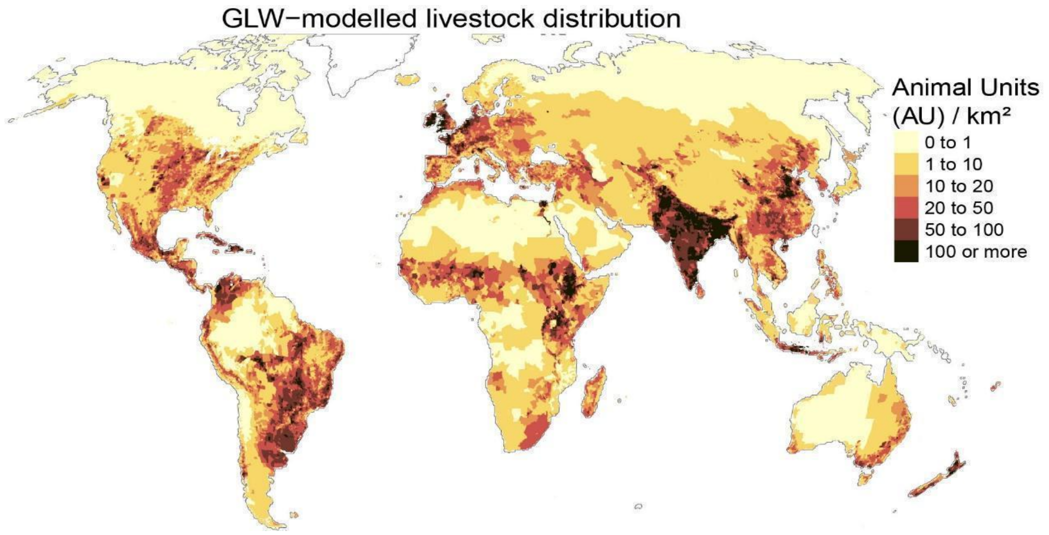

Figure S2. GLW-modelled livestock distribution.

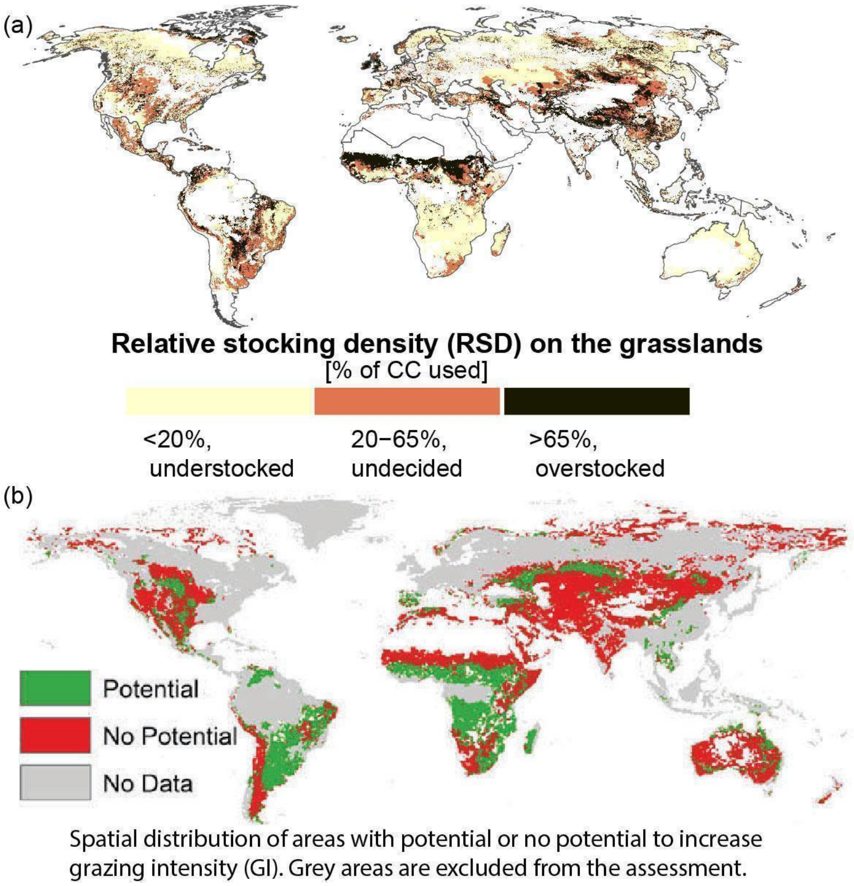

Figure S3. Comparison of (a) RSD estimates (see Figure 3) and (b) potential to increase grazing intensity (Fetzel et al., 2017a). Reproduced by permission, © 2017 John Wiley & Sons Ltd, Global Change Biology, 23, 1636–1647.

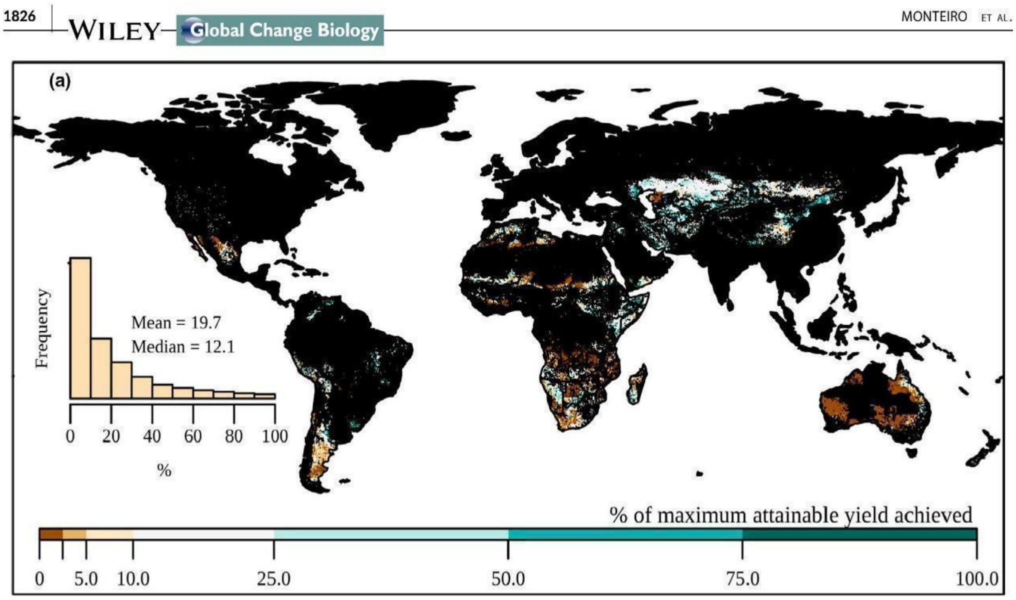

Figure S4. Yield gaps for all pasture lands (5′ × 5′ spatial resolution), considering total protein from meat and milk produced by cattle, sheep, or goats. (a) Yield gap expressed as the percent of achieved yield relative to the climate-adjusted maximum (Y_{95}) (Monteiro et al., 2020). Reproduced by permission © 2020 John Wiley & Sons Ltd, Global Change Biology, 26, 1820–1832.

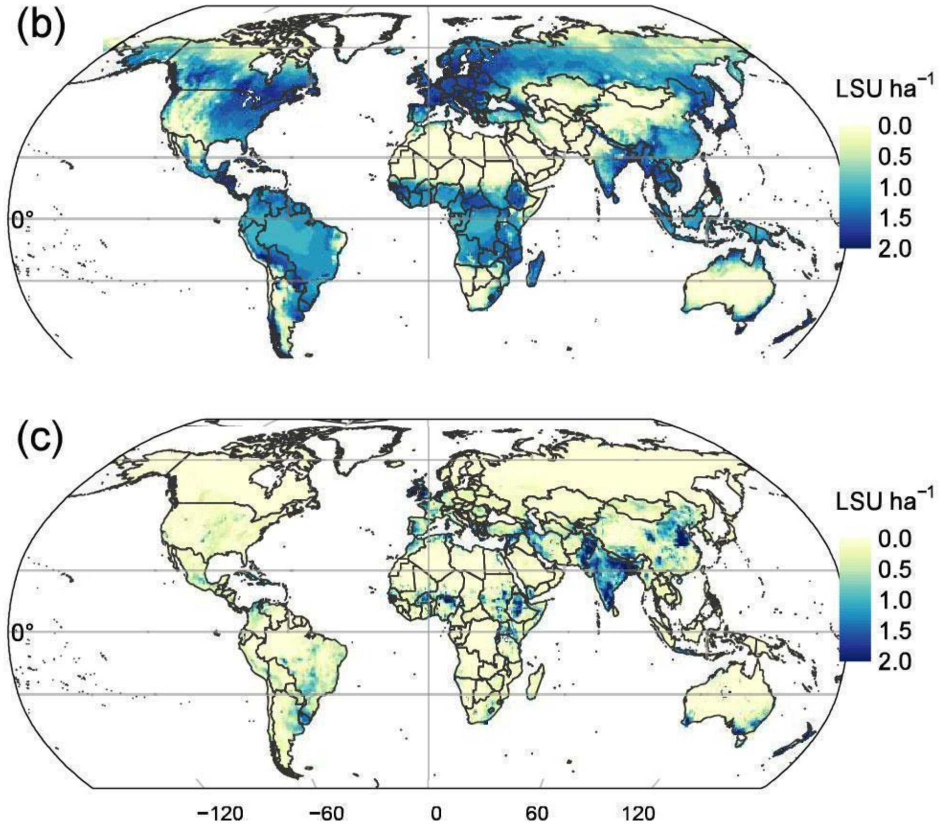

Figure S5. Distribution of livestock densities that result in (b) maximum LSU (Livestock Unit) that can be continuously supported by grazing only (LSU_{feed} in LSU ha^{-1}) under harvest option G_D averaged over the years 1998 to 2002. Reported livestock densities in pastoral and mixed livestock production systems (Robinson et al., 2014) are given as a comparison in panel (c) (Rolinski et al., 2018). This figure is licensed under the Creative Commons Attribution 4.0 License.