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Improving the estimation of grazing pressure in tropical rangelands

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Supplementary material for this article is available online

Abstract

Livestock grazing is a key land use globally, with major environmental impacts, yet the spatial footprint of grazing remains elusive, particularly at broad scales. Here, we combine livestock system indicators based on remote sensing and livestock vaccination data with a biophysical grass growth model to assess forage production, livestock carrying capacity, and grazing pressure on rangelands in the South American Dry Chaco. Specifically, we assess how considering different livestock systems (e.g. fattening in confinement, grazing with supplementary feeding, woodland grazing) changes estimations of grazing pressure. Our results highlight an average carrying capacity of 0.48 animal units equivalents (AUEs) per hectare for the Chaco (0.72 for pastures, 0.43 for natural grasslands, 0.37 for woodlands). Regional livestock requirements ranged between 0.02–6.43 AUE ha^{-1}, with cattle dominating livestock requirements (91.6% of total AUE). Considering livestock systems with different production intensities markedly altered the rangeland carrying capacity and degradation estimations. For example, considering confinements and supplementary feeding drastically reduced the pasture area with potential overgrazing, from about 58 000 km^2 to $<$19 000 km^2 (i.e. 13.5% vs 5.7% of the total rangeland area). Conversely, considering the typically unaccounted-for cattle of woodland smallholders markedly increased the potentially degraded woodland area, from 3.2% ($\sim$1000 km^2) to 12.1% (3700 km^2) of the total woodland area. Our work shows how ignoring production intensity can bias grazing pressure estimations and, therefore, conclusions about rangeland degradation connected to livestock production. Mapping indicators characterizing the intensity of livestock systems thus provide opportunities to understand better grazing impacts and guide efforts towards more sustainable livestock production.

1. Introduction

Livestock grazing is the most widespread land use globally (Ellis 2021), including in the tropics, leading to major social–ecological impacts (Herrero *et al* 2009, 2013). Livestock ranching provides protein and income for a range of actors, from subsistence smallholders to industrialized ranchers, and through this, contributes to food security and economic development (Godber and Wall 2014, Mehrabi *et al* 2020). However, livestock production is associated with high socio–ecological costs. Where livestock production expands into natural ecosystems, a massive erosion of biodiversity, carbon stocks, and ecosystem functioning is often the result (Zalles *et al* 2021). Overgrazing is also a major driver of land degradation (Lai and Kumar 2020, Sanjuán *et al* 2022), and the livestock sector is a major contributor to global greenhouse gas emissions (Tubiello *et al* 2021). Therefore, it is important to understand the spatial footprint of livestock production and its effects on society and the environment.

This is particularly so for tropical and subtropical dry woodlands and savannas (hereafter: dry woodlands), covering about a fifth of the world's land surface (Scholes and Archer 1997) and harboring high biodiversity and carbon stocks (Portillo-Quintero and Sánchez-Azofeifa 2010, Murphy *et al* 2016). Livestock production is widespread in dry woodlands, encompassing a variety of traditional, smallholder, and industrialized livestock systems (Baldi *et al* 2013, Pratzer *et al* 2024). Cattle production has been rapidly expanding and intensifying in many dry woodlands, especially in South America (Godde *et al* 2018). Given that expansion often occurs into areas of high conservation value (Buchadas *et al* 2023), finding ways to balance livestock production with environmental goals is important for dry woodlands (Parr *et al* 2014, Castonguay *et al* 2023).

Assessing livestock pressure on the environment depends on spatial data on livestock production, but these data are missing for most parts of the world (Kuemmerle *et al* 2013, Erb *et al* 2016). The first step in estimating grazing pressure is determining the forage available as feed (Piipponen *et al* 2022). Both Earth observation and biophysical models can now provide much-improved grassland forage estimates (Jin *et al* 2014, Petz *et al* 2014, De Leeuw *et al* 2019, Monteiro *et al* 2020), particularly when both are integrated (Fetzel *et al* 2017, Wolf *et al* 2021). However, in dry woodlands, these methods often represent forage available to livestock inadequately due to their high natural heterogeneity, with admixtures of trees, shrubs, and grass contributing to overall forage availability (Blanco *et al* 2016). Better indicators that capture and characterize this heterogeneity are needed to describe forage available to livestock in these systems (Baumann *et al* 2018, Cooper *et al* 2020, Vermeulen *et al* 2021, Nascimento *et al* 2022).

Forage indicators, when available, can be combined with livestock data to model grazing pressure. However, two main limitations exist for applying these models across large areas. First, fine-scale data on livestock numbers and composition are often unavailable (Robinson *et al* 2014). Datasets such as livestock vaccination or cattle transaction data could help bridge this gap, but they have not been used for this purpose so far (Vale *et al* 2019, Fernández *et al* 2020a). Second, livestock grazing varies across systems with different stocking rates, fodder sources and grazing management (Anadón *et al* 2014, Herrero *et al* 2013, Wang *et al* 2020), and ignoring them can potentially bias grazing pressure assessments.

Smallholder ranchers, for instance, are widespread in dry woodlands (Pratzer *et al* 2024), relying on natural vegetation for forage, yet are typically ignored in broad-scale grazing analyses (Ellis and Ramankutty 2008, Herrero *et al* 2013). Similarly, intensified livestock production practices, such as supplementary feeding, are widespread in dry woodlands, especially during dry periods (Fetzel *et al* 2017). Supplementary feeding ranges from strategic supplementation for specific herd categories or at a particular time of the year (Fernandez *et al* 2023) to being the primary feeding source in confinement areas, where feed consists of silage, grains, or industrial by-products (Naylor *et al* 2005). Broad-scale livestock assessments typically overlook such management variations, potentially leading to inaccurate estimates of grazing pressure (Piipponen *et al* 2022), livestock-related greenhouse emissions (Herrero *et al* 2013), or potential carbon sequestration in soils (Bossio *et al* 2020, Jordon *et al* 2022).

Here, we assess how grazing pressure and estimates of rangeland degradation change when considering the intensity of livestock production associated with different livestock systems. We do so for the Argentine Dry Chaco, a dry woodland where livestock ranching has recently expanded and intensified in major ways, leading to substantial socio-ecological trade-offs (Baumann *et al* 2017, Fernández *et al* 2020a). Specifically, our study aims to address the following questions:

1) What is the current livestock carrying capacity of the Argentine Dry Chaco grazing areas?
2) What are the patterns of livestock requirements across the region's woodlands and grasslands?
3) How does considering livestock systems' intensity alter grazing pressure and rangeland degradation estimations?

2. Methods

2.1. Study area

The Argentine Dry Chaco spans approximately 470 000 km^2, with annual rainfall varying from 300 to 1000 mm (figure 1(A)). Since the 1990s, the area has undergone a fast transformation, driven by expanding soybean cultivation and industrial cattle ranching (Baumann *et al* 2022). Yet, diverse livestock systems coexist within the Chaco landscape, characterized by different actors and management practices (figure 1(B)). A detailed description of the study area and its livestock systems is available in the supplementary information (text S1).

2.2. Estimation of annual forage and livestock carrying capacity

We estimated the annual forage available to livestock (kg dry matter per year) and compared it against field data collected during the July 2018 to June

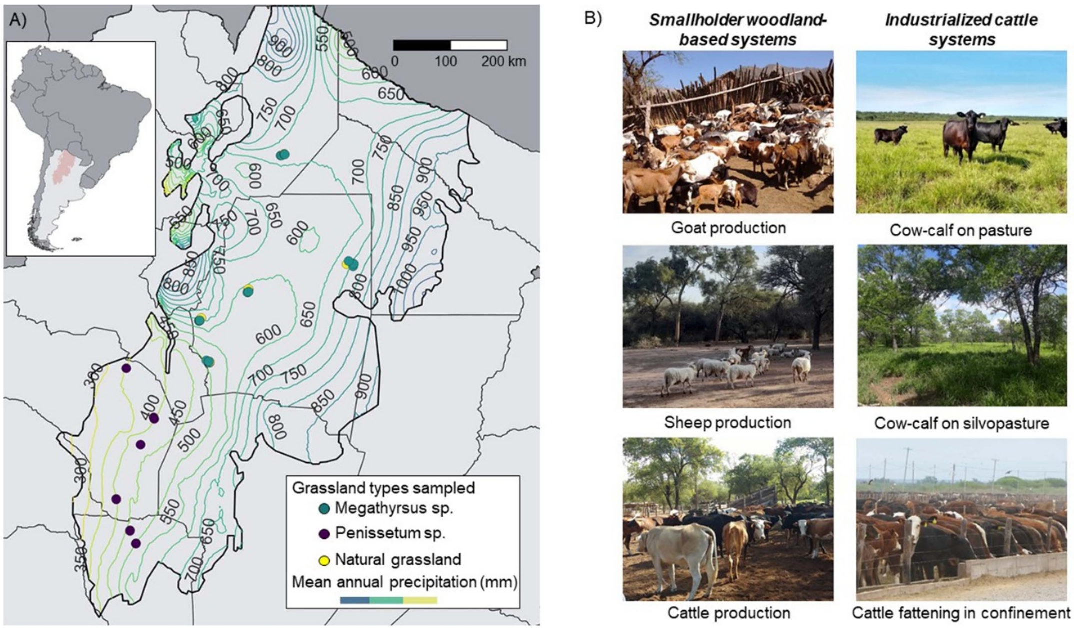

Figure 1. The study area in the Argentine Dry Chaco. (A) Annual rainfall patterns in the study area and locations where annual forage was measured in the field. (B) Examples of different livestock systems in the study area.

2019 productive cycle (figure 1(A)) (Fernández *et al* 2024). Importantly, field data was collected for three distinct types of grasslands: *Megathyrsus maximus* (Gatton Panic) sown pastures and *Pennisetum ciliare* (Buffel Grass) sown pastures and natural grasslands with a dominance of *Chloris spp. And Thricloris spp.* (figure 1(A)). We estimated forage available for all potentially grazeable land, including natural grasslands, woodlands with natural grass cover, and sown pastures (both treeless pastures and silvopastures), using 30 m-resolution land-cover maps for 2019 (Baumann *et al* 2022). To estimate annual forage, we tested two approaches. Our first approach consisted of a deterministic model of grass growth developed by McCall and Bishop-Hurley (2003) that was locally calibrated by Nasca *et al* (2020). In our second approach, we proxied annual forage using the MODIS net primary productivity product (NPP) (Running *et al* 2004), converted to annual forage following Piipponen *et al* (2022). For further details on the annual forage estimation and comparison with field data, refer to supplementary information (text S2).

We transformed the annual forage into accessible annual forage following Piipponen *et al* (2022). First, we applied a woody-cover multiplier (Piipponen *et al* 2022) using an available woody-cover map for 2016 (Baumann *et al* 2018), updated using the same method in 2019. Second, we multiplied this woody-cover adjusted map with a proper use factor (Piipponen *et al* 2022). This factor accounts for the proportion of biomass harvested for livestock, considering that not all produced plant biomass is consumable due to poor quality, inaccessibility, or toxicity. This study estimated the proper use factor as the proportion of total forage excluding the lignified biomass in the top 10 cm of soil, based on field data collected in 2018–2019 (i.e. 0.60), as reported in Fernández *et al* (2024). We provide more details on calculating forage maps in the supplementary information (text S3).

Next, we translated the accessible annual forage maps into a livestock-carrying capacity map to determine how many animals could be fed by the available forage. We divided the forage map into animal units equivalents (AUEs), defined as the amount of dry forage in kilograms consumed in a year by a 450 kg animal with a daily forage intake of 2.5% of its body weight (Society for Rangeland Assessment and Monitoring 2017). We then calculated the average livestock carrying capacity for the region's rangelands and each land cover separately (i.e. woodlands, pastures, natural grasslands).

2.3. Assessment of livestock requirements and grazing pressure

To assess the pressure of livestock systems on potentially available grazing land, we first estimated livestock forage requirements (kg dry matter.hectare^{-1} yr^{-1}) using livestock distribution data from the foot and mouth disease vaccination dataset provided by '*Servicio Nacional de Sanidad y Calidad Agroalimentaria*' (SENASA) for 2019. As we focused on meat production, we excluded the dairy sector (less than 1% of cattle stock) based on a dataset of dairy farms from our previous work (Fernández *et al* 2020a). The vaccination dataset holds a location (typically the center of a ranch) and associated stock composition in terms of livestock species (i.e. cattle, goats, sheep) and types (e.g. bull or cow) (Fernández *et al* 2020a). Argentina is considered free of foot-and-mouth disease, and all cattle in areas at risk of outbreaks (including the Chaco) must be vaccinated at least once yearly. Additionally, registration for the Registro Nacional Sanitario de Productores Agropecuarios (RENSPA) is mandatory for all livestock producers in Argentina. It serves as the national reference database for cattle traceability. It is thus fair to assume that almost all cattle are vaccinated. Small ruminant livestock undergoes the same vaccination process and is included in RENSPA. Although there is no official vaccination rate, it is known that some small livestock are unvaccinated (Fernández *et al* 2020a). We converted these data to AUE (see supplementary information table S1) to harmonize them. However, the dataset lacks information on animal breeds and productivity, which could influence AUE. However, it is standard practice to assume it remains constant throughout the year and across different breeds for large-scale analyses (Herrero *et al* 2013, Irisarri and Oesterheld 2020, Piipponen *et al* 2022).

Vaccination data are found at the center of the ranch, but livestock grazes across the entire farm or, in the absence of fences, in adjacent woodlands. For this reason, we distributed the AUE according to the surrounding potential grazing area to assess the stocking rate. We summed the AUE per $5 \times 5\ \mathrm{km}^2$ cell and then applied a moving window of 5×5 grids to estimate the mean stocking rate per grid. We divide this number by the area of the cell ($25\ \mathrm{km}^2$) to obtain the mean stocking rate per hectare for all potentially grazed areas, based on Baumann *et al* (2022). Depending on the type of livestock, we assumed different land-cover classes to compose potential grazing areas. Goats, which woodland-dependent smallholders predominantly raise, were assumed only to graze and browse on leaves and fruits of shrubs and trees in woodlands (Cáceres *et al* 2015, Nanni *et al* 2020, Levers *et al* 2021). Cattle and sheep were considered to graze only in pastures and natural grassland, except in woodland smallholder systems, where these livestock also forage in woodlands.

Using the maps of potential carrying capacity and actual livestock requirements (based on current livestock stocks), we then estimated actual grazing pressure, defined as the relative stocking density (Piipponen *et al* 2022), by dividing the livestock requirements per hectare by the potential carrying capacity per hectare (equation (1))

$$\text{Grazing pressure} = \frac{\text{livestock requirements}\ \left(\text{kg dry matterforage} * \text{year}^{-1}\right)}{\text{carrying capacity}\ \left(\text{kg dry matterforage} * \text{year}^{-1}\right)}. \tag{1}$$

We classified grazing pressure values lower than 0.25 as moderate, 0.25–0.65 as intermediate, and values exceeding 0.65 as potentially overgrazed. The 2018/2019 productive cycle was considerably wetter on average than the regional mean (supplementary figure S2), so we set a more conservative threshold than those developed by Piipponen *et al* (2022) for labeling different grazing pressure conditions.

We developed the grazing pressure and related maps using Google Earth Engine and R. The code is available at https://github.com/pedrofernandez91/Grazing-Intensity/tree/main.

2.4. Intensity of livestock grazing systems

To understand how considering the intensity of livestock systems modifies the assessment of grazing pressure, we assembled three livestock system indicators: (1) large cattle confinement areas, (2) silage bags holding supplementary feed in intensified cow-calf or rearing systems, and (3) homesteads of woodland-based smallholders that practice woodland grazing (hereafter: woodland smallholders; figures 2(A) and (B)). We used each indicator to estimate changes in grazing pressure individually and in combination.

Large cattle confinement areas (also known as feedlots) are enclosed spaces where animals are kept for feeding, management, or other husbandry purposes (Naylor *et al* 2005). We employed a random forest (RF) model using Sentinel-1 and Sentinel-2 imagery to map these large confinement areas for 2021. We trained the RF model with over 1200 polygons of confinement areas identified in very high-resolution imagery (further details on training data collection, model tuning, and validation are provided in supplementary information text S4). The size of a large confinement area correlates directly with the number of cattle heads it can support. While the area can range according to precipitation and temperature from 12–40 m^2, in the Dry Chaco, 20 m^2 is the average space allocated per calf or steer (Racciatti *et al* 2022). We estimated the carrying capacity for each mapped large confinement area. Then, we subtracted this value (AUE) from the AUE at the nearest cattle vaccination point. This adjustment enabled us to estimate confined cattle and the corresponding reduction in livestock requirements on surrounding rangelands.

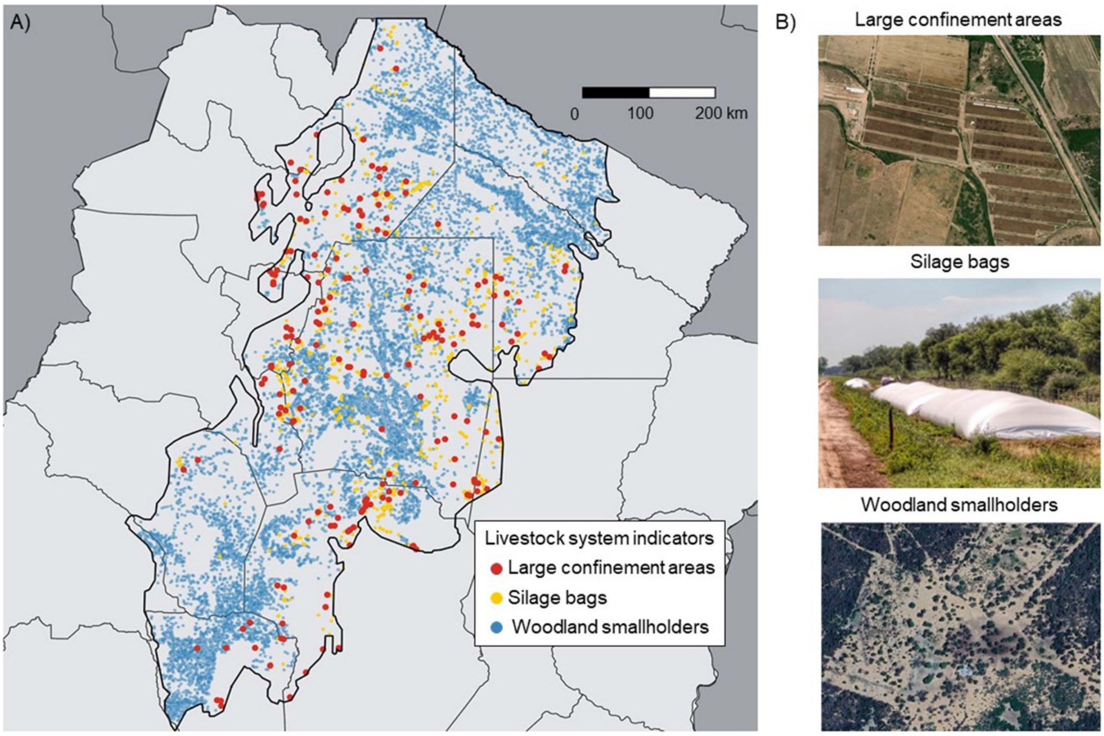

Figure 2. Livestock system indicators. (A) Distribution of indicators describing different livestock systems across the Argentine Dry Chaco. (B) Examples of a large confinement area, silage bags, and a woodland smallholder homestead.

Our second indicator was a map of silage bags, signaling cattle ranching intensification through supplementary feeding (Fernandez *et al* 2023). Silage can be used for supplementary feeding in grazing or confinement (Wilkinson and Rinne 2018). Still, the use of silage in confinement systems was excluded due to the risk of double counting with the first indicator. We estimated the forage stored in silage bags using a high-resolution (10 m) map from our previous work (Fernandez *et al* 2023). We converted the silage cover into silage forage (kg dry matter) (details in supplementary information text S5). We then calculated silage-based carrying capacity based on the same AUE factors described above. This additional silage-carrying capacity was spatially distributed to the surrounding sown pasture area, and we compared grazing pressure with and without the silage fodder subsidy.

The third indicator pertained to woodland smallholders, based on a comprehensive dataset of their homesteads in woodlands (Levers *et al* 2021). We assumed all goats were part of this system and grazed in woodlands (details in supplementary information S6). To estimate the cattle and sheep stock in woodland smallholder systems, we linked their locations to vaccination data from such smallholders (i.e. farms with fewer than 300 cattle heads). We then compared grazing pressure in woodlands with and without cattle and sheep associated with woodland smallholder systems.

3. Results

3.1. Patterns of livestock carrying capacity

Among the forage models we tested, our first approach based on a biophysical growth model had a higher agreement with our field data, with an R^2 of 0.38 and RSME = 1415 kg dry forage. The satellite-based measures had a much lower level of agreement ($R^2 = 0.0001$ and RSME = 2246; see supplementary information text S7 for further details). Different grassland types had different levels of agreement with field data when estimating their forage in the biophysical growth model, with sown pastures based on Gatton Panic (field samplings = 23), the most widespread pasture type in the area, with an R^2 of 0.46 and RSME = 1615; Buffel Grass ($n = 9$) with an R^2 of 0.58 and RSME = 1518) and natural grasslands ($n = 4$) with an R^2 of 0.38 and RSME = 1351. Therefore, we used the forage estimates from the biophysical growth model in all subsequent analyses.

Estimating livestock carrying capacity across the Dry Chaco revealed an average of 0.48 AUEs per hectare, with sown pastures (and silvopastures) achieving average livestock carrying capacity of 0.72 AUE ha^{-1}, natural grasslands of 0.43 AUE ha^{-1}, and woodlands of 0.37 AU ha^{-1} (figure 3(A)). The highest values, close to 1.8 AU ha^{-1}, were associated with sown pastures in the study area's eastern and western borders, aligned with the areas with the highest rainfall (figure 3(A)). The center and the southwest of the

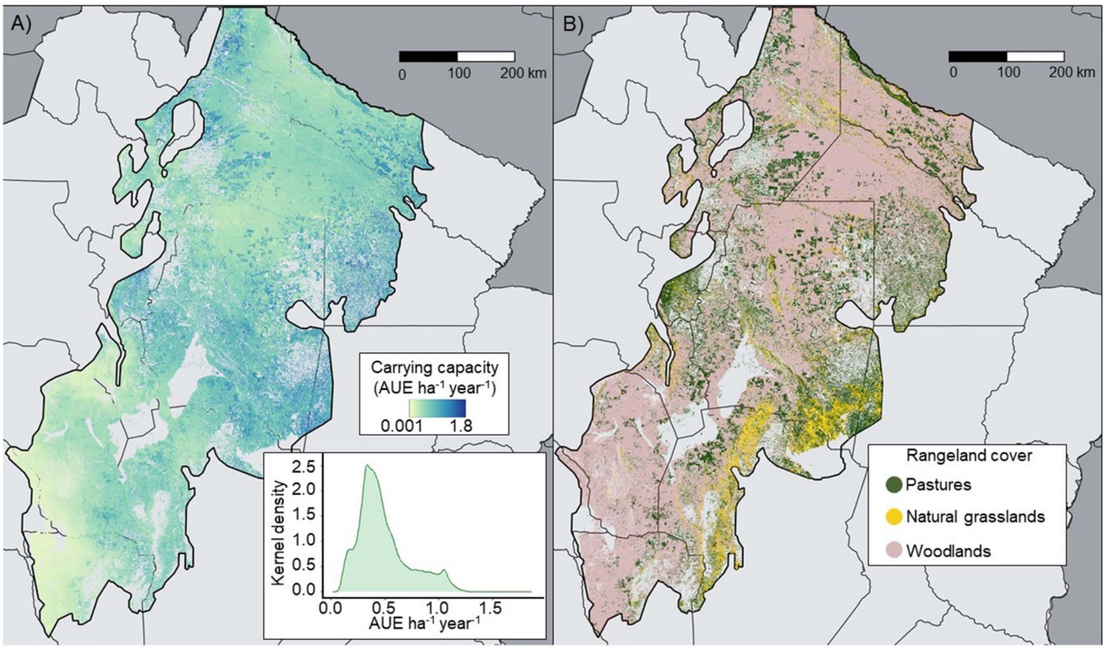

Figure 3. Livestock carrying capacity in the Argentine Dry Chaco. (A) Carrying capacity (kg of forage dry matter year^{-1}) estimated with the grass growth model for grazeable land. This includes sown pastures (treeless and silvopastures), natural grasslands, and woodlands (with natural grasses cover) for 2018–2019. The inset graph shows the AUE distribution. (B) Spatial distribution of sown pastures, natural grasslands, and woodlands for 2019.

study area had lower values, coinciding with the driest parts, where most remaining woodlands and natural grasslands are found (figure 3(B)).

3.2. Patterns of grazing pressure

The spatial patterns of livestock requirements (i.e. forage needed given current livestock stocks) varied for different livestock species (figure 4). Cattle were primarily distributed in the more productive sown pastures, averaging 0.12 AUE and a maximum of 3.13 AUE per hectare of grassland (figure 4(A)). Goats were concentrated in the northeast and southeast areas, with very low requirements (averaging 0.0005 AUE, maximum of 0.10 AUE per hectare of woodland) (figure 4(B)). Sheep, averaging 0.005 AUE per grassland hectare with a maximum of 0.45 hectare, were also scattered across the entire region, with a concentration in the southeast (figure 4(C)). The total livestock requirement was dominated by cattle (91.6% of the total livestock requirement), followed by sheep (6.1%) and goats (2.3%). The average AUE for all rangeland areas was 0.02 AUE ha^{-1}, with maximum values of 6.71 AUE ha^{-1} (see supplementary information figure S5).

3.3. Intensity of livestock grazing systems

Including livestock system indicators drastically altered grazing pressure estimates, reducing the area with potential overgrazing (i.e. high and intermediate grazing pressure) from 13.7% to 5.3% of the total rangeland area, which includes all pastures and silvopastures, natural grasslands, and woodlands (figure 5(A)). When all livestock system indicators were included, 4600 km^2 (1.1% of total rangeland area) were classified as overgrazed, and 18 333 km^2 (4.2%) had intermediate grazing pressure. These areas were scattered throughout the region, with concentrations in the southwestern woodlands and northwestern pastures (figure 5(B)).

Although cattle in large confinement areas were only 6.5% of the total cattle stock, considering them and thus removing their grazing requirement from rangelands reduced the area estimated to be overgrazed by 46.5%. We estimated the carrying capacity related to silage forage to be only 2% of the total forage needed for cattle in the 2018/2019 cycle, when rainfall was above average (supplementary figure S2). Finally, the livestock requirements for woodland increased by 268% when considering woodland smallholders' cattle, goat, and sheep livestock. However, allocating this livestock to woodland grazing reduced grazing pressure on the remaining pastures and natural grasslands, decreasing the area with moderate and overstocked pressure by 54.2% (figure 5(A)).

4. Discussion

Grazing is a major land use in the world's rangelands, yet grazing pressure varies substantially. A better understanding of the environmental impact of grazing hinges on data on the extent and intensity of livestock production, but such data is often missing. This is particularly so for the world's tropical dry woodlands, where livestock production is the main driver of land-use change. Using the Argentinean Dry Chaco

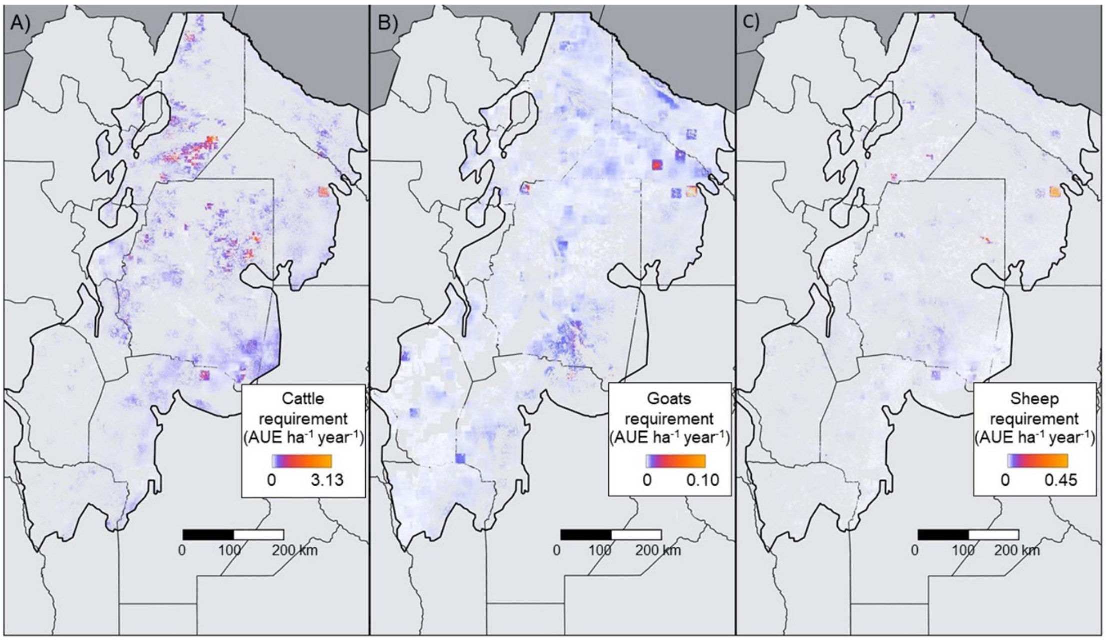

Figure 4. Livestock requirements. (A) Cattle requirements in sown pastures, silvopastures, and natural grasslands. (B) Goat requirements associated with woodlands. (C) Sheep requirements associated with sown pastures and natural grasslands.

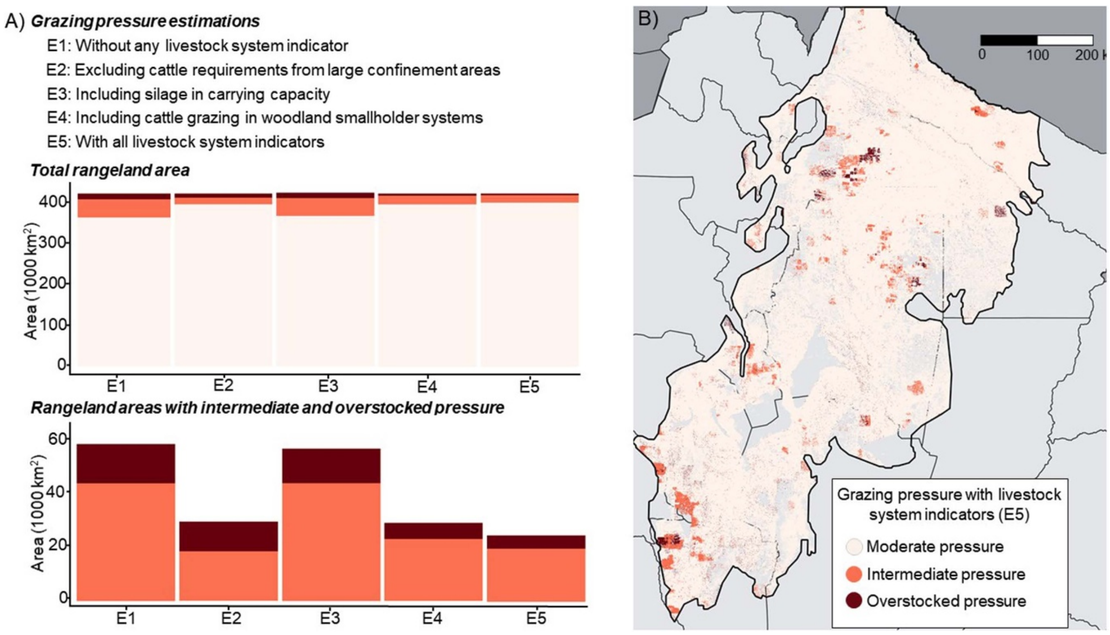

Figure 5. Grazing pressure estimations when considering different livestock system indicators. (A) Area with moderate and high grazing pressure without any of our indicators (E1), when including individual indicators (E2–E4) or when including all indicators (E5) to describe livestock systems in the study region better. (B) Grazing pressure map when including all indicators (E5).

as a case study, we showed how considering indicators of the intensity of different livestock systems drastically improves estimations of grazing pressure. Specifically, creating maps of available fodder and carrying capacity maps showed that pastures and silvopastures have, on average, twice the carrying capacity of woodlands and natural grasslands. Mapping livestock requirements across the rangelands of our study region confirmed the overwhelming dominance of cattle (94% of the livestock requirement), and mapping larger confinement areas revealed, for the first time, the spatial footprint of landless livestock. Most importantly, these indicators of livestock production led to major changes in estimating rangeland overgrazing, reducing the pasture area estimated to be overgrazed threefold and substantially increasing the woodland area estimated to be under high grazing pressure. This highlights the potential of considering the intensity of livestock production to estimate the environmental impact of grazing and, more generally, potentially rangeland degradation better.

The grass growth model estimates of accessible annual forage were more related to field data than those from the satellite MODIS NPP product. Several factors explain this finding. First, MODIS NPP products are based on the calendar year, from December to January (Running *et al* 2004), which mismatches the regional rangeland growing season (from September to March; Blanco *et al* 2016). Using forage models based on temporally more detailed satellite products could help address this temporal misalignment (Baldassini and Paruelo 2020), even in cases with multiple plant species and strata (Robinson *et al* 2019, Jones *et al* 2021). Second, satellite-based forage estimates struggle in complex vegetation systems such as tropical dry woodlands, where trees and shrubs are in various proportions, forming complex vegetation structures and ecotones. Techniques such as pixel unmixing can potentially describe this complexity better (Blanco *et al* 2016, Robinson *et al* 2019, Riquelme *et al* 2022). Without such products, we used tools like a tree-cover multiplier to help proxy translate NPP into annual forage, as Piipponen *et al* (2022) demonstrated. Third, our biophysical model allowed us to account for different grass species (i.e. *Pennisetum, Megathyrsus and Thricloris*; Supplementary Information Text S7), which the satellite-based estimates do not. Combining growth models with satellite products could further improve forage estimations, as shown in studies conducted at both local and global scales (Fetzel *et al* 2017, Nasca *et al* 2020). However, future applications should incorporate a comprehensive validation process to allow the use of the forage maps in decision-making (Wu *et al* 2019).

We found that the disaggregation of livestock type and location was important for identifying areas with a high risk of overgrazing. Despite nearly three million small ruminants (i.e. goats and sheep) in the Chaco, their total requirement accounted for only 6% of the total livestock requirement. Small ruminants are important for woodland smallholders in tropical dry forests (Pratzer *et al* 2024), such as in the Dry Chaco (Cáceres *et al* 2015)and have often been linked to major rangeland degradation (Abril *et al* 2005). However, our analyses suggest their feed requirement is overall small, and cattle raised by smallholders and medium to large cattle ranchers exert most of the grazing pressure on the region's pastures and woodlands (Rueda *et al* 2013). Unfortunately, we lack detailed data on animal weight and breeds that would allow for an even more precise estimation. Our analyses also suggest that differences in cattle grazing systems lead to variations in grazing pressure (figure 5), which may impact rangeland functionality and species richness (Herrero-Jáuregui and Oesterheld 2018). Such variations are not captured by coarse-grained datasets such as the Gridded Livestock of the World (Robinson *et al* 2014). Using fine-grained data such as vaccination records in our case might thus help to estimate the spatial patterns and variation of grazing pressure in tropical dry woodlands and rangelands better (Schulz *et al* 2019). In eleven cattle-producing countries, such as Argentina, Brazil, or Uruguay (or specific zones within them), vaccination against foot-and-mouth disease is mandatory to maintain a disease-free status (WOAH 2024). When georeferenced and available, these vaccination records can potentially increase our understanding of livestock systems in major ways. For instance, they can help map the spatial distribution of livestock systems (Fernández *et al* 2020a) or link livestock dynamics to land-use changes and deforestation (Klingler *et al* 2018). Despite this potential, vaccination data remain heavily underutilized. Here, we demonstrate the value of leveraging vaccination data to assess the broader impacts of livestock production systems.

Similarly, mapping livestock systems characteristics improved grazing pressure estimations in major ways. Most importantly, we pioneered mapping large confinement areas, thereby putting landless cattle on the map (Naylor *et al* 2005, Vale *et al* 2019) and avoiding that they are wrongfully attributed to pastures. Raising cattle in confinement systems is suggested to boost land productivity and lower GHG intensity (Gerber *et al* 2015, Vale *et al* 2019) while potentially lowering land demand (Latawiec *et al* 2014, Gerssen-Gondelach *et al* 2017). However, they are still connected to major environmental impacts in terms of emissions, pollution, and water use and are seen as problematic from an animal welfare perspective (Smit and Heederik 2017, Balmford *et al* 2018). Mapping large confinement areas (i.e. feedlots) across larger geographies has major potential to help better understand the relationship between intensification and the social–ecological impact of cattle production, which would be particularly key for the world's tropical dry woodlands (Latawiec *et al* 2014, Gerssen-Gondelach *et al* 2017, Kreidenweis *et al* 2018).

Supplementary fodder, such as crops, crop residues, or other by-products, are key in livestock production and could be crucial for the much-needed transition towards circular food systems (Sandström *et al* 2022). Feed subsidies are often overlooked when estimating grazing pressure, although external fodder can help explain the differences between rangeland carrying capacity and livestock stocking rates (Fetzel *et al* 2017, Irisarri and Oesterheld 2020, Piipponen *et al* 2022). However, in our case study, the importance of external fodder was small compared to the total grassland forage offered (figure 5), except in certain pasture areas in the Chaco (figure 2), where carrying capacity increased by up to 50% due to silage. The type of forage stored in silage bags varies (e.g. entire plants, grains, crop residues), influencing factors such as daily weight gains and GHG emissions for beef. While our approach cannot capture such variability, this data would be useful to refine silage fodder estimations at regional scales further. Likewise, mapping silage infrastructures would be useful, although we note that these are not widespread in Chaco presently (Fernandez *et al* 2023).

We find a threefold increase in the woodland area potentially affected by overgrazing, with nearly 10% of the total livestock, at least 400 000 AUEs, relying on woodland for fodder. This livestock is predominantly associated with woodland smallholders and is widespread in the region (Levers *et al* 2021). Although we used detailed vaccination data to make this estimation, it is still likely conservative, as it does not account for the grazing pressure on woodlands from cattle in industrialized ranches during the dry season, which can be substantial (Fernández *et al* 2020a). Thus, while our study shows that considering the contribution of woodlands to livestock production is key, it also corroborates that data on the livestock footprint in woodlands is uncertain (Erb *et al* 2018). Local analysis has shown that cattle impact Chacoan woodland structure in major ways, even within some protected areas (Tálamo *et al* 2015, Trigo *et al* 2020). However, the extent of this impact remains largely unquantified. Strictly protected areas in the Argentine Dry Chaco cover a small area overall. Yet, sustainable use areas that mandate the maintenance of (some) woodland and tree cover while allowing grazing within these areas are very widespread, with many likely being overgrazed/browsed (Fernández *et al* 2020b). Integrating livestock data, such as the vaccination data we used, with satellite time series (Marzo *et al* 2021) could provide a more comprehensive understanding of livestock grazing impact on woodlands (Nanni *et al* 2024, Peri *et al* 2024). Similarly, better data on woodland smallholders could help to consider these actors and their relation to woodlands in sustainability planning (Del Giorgio *et al* 2021, Levers *et al* 2021, Pratzer *et al* 2024). Finally, overlaying woodland grazing pressure with the locations of protected areas and forest zoning restrictions would be crucial for identifying regions where livestock exclusion measures could help promote high-value forest recovery.

Understanding the broader impacts of livestock production requires better characterization of livestock systems, including the spatial footprint and intensity of grazing. Here, for the Chaco, a global hotspot of environmental degradation and livestock production, we demonstrate how mapping different livestock system indicators considerably modifies estimations of current grazing pressure. Our findings highlight the importance of accounting for livestock production intensity to avoid biases in grazing pressure estimations. For instance, the recent finding of about two-thirds of all grasslands globally being overgrazed (Piipponen *et al* 2022) might have to be revised once landless livestock, supplementary feeding and the heterogeneity of livestock distributions are considered—which they are currently not in global analysis. Conversely, capturing livestock in smallholder systems associated with woodland use would provide a more realistic picture of grazing pressure on tropical dry woodlands, likely underestimated globally. Here, we showcase how relatively simple indicators can achieve both goals. However, we caution that our study, like other broad-scale assessments, could not employ comprehensive validation methods due to a lack of sufficient ground data at resolutions comparable to the remote sensing data. Global initiatives such as the Global Pasture Watch (Parente *et al* 2024) are beginning to fill this gap by collecting field data and making accessible field data such as the from eddy covariance measurement towers in rangelands (Pastorello *et al* 2020). Scaling up such analyses will enhance grazing impact assessments and turn this information into stakeholders' decision-making, from farmers to policymakers. This step is crucial for fostering sustainable food systems and achieving global conservation and restoration goals (Dudley *et al* 2020, WCPA 2023).

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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