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Seasonality constraints to livestock grazing intensity

Seasonality constraints to grazing intensity

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Abstract

Increasing food production is essential to meet the future food demand of a growing world population. In the light of pressing sustainability challenges like climate change and the importance of the global livestock system for food security as well as GHG emissions, finding ways to increasing food production sustainably and without increasing competition for food crops is essential. Yet, many unknowns relate to livestock grazing, in particular grazing intensity, an essential variable to assess the sustainability of livestock systems. Here we explore ecological limits to grazing intensity (GI; i.e., the fraction of Net Primary Production consumed by grazing animals) by analysing the role of seasonality in natural grasslands. We estimate seasonal limitations to GI by combining monthly Net Primary Production data and a map of global livestock distribution with assumptions on the length of non-favourable periods that can be bridged by livestock (e.g., by browsing dead standing biomass, storage systems or biomass conservation). This allows us to derive a seasonality-limited potential GI, which we compare with the GI prevailing in 2000. We find that GI in 2000 lies below its potential on 39% of the total global natural grasslands, which has a potential for increasing biomass extraction of up to 181 MtC/yr. In contrast, on 61% of the area GI exceeds the potential, made possible by management. Mobilizing this potential could increase milk production by 5%, meat production by 4%, or contribute to free up to 2.8 Mio km^2 of grassland area at the global scale if the numerous socio-ecological constraints can be overcome. We discuss socio-ecological trade-offs, which may reduce the estimated potential considerably and require the estabilishment of sound monitoring systems and an improved understanding of livestock system's role in the Earth system.

1. Introduction

Grazing of domesticated livestock is the largest single land use activity (Erb et al. 2007) and provides essential services for humanity: It creates income and nourishment for more than 1.3 billion people (Herrero et al. 2013) and allows for utilization of land that is not suitable for other food production, e.g., crop production (Asner et al. 2004; Thornton 2002). Livestock products are already an essential source of food for many and make up for 17% of the total global energy intake (Herrero et al. 2009). Livestock systems also play an essential role in global GHG emissions (Godfray et al. 2010; Havlik et al. 2012; Herrero and Thornton 2013). In the light of the projected population and income growth, demand for livestock products is expected to further increase until 2050 (Tilman and Clark 2014). However, increasing food production from grasslands, e.g., by increasing feeding conversion ratios through improved feedstuff or land-use expansion, relates to massive trade-offs, such as carbon and biodiversity losses (Steinfeld and Gerber 2010; Herrero and Thornton 2013, Peters et al. 2013; Petz et al. 2014; Schader et al. 2015).

In the past, land expansion to produce new pastures or cropland (Searchinger et al. 2015) has resulted in significant losses of biomass and soil carbon stocks through degradation, which is already widespread and dominant in almost 20% of world's pasture area (Postel 1994; Asner et al. 2004; Gang et al. 2014). In this context, using the available grassland resources more efficiently can substantially contribute to achieving future sustainability goals incl. climate change mitigation (De Oliveira Silva et al. 2016).

Despite the central role of grasslands for tackling climate change and future food security (Erb et al. 2016), quantitative global analyses of the spatial pattern and dynamics of grazing and grazing intensity (GI; e.g., the amount of NPP available for grazing removed by grazing animals in a year) are rare (but see Petz et al. 2014; Kuemmerle et al. 2013; Rufin et al. 2015). Available studies are often limited in spatial extent or to specific questions (Asner et al. 2004; Steinfeld and Gerber 2010; Milchunas and Lauenroth 1993). In addition, for many important aspects, e.g., forage use or the availability of storage systems, global data are not readily available (Kuemmerle et al. 2013).

We aim to narrow this knowledge gap by applying a Net Primary Production (NPP) perspective to systematically explore patterns and constraints of GI. Focusing on NPP allows for an integrated perspective on a central ecosystem variable (Odum and Barrett 2005; Oesterheld et al. 1999) which integrates bioclimatic (e.g., precipitation; Milchunas and Lauenroth 1993; Oesterheld et al. 1999) and edaphic factors (Asner et al. 2004) and is a key process underlying carbon storage and food production (Haberl et al. 2014). Thus, it allows analysing socio-ecological trade-offs of land-use competition (Erb et al. 2016). We focus here on the role of seasonality for GI, which plays an important role in determining potentials of biomass usage by creating periods of shortage and surplus. Many grasslands are characterized by strong seasonal growth patterns, with pronounced productive periods and dry or cold unproductive periods. Because livestock needs permanent feeding, such seasonal variations as well as the availability of alternative feedstuff or storage systems for forage, determine livestock density in a region.

In this work, we present an assessment of seasonality-constrained maximum GI (i.e., maximum biomass offtake levels defined by the availability of biomass in the unproductive period) and compare this potential level to currently observed levels of GI. Comparing the two metrics allows us to highlight areas where additional biomass could potentially be extracted. In our novel approach, we apply the most recent data on feed-demand, its composition and spatially explicit information about the nutritional value of grasses, while existing studies often rely on coarse estimates of feed-demand (e.g. based on assumptions about the daily dry matter intake per animal in relation to body weight; Petz et al. 2014) and biomass available for grazing. In addition, we perform a sensitivity analysis by using two different NPP products over a range of 10 years, which allows us to provide a range of estimates (e.g., 20 maps) for the potential maximum biomass extraction. We highlight areas where biomass extraction could be increased and discuss the numerous socio-economic and ecological constraints that could limit the potential at the local level. This knowledge contributes to a better understanding of maximum potentials for livestock production systems at the global level, information that is essential in the light of current trajectories in production and consumption of livestock-based products.

1. Materials and Methods

This analysis builds on a wide range of available data on grazing systems. We use data on the extent of natural grasslands and their NPP, as well as information on the demand of roughage, i.e., the feed-demand of sheep, goats, buffaloes or cattle covered through grazing. The data sets refer to the year 2000, except the biome maps, which represent the potential distribution of grassland biomes. We aggregate all available data sets to 0.5° to cope with different spatial resolutions.

We restrict our analysis to potential grazing lands by using data on grassland biomes from three maps, the FAO Eco-floristic zones map (FAO 2008), Olson biomes (Olson et al. 2001) and the potential natural vegetation from Foley and Ramankutty (2010). In a next step, we extract areas, where all three biome maps indicate natural grassland biomes, including temperate grassland, steppe, tundra, savannah, shrubland and tropical and sub-tropical dry forests in our assessment (see Figure 1 and SI). This represents a progressive restriction of our analysis to potential grazing lands and so increases the probability that each of the selected grid-cells indeed is situated in a natural grassland biome.

We further restrict the resulting natural grassland area to the current extent of grazing land (within the boundaries of natural grasslands) using data from Erb et al. (2007), because large parts of natural grasslands have been converted into other land-uses (e.g., cropland or built-up land). Compared to the other maps (e.g., from Ramakutty et al. 2008 or Klein-Goldewijk et al. 2007), the Erb et al. (2007) grazing land estimate is at the upper end (similar to the FAO/IIASA 2012 map), because it considers unmanaged non-permanent grazing land as well. Hence, the resulting grazing area refers to all grazing land detected by Erb et al. (2007) occurring within the extent of natural grassland biomes (see SI). All grassy land-use types outside this area are excluded from the analysis (e.g., large parts of Europe and Asia). Other maps on grazing area, in particular those by Ramankutty et al. (2008) and Klein-Goldewijk et al. (2007) largely rely on FAO statistics for pasture and hence do not account for non-permanent grazing areas and are likely to underestimate the actual grazing land extent. In fact, using another grassland map for our analysis could substantially impact our results. For this reason, we include information about how the differences in grassland area would change our results in Table (2). In addition, we exclude areas less likely used for grazing (e.g., where steep slopes >40° prevail; Robinson et al. 2014; using data from Jarvis et al. 2008), areas with tree-cover above 30% in the year 2000 using data from Hansen et al. (2013) because such areas can be considered potential forest land as well as IUCN protected areas (IUCN 2015) to exclude large game reserves.

To assess and localize feed demand and calculate GI in the year 2000, we apply a number of data sources (Table 1). This includes the Gridded Livestock of the World (GLW) map (FAO 2007; Robinson et al. 2014) and the distribution of Livestock Production Systems (LPS; Robinson 2011). Feed-demand data for cattle, buffaloes, sheep and goats for world-regions and livestock production systems are extracted from Herrero et al. (2013). These data include information on the feed demand and composition for beef cattle, dairy cattle, sheep and goat for 28 world-regions and 8 Livestock Production Systems. Animal numbers are converted to tropical livestock units (TLU; 1 TLU = 250 kg body weight; FAO 2015). We distinguish between total feed-demand in tC/yr covered through grazing and other feed, i.e., feedstuff from stover, occasional feeds or grain, and we include cattle, buffaloes, sheep and goats in our analysis.

Data-Set	Type/Resolution	Purpose	YEAR	Reference
Grazing area, km²	Raster, 0.083°	Current grazing area	2000	Erb et al. 2007
FAO Eco-Floristic-Zones	Shapefile	Potential grassland extent	Potential	FAO 2008
Terrestrial Ecoregions of the world	Shapefile	Potential grassland extent	Potential	Olson et al. 2001
Potential Vegetation	Raster, 0.5°	Potential grassland extent	Potential	Foley and Ramankutty 2010
Livestock density	Raster, 0.05°	Current livestock density	2000	FAO 2007
Livestock Production Systems (LPS)	Raster, 0.0083°	Distribution of livestock production systems	2000	Robinson et al. 2011
Feed demand	LPS/World regions	Feed-demand for grazing animals for different LPS and world-regions	2000	Herrero et al. 2013
Share of Cattle, Sheep and Goat on total grazer's feed-demand	Country-Level	Estimate feed-demand of all domestic grazers	2000	Krausmann et al. 2013
Natural Net Primary Production (NPP)	Raster, 0.5°	Monthly patterns of NPP	1994-2004	ESGF 2013
Length of growing period	Raster, 0.083°	Length of growing period	2000	Van Velthuizen 2007

Table 1: List and specifications of input-datasets

These 4 animal types make up for approximately 79% of the total feed-demand of all domestic grazing animals in 2000 (including cattle, buffaloes, sheep, goats, horses, asses, mules, camels and other camelids estimated by Krausmann et al. 2013).

To estimate the potential biomass supply, we use monthly NPP data from two different Earth System models, the JULES and ORCHIDEE model available from the ISI-MIP Fast-Track (ESGF 2013). We use monthly NPP data, i.e., the sum of NPP accumulated over the period of one month in tonnes carbon per grid-cell, based on model results for natural vegetation for the years 1994-2004 to delineate climatic induced variations in available NPP in natural grassland areas. The data are available at geographic resolution of 0.5° and the outputs were driven by the HadGEM2-ES climate model. Using NPP data for the natural vegetation helps us avoiding inconsistencies resulting from varying assumptions concerning land-use underlying the modelling process. Please note that all estimates refer to the grassland extent for the year 2000. We decided to apply data from JULES and ORCHIDEE, two widely used model environments for global change studies. The two models differ strongly regarding their NPP estimates and represent well the uncertainty across a wider range of models. This procedure provides us with a total of 20 different estimates for each grid-cell. Because the applied NPP data represent potential natural vegetation we are not able to account for the feedback between biomass removal and primary productivity. Grazing can, for instance, increase NPP by promoting compensatory growth, or decrease NPP through biomass removal or due to trampling.

Despite the focus on grassland areas within grassland biomes, a mixture of woody and grass species is common in many regions. Hence, not the entire aboveground NPP (aNPP) is accessible for animals, e.g., leaves from trees are only partly reachable. To account for this, we reduce NPP accessibility in areas where trees are observed by current tree-cover data from Hansen et al. (2013) to 15% (following average values from the literature; see SI). This follows the assumption that tree-cover observed in potential grasslands (e.g., not converted from former forest land) would also occur in the absence of human land-use.

We calculate current GI ($GI_{observed}$) by relating grazing demand (derived by multiplying the estimated biomass grazed by animals in tC/yr per TLU reported by Herrero et al. (2013) with the livestock density map) to the estimated aNPP available for grazing in the year 2000. In some pixels, this approach results in GI > 100%, which is likely the result of accumulated uncertainties and basically means that the modelled NPP is not sufficient to cover the estimated grazing feed-demand. To deal with this issue, we apply maximum GI levels for world-regions and climatic zones based on a large collection of local case studies available for the period between 1966 to 2015 (see SI) to the respective grid-cells. Studies reporting GI are rare and often concentrated on hotspots like for instance Northern America, New Zealand and natural grassland areas like the Mongolian Steppe etc. For this reason, we also rely on older data to provide the best coverage of values in all world-regions. This can, of course, result in an under- or overestimation of the current maximum GI observed in some regions, but the impact of this is rather small because only very few grid-cells are subject to such a correction.

The seasonally limited maximum GI (GI_{season}) is defined as the maximum GI that can be sustained during periods of minimum biomass supply in shortage periods. Similar to $GI_{observed}$, we do not allow GI_{season} to exceed the literature derived maximum GI level to ensure our results are realistic and rather on the conservative side. However, simply referring to the month with the minimum biomass supply would be inappropriate because it would neglect the fact that livestock can survive non-favourable periods by feeding on stored or old, i.e., dead biomass from earlier periods that is not yet decayed. In addition, improved management strategies such as the storage and conservation of biomass could help to achieve a better utilization of the available grass resources, but no information is available on the impact of these two factors on forage supply. To explore the range of possible impacts on GI, we assume that animals can survive shortage periods between 1 and 5 months. The appropriate number of months is assigned to each grid-cell using information on the length of growing period (or in other words the length of the shortage period), because this essentially determines forage availability and quality (see SI; Gerrish et al. 1998). We limit the number of months that can be survived without fresh growth to five in order to guarantee a conservative estimate, although animals even survive for longer, e.g. in regions or systems with permanent supplementary feeding. Our GI_{season} estimate hence represents the grazing intensity that could be sustained in the month with the minimum biomass supply (calculated as the moving average of 1-5 months). In addition, it is important to estimate the effect of declining feed quality after the end of the growing period (decay), yet such data are not readily available at the global level. To test the effect of such a decline we assume a quality drop of 3% per week (Mobile Farms 2015) for all our calculations.

To identify areas where biomass extraction could be increased, we compare $GI_{observed}$ to $GI_{season.}$ Areas where $GI_{observed}$ is well below the seasonality induced maximum GI (GI_{season}) could exhibit potential to increase biomass extraction. Increasing $GI_{observed}$ to the level of GI_{season} could contribute to increasing milk/meat production within the boundaries set by seasonality or to release area from production. To realistically estimate how much more milk or meat could be produced from one tonne additionally available carbon, the nutritional quality of grasses must be considered. We account for this by applying data from the Herrero et al. (2013) database, who assess the information at the level of livestock production systems distinguishing world-regions.

Another interesting aspect is how the observed grazing intensity interacts with the amount of other feed fed to animals. For this analysis and the sake of simplicity we have subsumed the three classes “stover”, “occasional”, and “grains” reported in the original Herrero et al. 2013 data set under the category “other feed”. To see how other sources of feed interact with shortage periods, we extract the number of months with insufficient biomass provision to sustain the estimated feed-demand and relate this to the total amount of other feed fed in each grid-cell. This shows how the length of seasonal limitations interact with the total demand for other feeds. As already outlined, the GI estimate is based on figures on grazing feed demand as presented by Herrero et al. (2013) and accumulated uncertainties in input-data products occasionally results in grid-cells where the available NPP is not sufficient to cover the estimated feed demand. In these grid-cells, we assume that the remainder must come from another source of feed and shift the excess to the “other feed” category. This adjustment, however, most likely interacts strongest with the “Occasional” feed category reported in the original data by Herrero et al. 2013. For this reason, the “other feed” category does not exactly reflect figures from Herrero et al. (2013) and differences highlight uncertainties in NPP, feed-demand and livestock distribution estimates.

All biomass flows, i.e., NPP and feed demand, are presented in carbon units. The study is restricted to the aboveground fraction of the total NPP by applying a factor of 60% (aNPP; House and Hall 2000) to the original NPP values. Feed-demand estimates are converted from dry-matter to carbon assuming a carbon content of 50% (Gibbs 2006; Mackey 2008; Saatchi et al. 2011). We present our results for 11 world regions: Central Asia and Russia (CA&RUSSIA), Eastern- and South Eastern Europe (E&SE EUR), Eastern Asia (EA), Latin America (LAM), Northern Africa and Western Asia (NAWA), Northern America (NA), Oceania (OCE), South-Eastern Asia (SEA), Southern Asia (SA), Sub-Saharan Africa (SSA), Western Europe (WEUR). A flowchart displaying the major steps of the data analysis process is presented in the SI.

2. Results

2.1. Grazing intensity and seasonality

$GI_{observed}$ in world’s natural grasslands lies below 15% on almost 79% of the total area (Figure 1a). On 36% of the area, GI is below 2%, on 56% below 5% and on 71% below 10%. Very low levels of $GI_{observed}$ can be found on all continents, but are particularly dominant in parts of Sub-Saharan Africa, Latin America, Central Asia and Russia, Eastern Asia and Northern America. High $GI_{observed}$ prevails in arid and semi-arid regions where it can exceed 50%. Such areas are mostly located in Eastern Asia, Sub-Saharan Africa, Northern Africa and Western Asia and Southern Asia but cover only 4.6% of the total area. Figure 1b shows the distribution of GI_{season}, e.g., the potentially feasible GI considering that animals can survive a certain time without new biomass growth (e.g., 1-5months) by feeding from dead or decaying grasses, leaves or stored biomass. In contrast to $GI_{observed}$, GI_{season} exceeds 10% on approximately 33% of all grazing lands. GI_{season} > 10% is the dominant pattern in many parts of Latin America and Sub-Saharan Africa, areas where $GI_{observed}$ is often below 2%. Other hotspots with a relatively high GI_{season} are located in Northern America, parts of Europe and Eastern Australia. In arid areas (e.g., Eastern North America, the Atacama, the Sahel zone in Africa, and dry regions of Asia and Australia; see Figure 1b, dark blue grid-cells) GI_{season} is often close to or zero, covering up to 44% of the total natural grassland area.

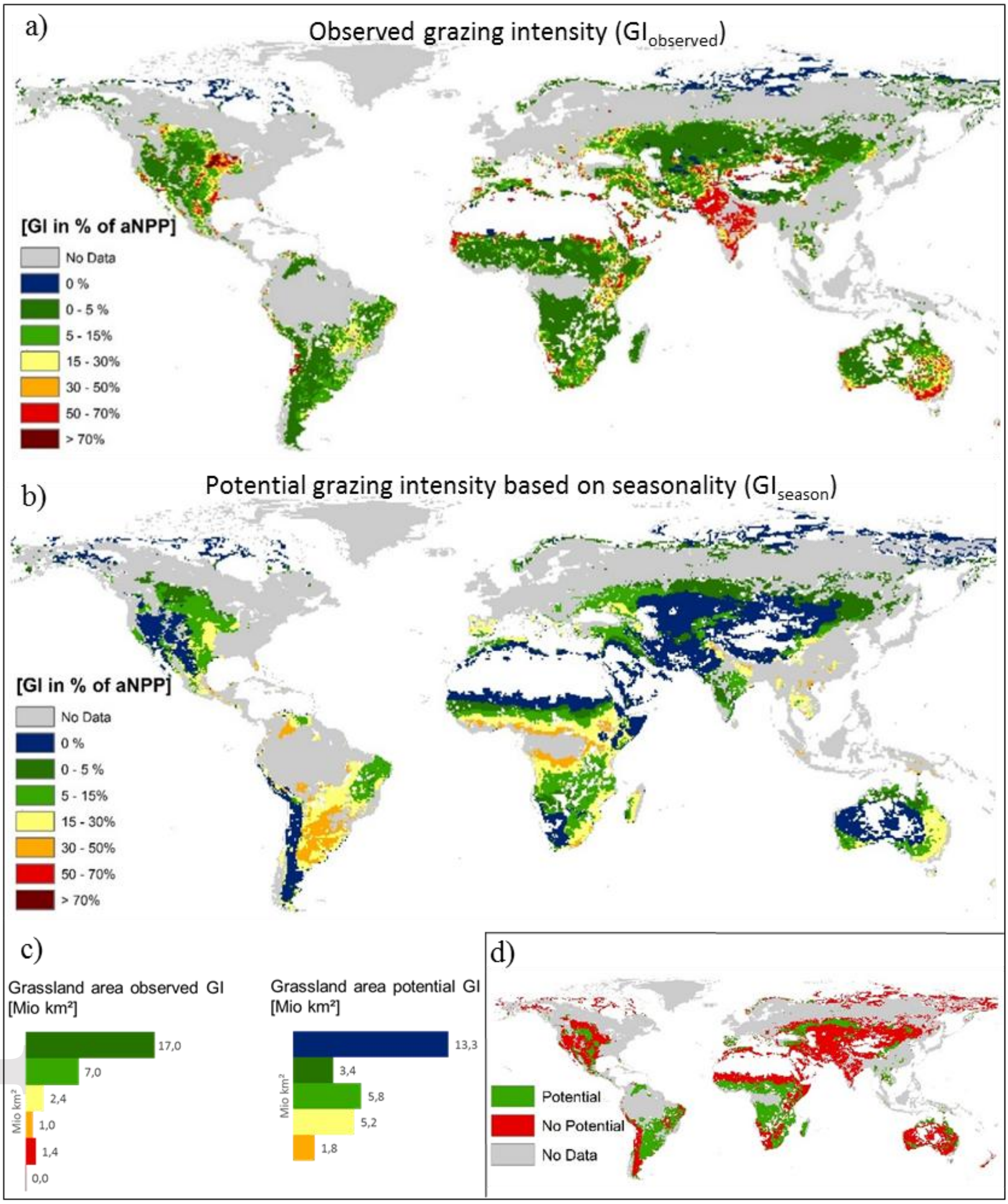

Figure 1: Global pattern of grazing intensity (GI) in natural grasslands (GI = grazing feed-demand/aNPP). a) Observed grazing intensity ($GI_{observed}$) in the year 2000; b) potential grazing intensity based on seasonality (GI_{season}); c) Grassland area for each group displayed in a and b for $GI_{observed}$ and GI_{season}. d) Spatial distribution of areas with potential or no potential to increase GI. Grey areas are excluded from the assessment, because we focus on natural grassland extent only.

The reason for this is that biomass supply drops to zero even when considering that animals can feed up to 5 months from dead biomass. In these areas, keeping ruminant animals requires to deal with periods of 5 months or more of feed deficiency. Assuming that more than 5 months could be bridged would eventually allow to come up with a potential for further biomass extraction in these regions and indeed it is well known that winter grazing without any supplements is not uncommon, for instance in North America. Yet, increasing biomass removals in regions with very long shortage periods would come at substantial socio-economic cost in terms of management, storage technologies and supplementary feed. Applying a maximum of 5 months hence allows to come up with a more realistic estimate and to exclude potentials associated with a very high socio-economic effort.

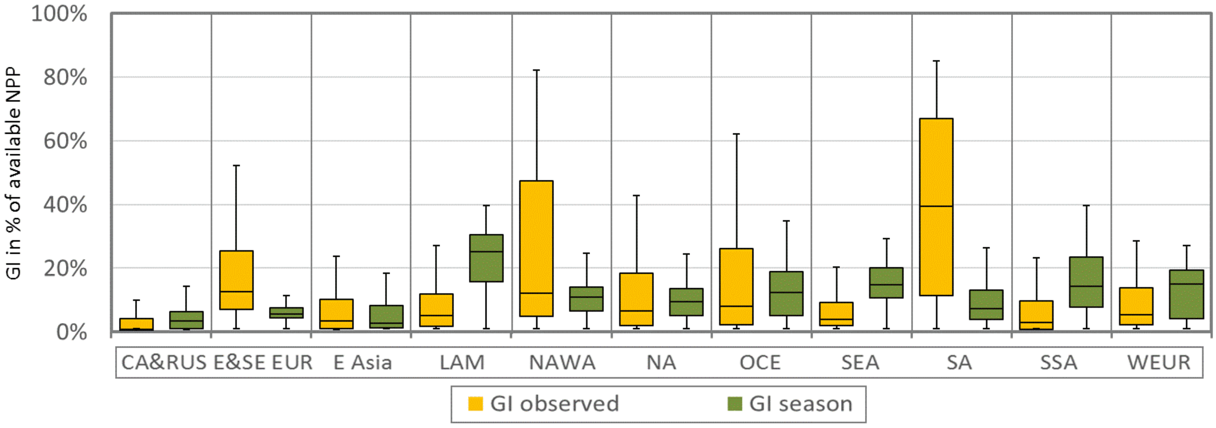

Figure 2: Boxplot of global pattern of grazing intensity (GI) in natural grasslands and world-regions for current grazing intensity ($GI_{observed}$) in the year 2000 and potential grazing intensity (GI_{season}). The box represents the inner quartiles, whiskers the minimum and maximum respectively. The discrepancy between $GI_{observed}$ and GI_{season} is due to the availability of storage systems and a more efficient use of the available grass resources. World regions: CA&RUS = Central Asia and Russia, E&SE EUR = Eastern and South-Eastern Europe, E Asia = Eastern Asia, LAM = Latin America, NAWA = Northern Africa and Western Asia, NA = Northern America, OCE = Oceania, SEA = South-Eastern Asia, SA = Southern Asia, SSA = Sub-Saharan Africa, WEUR = Western Europe.

World-regions with dominant hotspots like Southern Asia, Northern Africa and Western Asia, North America, Oceania or Eastern and South-Eastern Europe also show a widespread distribution of $GI_{observed}$ which often exceeds GI_{season} (Figure 2) by far. A high $GI_{observed}$ can be explained by improved management (e.g., a more efficient use of the available resource) but often strongly relies on the availability of other feed sources. On the other hand, in regions like Latin America, Sub-Saharan Africa, or South-Eastern Asia $GI_{observed}$ lies significantly below GI_{season}. The potential GI_{season} exceeds $GI_{observed}$ in Latin America (16 vs 7%), Sub-Saharan Africa (10 vs 5%) or South-Eastern Asia (16 vs 6%; see Figure 3a and Table 5 SI). Due to variations in climatic factors, $GI_{observed}$ varies drastically between years (Figure 3b). On average, $GI_{observed}$ is highest in Southern Asia (52%) followed by Eastern and South-Eastern Europe (22%) and Oceania (18%) and lowest in Central Asia and Russia (4%) followed by Eastern Asia (5%), Sub-Saharan Africa (5%), South-Eastern Asia (6%) and Latin America (7%).

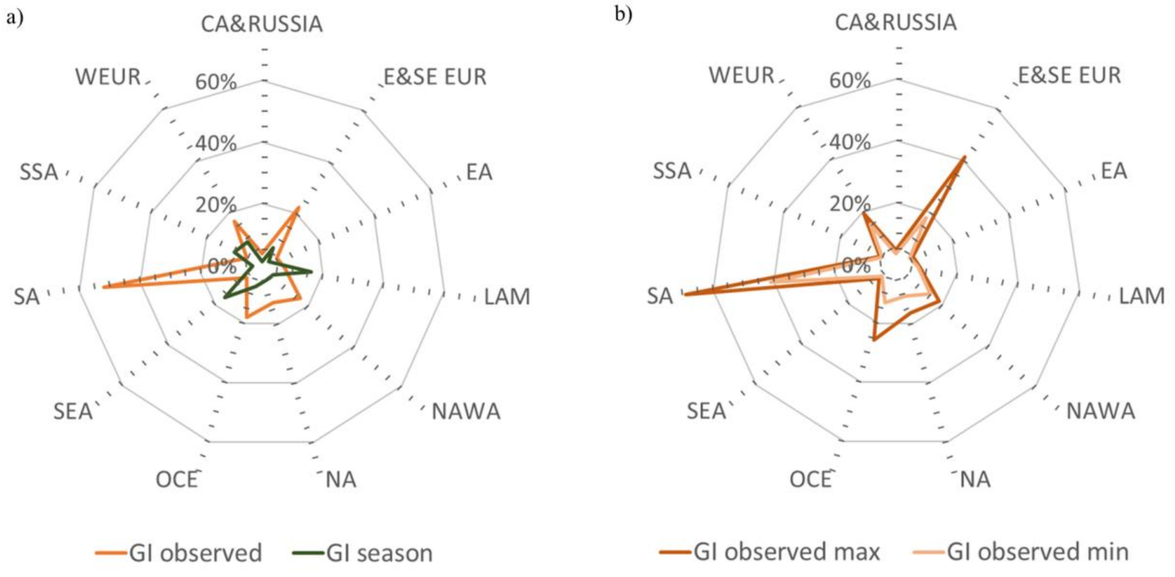

Figure 3: Patterns of average GI for world-regions. a) Regional averages of $GI_{observed}$ (values for the year 2000), GI_{season} and b) Variation of $GI_{observed}$ (minimum and maximum observed in the period 1994 – 2004, considering the range of estimates resulting from the two NPP data products).

Accounting for the difference between $GI_{observed}$ and the estimated GI_{season} shows that within the 10 simulated years at minimum 182 Mio tC/yr and at maximum 997 Mio tC/yr of potential surplus biomass could be available before reaching the estimated GI_{season} (Table 2). The large range of results is mainly influenced by interannual variations in biomass supply driven by climatic variables like precipitation (Yan et al. 2015) and differences in the two NPP data-products. Sub-Saharan Africa (45%) and Latin America (52%) contribute most to the total potential.

The estimated minimum potential (e.g., 182 Mio tC/yr) could support an additional milk production of up to 29 Mio t/milk/yr, which is equivalent to a growth of 5% compared to the production reported by Herrero et al. (2013) for the year 2000. On the other hand, the surplus could allow an additional meat production of up to 2.6 Mio t/meat/yr (+4% compared to 2000) or contribute to release up to 2.8 Mio km² of natural grazing lands from production.

Surplus NPP in tC/yr

Region	Minimum	25th quartile	Average	75th quartile	Maximum	Variation grassland area
South-Eastern Asia	3,3	8,8	13,1	19,1	26,8	-+94/0%
Sub-Saharan Africa	77,3	151,8	221,5	328,6	483,4	-+46/5%
Latin America	99,3	165,4	207,8	277,8	358,4	-+27/4%
Other	2,0	30,7	29,7	75,3	128,8	-+25/12%
World	181,9	356,8	472,0	700,8	997,4	-+38/4%

Table 2: Potentially available surplus NPP. Figures reflect the potential for further biomass extraction defined as the difference between GI$_{observed}$ and the respective estimate for GI$_{season}$. The presented values refer to the minimum, quartiles, average and maximum for the range of values derived from the two independent NPP estimates and the ten years 1994-2004, the underlying grassland extent is constant. The last column highlights changes to the estimates resulting from varying the underlying grazing area maps (Please note that the negative variation is larger, because the Erb et al. 2007 dataset is already at the higher end of the spectrum).

2.2. Interaction of GI, other feed sources and seasonality

Pushing GI beyond its seasonal potential comes with an increased socio-economic cost, e.g., the need for management such as the implementation of storage facilities or the exploitation of other sources of feed to avoid overgrazing and damage to the land like soil erosion. Total estimated supplementary feed ranges between 466 – 510 Mio tC/yr, the bulk of which is fed to animals in Southern Asia, Sub-Saharan Africa and Latin America (Figure 4a) in particular in mixed systems (72%). Arid areas account for up to 59% of the global total (Figure 4b). Our results show that the distribution of supplementary feed is not necessarily related to seasonal limitations. Of the total other feeds, 20% are fed in areas without seasonal limitations, followed by 12% fed in areas with limitations of 1-3 months and 18% with 4-6 months. Up to 49% is fed in areas with very strong seasonal limitations between 7 and 11 months, mainly in Southern Asia (36% of the global total) and smaller fractions in other world regions. In Latin America and Sub-Saharan Africa, which together make up for 35% of the global total other feed, 73% and 32% of the regional other feed is fed in areas where no seasonal constraints occur. Another 17% in Latin America and 25% in Sub-Saharan Africa are fed in regions, where seasonal limitations are only minor with 1-3 months of feed-deficiency. Hence, globally 32% of the total other feed is fed in regions with no or only small (1-3 months of deficiency) seasonal limitations, areas where the share of other feed could be reduced in theory. But in practice this will depend on the nutritional value of the available grasses at the specific location.

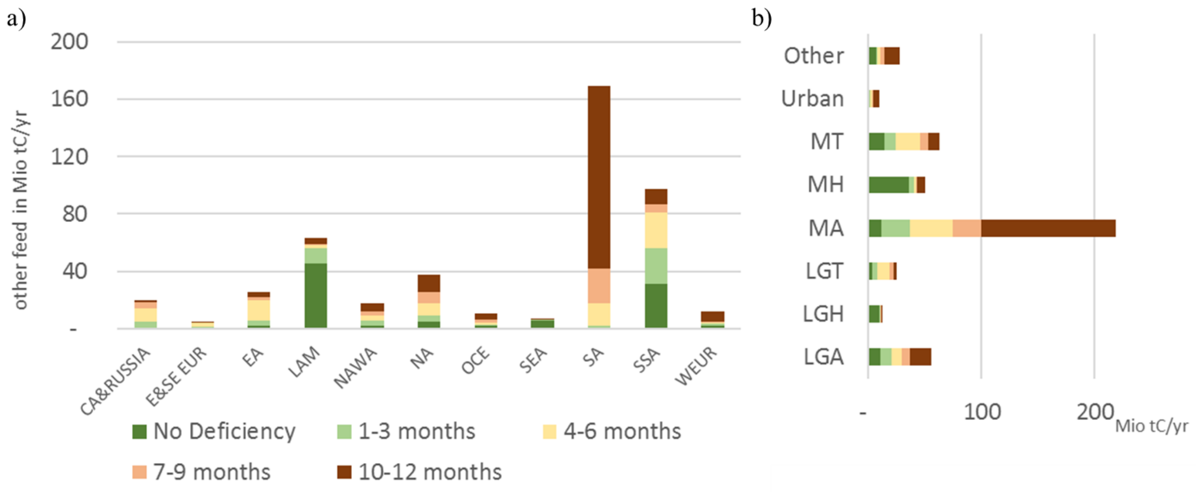

Figure 4: Supplementary feed in Mio tC/yr, divided into periods of feed-deficiency in a) world regions and b) livestock production systems: based on feed-demand Herrero et al. (2013) and accessible aNPP; LGA = Rangeland-based arid, LGH = Rangeland based humid, LGT = Rangeland based temperate/tropical highland, MA = Mixed arid, MH = Mixed humid, MT = Mixed temperate/tropical highland, Urban & Other.

The average other feed as presented in Figure 4 differs slightly from the data presented in Herrero et al. (2013) because in grid-cells with insufficient simulated NPP provision, we shift the remaining feed-demand from grazing to other feed categories. The necessity to adjust for this is a result of accumulated uncertainties resulting from the combination of NPP data, animal distribution, local variations in common feeding practices which cannot exactly be reflected using regional level data and problems of delineating grasslands from other land-uses.

3. Discussion and conclusions

The comparison of grazing intensity observed in the year 2000 ($GI_{observed}$) and the potential maximum grazing intensity (GI_{season}) defined by limitations of biomass supply in shortage periods reveals a theoretical potential for increasing biomass extraction from grasslands biomes between 182 and 997 Mio tC/yr (see Table 2). The presented range is based on variations from two different NPP data products and reflects inter-annual variations in biomass supply as a result of climatic variations. $GI_{observed}$ in the year 2000 generally shows an heterogenous distribution but is low in most parts of world's natural grassland biomes. Hotspots of very high $GI_{observed}$ are located on all continents, but are particularly dominant in arid and semi-arid areas of Africa and Asia. $GI_{observed}$ lies well below the potential maximum imposed by seasonality (GI_{season}) in large parts of Latin America, Sub-Saharan Africa and to a smaller extent in other world-regions. These areas theoretically exhibit the potential to increase GI to the estimated seasonal potential by applying bridging technologies like storage, biomass conservation or grazing dead standing biomass. Latin America and Sub-Saharan Africa exhibit the bulk of the estimated potential by accounting for 52% and 45% respectively. In addition, they account for up to 35% of the global total other feed fed to animals and a large fraction of this is fed in areas with no apparent seasonal limitations of biomass supply (e.g., 73% in LAM and 32% of other feeds in SSA; see Figure 4a). Globally, feed from other sources amounts to 466-510 Mio tC/yr. Increasing $GI_{observed}$ to the estimated seasonal potential (GI_{season}) could allow reducing the fraction of other feeds on total feed demand and at the same time keeping the production at the same level. This could be an essential strategy to reduce environmental burdens (Schader et al. 2015) related to crop production. Increasing the utilization levels of available grass resources in the respective regions could also contribute to increasing milk or meat production or carbon sequestration by releasing areas from production. According to our conservative results (i.e., 181 Mio tC/yr) either up to 2.8 Mio km² of grasslands could be released from production or the surplus NPP could contribute to increasing milk production by 5% (29.2 Mio t/yr) or meat production by 4% (2.6 Mio t/yr). The results clearly show, that there is at least some space to improve resource use efficiency by applying proper management to the current grassland resources. Yet, efforts to increasing the efficiency of livestock systems are often hampered by massive socioeconomic and institutional constraints (Alkemade et al. 2013).

Regions with potential to increase biomass extraction

We assume that it is easiest to utilize the estimated potential surplus biomass in regions, where mixed crop-livestock systems are dominant (IAC 2005; Herrero et al. 2013; Thornton 2010) and the use of crops or residues as supplementary feed is currently not well implemented or inefficient. The surplus biomass could be used by increasing animal densities and a better management of the available supplementary feeds could help to feed the animals in periods of insufficient biomass supply and lower the resilience towards extreme events. Such a situation has been reported for large parts of Sub-Saharan Africa where valuable feed sources like trees or crop residues are often not well integrated (Lenne and Thomas 2006). In these regions, a combination of better utilizing the available crop residues and grass resources could exhibit substantial potential. In contrast to the African continent, other nutrient rich sources of feed like soybean are sufficiently available and integrated in mixed livestock systems in Latin America, where cereal stovers play a less important role (Herrero et al. 2013). But the good availability of other feed sources came at the expense of massive deforestation for cropland and pasture expansion in the past 30 years (Thornton 2010) and the resulting land abundance has largely prevented efficiency improvements (Alkemade et al. 2013). Using the available pasture resources more efficiently in these regions of Latin America could hence help to avoid further deforestation, facilitating a better integration of crop residues in livestock feed and help to reduce the fraction of nutrient rich feeds like soybeans in a region where seasonal limitations are marginal.

Socio-economic, abiotic and data driven limitations

Many regions where we identify a potential to increase biomass extraction are often relatively remote with a lack of infrastructure (e.g., storage facilities, transportation), labour constraints, competition among stakeholders, a lack of market access, knowledge or finance (Lenne and Thomas 2006; Kindu et al. 2014; Jayne et al. 2014, Rufino et al. 2008; Muhereza et al. 2014), or have been identified as hotspots of biodiversity (e.g., endemism richness going along with low land use intensity in Mesoamerica, Eastern Africa or SEA; Kehoe et al. 2015).

Intensification of land-use is often related to negative environmental impacts such as the degradation of ecosystems and soils, the pollution of groundwater and air or biodiversity loss (Erb 2012; Millennium Ecosystem Assessement 2005, Tilman 2006). Negative effects of grazing have been widely discussed in the scientific community. Overgrazing and the expansion of grazing lands into pristine ecosystems (factor 6 since 1800; Steinfeld et al. 2006) for instance have resulted in soil erosion, a depletion of carbon stocks and contributed to increasing GHG emissions (O'Mara 2012). Furthermore, social problems related to the intensification of grazing systems like commodification, alterations in the access to resources or the marginalization of the poor etc. (FAO 2011) have been identified as important factors. This is particularly true for Sub-Saharan Africa where a combination of population growth, urbanization, changes in land-tenure, international land deals and restricted access to traditional grassland areas have led to widespread degradation (Conant and Paustian 2002; Jayne et al. 2014; Fetzel et al. 2016).

A major issue relates to the fact that the impact of changes in ecosystem processes resulting from variations in GI still cannot be represented well at the aggregated level (Kaplan et al. 2009). While many of these factors, like the impacts of grazing on species diversity and composition, primary productivity and hydrology are very well understood at the local level (Illius and O'Connor 1999, Noy-Meir 1975; Fynn and O'Connor 2000; Oesterheld et al. 1999; Milchunas and Lauenroth 1993; Sasaki et al. 2007), the complex interlinkage of variables like grazing history and frequency, or stocking rate, hamper an aggregated representation (Milchunas and Lauenroth 1993). Together with the essentially nonlinear responses of NPP to grazing (Sasaki et al. 2007; Oesterheld et al. 1999) the definition of generalizable thresholds for GI at higher levels (e.g., regions or biomes) becomes intricate and context specific.

In addition, abiotic factors (e.g., droughts) play an essential role in determining biomass provision in arid and semi-arid regions of the world (Vetter 2004). Although the limitation of biomass through droughts is generally considered in Earth System models and hence in the applied NPP data, the limited range of our data (e.g., 10 years) may miss out on extreme drought events and introduce uncertainty to the estimated availability of biomass. As a result, livestock mortality is high (often higher than 20% per year; Duncan et al. 2013) and herd recovery after shocks like droughts can be very slow (Lesnoff et al. 2012). Another issue is related to variations in feeding quality of grasses, which is generally considered in the data by Herrero et al. (2013), yet the regional level data are not able to appropriately capture local level variations and cannot account for abiotic factors like the impacts of droughts on the feeding quality of grasses. Also, grazing influences productivity, e.g. by reducing the total NPP through grazing and trampling or increasing NPP through compensatory growth, yet, we do not consider such interactions in our work and this could impact the actual potential at the local level.

Advantages of improved efficiency

In the light of projected future sustainability challenges and issues of food security it appears timely to focus on improving the efficiency of biomass use on existing areas rather than promoting further land expansion (Fetzel et al. 2016; Herrero et al. 2013, O'Mara 2012). Our results support this notion and show that even when considering a wide range of estimates including the application of different NPP data products and considering climatic limitations imposed by interannual variations in biomass supply, some potential surplus NPP is available in most world-regions.

Despite all constraints, utilizing even parts of this potential could be an asset to food security and reduce pressure on world’s croplands of which 1/3 is already in use for feeding livestock (Foley et al. 2011). In addition, a better integration of crop residues and other sources of feed in animal feed would not only help to increase GI but also make farmers more resilient towards climatic fluctuations and extreme events like droughts. Yet, local constraints need to be overcome and potential (positive or negative) environmental trade-offs must be considered carefully. Sound, regionally balanced management strategies in combination with sustainable intensification measures targeted at increasing productivity could generate substantial benefits by helping to reduce the fraction of other feed, increasing production, restoring degraded lands and even contribute to reduce GHG emissions by promoting carbon sequestration in soil carbon stocks (Soussanna et al. 2013; Schader et al. 2015). In addition, alleviating land competition by reducing the pressure on croplands for animal feeding could have positive net effects on many environmental variables due to the favourable energy balance of cropland over animal products (Schader et al. 2015).

Our results provide strong evidence that there is potential to use the available resource more efficiently by promoting improved grazing management. Measures should target at the improvement of the knowledge base of land users and include management practices such as timing, duration and spatial distribution of grazing (rotational grazing), appropriate stocking rates, the implementation of storage facilities, sowing of legumes and high productive species, fire management, fertilization and the promotion of an efficient integration of other feed sources and the conservation of forage in storage systems where possible (Sternberg et al. 2000; Lal, 2004; Smith et al 2007; NRCS 2011; Henderson et al. 2015). Achieving this potential might be a challenge in areas where abiotic factors like precipitation result in extended droughts and hence limited biomass availability in some years. It is the combination of several factors like the availability of and ability to buy supplementary feeds, a certain flexibility of farmers to alter herd size, the implementation of storage systems and free access to infrequently used grazing areas (e.g., in transhumance systems) that could help extracting more biomass. Free accessibility is an essential strategy to coping with the effects of droughts (Bayer and Waters-Bayer 1994) and indeed, it has been argued that restricting pastoralists access to historically grazed areas resulted in increased grazing pressure and local degradation in the remaining areas (Vetter 2004). A combination of the storage of excess biomass from surplus periods from either grasslands or croplands (crop residues or fodder-crops), free access to traditionally used land and a good market access which could help farmers to quickly adapting stocking density or buy supplementary feeds could help tackling the risks of increasing stocking densities in these regions.

Grasslands are an important asset for humans providing food and income for many people and grazing allows the utilization of land not suitable for other land-uses such as cropping and is vital for maintaining food security. Grasslands also play an essential role for increasing food production to meet projected future food demands. To achieve this target in a sustainable manner, it appears timely to focus on a more efficient use of the currently available land-resources instead of promoting further land expansion. By mapping grazing intensity and seasonal constraints to GI at the global level, we show that advanced management would allow compensating (at least partly) for seasonality-related feed-shortages on 39% of natural grasslands, e.g., by implementing storage systems or proper management of grazing (in terms of onset, duration and recovery time) and the better integration of already available other feeds. Warranting cautious and sensible management, mobilizing these potentials could free a considerable biomass flow, mainly in Sub-Saharan Africa and more realistically in Latin America. However, the required knowledge for such a best-practice grassland management, e.g., on safe levels of grazing intensity, onset, duration and timing of grazing, as well as the implementation of storage facilities that can help to better utilize the available resources, is still limited. To reap the socio-economic and environmental benefits related to the mobilization of such a potential, while avoiding socioecological detriments requires a significantly advanced understanding of grazing systems as well as proper policy frameworks that integrate local, regional and global socio-economic and ecological perspectives.

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Figure 5: Global pattern of grazing intensity (GI) in natural grasslands (GI = grazing feed-demand/aNPP). a) Observed grazing intensity ($GI_{observed}$) in the year 2000; b) potential grazing intensity based on seasonality (GI_{season}); c) Grassland area for each group displayed in a and b for $GI_{observed}$ and GI_{season}. d) Spatial distribution of areas with potential or no potential to increase GI. Grey areas are excluded from the assessment, because we focus on natural grassland extent only.

Figure 6: Boxplot of global pattern of grazing intensity (GI) in natural grasslands and world-regions for current grazing intensity ($GI_{observed}$) in the year 2000 and potential grazing intensity (GI_{season}). The box represents the inner quartiles, whiskers the minimum and maximum respectively. The discrepancy between $GI_{observed}$ and GI_{season} is due to the availability of storage systems and a more efficient use of the available grass resources. World regions: CA&RUS = Central Asia and Russia, E&SE EUR = Eastern and South-Eastern Europe, E Asia = Eastern Asia, LAM = Latin America, NAWA = Northern Africa and Western Asia, NA = Northern America, OCE = Oceania, SEA = South-Eastern Asia, SA = Southern Asia, SSA = Sub-Saharan Africa, WEUR = Western Europe.

Figure 7: Patterns of average GI for world-regions. a) Regional averages of $GI_{observed}$ (values for the year 2000), GI_{season} and b) Variation of $GI_{observed}$ (minimum and maximum observed in the period 1994 – 2004, considering the range of estimates resulting from the two NPP data products).

Figure 8: Supplementary feed in Mio tC/yr, divided into periods of feed-deficiency in a) world regions and b) livestock production systems: based on feed-demand Herrero et al. (2013) and accessible aNPP; LGA = Rangeland-based arid, LGH = Rangeland based humid, LGT = Rangeland based temperate/tropical highland, MA = Mixed arid, MH = Mixed humid, MT = Mixed temperate/tropical highland, Urban & Other.

Table 3: List and specifications of input-datasets

Table 4: Potentially available surplus NPP. Figures reflect the potential for further biomass extraction defined as the difference between $GI_{observed}$ and the respective estimate for GI_{season}. The presented values refer to the minimum, quartiles, average and maximum for the range of values derived from the two independent NPP estimates and the ten years 1994-2004, the underlying grassland extent is constant. The last column highlights changes to the estimates resulting from varying the underlying grazing area maps (Please note that the negative variation is larger, because the Erb et al. 2007 dataset is already at the higher end of the spectrum).