Global Environmental Change 98 (2026) 103156

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Mapping the geography of livestock systems in South America's dry diagonal

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ARTICLE INFO

Keywords:
Livestock distribution
Livestock systems
Pastoralism
Smallholder farming
Active learning
Tropical dry woodlands and savannas
Dry Diagonal
South America

ABSTRACT

Livestock production is a major driver of global environmental change, contributing to greenhouse gas emissions and biodiversity loss, primarily through the conversion of tropical forests to pasture. Yet, livestock occur in diverse production systems, each with unique impacts depending on the social-ecological context in which they are embedded. While understanding the spatial distribution of different livestock systems is crucial for sustainability planning, this geography remains unmapped for many regions, leaving policymakers and researchers with a critical data gap. Here, we use largely untapped spatial datasets on livestock, including vaccination, registers, and transaction data, and apply active learning and decision trees to classify and map major livestock systems at scale. We demonstrate our approach for the 4.2 million km^2 Dry Diagonal covering the Caatinga, Cerrado, Chiquitano, and Chaco ecoregions across parts of Argentina, Bolivia, and Brazil, which are global hotspots for livestock production and deforestation. Three main findings emerge. First, we identified eleven distinct livestock systems across the South American Dry Diagonal, encompassing pastoralists, small-scale, and capitalized systems. Second, analysing the spatial determinants of these livestock systems revealed small-scale and pastoralist systems' association with arid, less productive areas, highlighting their adaptive capacity as well as marginalization. Third, mapping livestock systems revealed a clear spatial segregation of production models: large-scale, capitalized systems dominate the Cerrado and Humid Chaco, while small-scale and pastoralist systems are concentrated in the more arid Dry Chaco and Caatinga. This reflects historical land-use patterns, institutional factors, and local social-ecological conditions. Together, the diverse patterns of livestock production we uncover highlight the need for targeted, context-sensitive land and livestock management strategies in tropical dry woodlands.

1. Introduction

Livestock are 'creatures of the Anthropocene' (Ficek, 2019). Of the Earth's arable land, nearly 80% is used, in some way, for livestock production (Ritchie and Roser, 2019), and human-livestock biomass combined dwarfs that of wild mammals (Greenspoon et al., 2023). Whilst providing animal protein, subproducts, and profit, the livestock sector is also responsible for huge environmental impacts, accounting for 12% of all anthropogenic greenhouse gas emissions (FAO, 2023), widespread ecosystem transformation (Garrett et al., 2018; Godde et al.,

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https://doi.org/10.1016/j.gloenvcha.2026.103156
Received 17 December 2024; Received in revised form 20 February 2026; Accepted 6 April 2026

2018), and, consequently, major losses of biodiversity and ecosystem services (Gibbs et al., 2010; Steinfeld et al., 2006). Understanding and mitigating the adverse social-ecological impacts of livestock production is a central sustainability challenge.

This is particularly relevant for South America, where livestock production has grown rapidly in recent years. South America now produces 22% of the world's beef, 8% of its milk, 6% of its pork, and 18% of its poultry, with Brazil being the largest contributor in all categories, followed by Argentina (Williams and Anderson, 2019). Whilst illustrating the livestock industry's importance to the regional economy, the flipside reveals its ties to the widespread clearing of tropical and subtropical forests and savannas (Baumann et al., 2017b; le Polain de Waroux et al., 2019; da Silva et al., 2020), often producing unsavory social and environmental outcomes (Cáceres et al., 2020; Garrett and Rausch, 2016; Gerber et al., 2015). Outcomes and the depth of their impacts, however, vary in major ways depending on the modes and intensities of livestock production, the livestock species reared, and the local social-ecological context in which livestock are embedded (e.g., the natural vegetation formations or the local cultural practices). Existing spatial data on livestock distribution are often too coarse or simply inadequate for sustainability assessments, as they typically map livestock densities but fail to distinguish between different production systems (Gilbert et al., 2018; Robinson et al., 2014; Wint and Robinson, 2007).

Identifying and mapping different types of livestock systems—such as pastoralist vs. capitalized ranching (e.g., Pratzer et al., 2024), or forest-integrated vs. pasture vs. confinement-based ranching—is a promising way to capture their heterogeneous social-ecological effects (Gerber et al., 2015) and inform targeted policy responses. For instance, although pastoralist systems support millions of livelihoods globally (Scoones, 2023), where they occur is often unclear, hindering policymaking and sustainability planning (Dong et al., 2011). Similarly, knowing the distribution of capitalized pasture-based systems, expansive by nature and often drivers of deforestation (Baumann et al., 2017b), can guide policies to mitigate further habitat conversion. Likewise, mapping the location of confinement-based systems (e.g., Kuemmerle et al., 2025) can pinpoint hotspots of environmental and health risks, such as atmospheric and freshwater pollution (Naylor et al., 2005) and zoonotic disease outbreaks (Hayek, 2022; Jones et al., 2008). Finally, mapping the spatial footprint of capitalized livestock systems, often associated with fencing formerly open rangelands, can reveal where conflict with local communities might occur (del Giorgio et al., 2021; Scoones, 2023; Totino et al., 2024). Better mapping these systems is therefore important for devising policy frameworks to reduce negative social-ecological impacts and promote equitable outcomes (Fernández et al., 2020; Kuemmerle et al., 2013; Lambin et al., 2018).

To date, no maps adequately represent the diversity of livestock systems in South America. Available global livestock maps (Gilbert et al., 2018; Robinson et al., 2014; Wint and Robinson, 2007) rely on modeled estimates derived from aggregated national or subnational statistics, which often obscure local variability and fail to reflect the complexity of mixed, smallholder, pastoralist, and capitalized systems (Fernández et al., 2020). These maps typically prioritize livestock density and broad distribution patterns, neglecting the social-ecological contexts that differentiate systems. Similarly, satellite-based land cover and vegetation indices (Baumann et al., 2017b; Kruska et al., 2003; Robinson et al., 2014), while useful for identifying land-use changes, cannot discern between these types of livestock systems. Thus, they are unable to link specific practices to social-ecological impacts. As a result, there is a lack of detailed maps that could support a deeper understanding of livestock system geography and guide sustainability planning.

New data sources and methodologies, however, present promising opportunities to close this gap. For example, livestock vaccination records have been used to map cattle production systems in the Argentine Chaco (Fernández et al., 2020) and livestock transaction data have shown how cattle farms, slaughterhouses, and deforestation are linked in the Cerrado and Amazon (Brandão Jr. et al., 2023; Levy et al., 2023; Skidmore et al., 2021). Despite the availability of such data at scale, no study has mapped livestock system distributions for larger areas of tropical and subtropical dry forests, shrublands, and savannas (hereafter: tropical dry woodlands). Moreover, research has primarily focused on cattle systems, providing limited or no information on other livestock types, such as goats or sheep, which are also prevalent in these regions.

The Dry Diagonal—a belt of tropical dry woodlands in South America including the Caatinga, Cerrado, Chaco, and Chiquitano ecoregions, extending from Brazil to Paraguay, Bolivia, and into Argentina—is a particularly important, yet understudied region. Livestock production is increasingly expanding into these ecoregions, which are under high and growing pressure but receive much less attention and protection than humid ecoregions, despite the high biodiversity they harbour that includes many endemic species, especially among plants, and iconic megafauna such as the jaguar *(Panthera onca)*, Chacoan peccary (*Catagonus wagneri*) (Camino et al., 2022) and Maned wolf (*Chrysocyon brachyurus*) (Silveira et al., 2009). The Dry Diagonal is also culturally diverse, including pastoralist and smallholder farmers who have inhabited these regions for generations, and Indigenous Peoples who have been present for millennia (Camino et al., 2023; Garnett et al., 2018; Lima et al., 2022).

In addition, a range of livestock systems have flourished there, each reflecting the distinct socioeconomic, cultural, historical, and environmental conditions from where they originate. Each system produces various social and environmental benefits and risks (Herrero et al., 2013). Conflicts between these livestock systems also often arise, particularly where agribusiness displaces traditional livestock producers, raising important questions about environmental justice (de la Vega-Leinert, 2020; del Giorgio et al., 2022; Vigroux et al., 2023). Understanding which types of livestock systems expand where, and how they interact with local social-ecological contexts, is therefore important. While existing studies point to factors such as aridity, vegetation types, and land accessibility as key influences on livestock ranching distributions in South America (Fernández et al., 2020; Guevara et al., 2017; Pacheco, 2005), there has been little effort to explore this regionally, nor to assess more deeply the differences between types of ranching. Here, we create the first set of transboundary, system-specific maps to address these gaps, thereby providing a foundational dataset for scientific inquiry as well as for policymakers and organizations seeking to support sustainability planning and contextualized, targeted interventions.

The primary objective of this study was therefore to identify and map the key livestock systems across the South American Dry Diagonal. To achieve this, we leveraged underused, broadscale data on livestock—specifically livestock vaccination, register, and transaction data—and employed a semi-supervised machine learning approach, combining active learning with random forests, to identify and map distinct livestock systems. We then utilized Boosted Regression Trees to explore their relationships with socio-ecological determinants. Specifically, we assessed the following research questions:

What are the main livestock systems in the South American Dry Diagonal?
What are the spatial determinants of different livestock systems?
How are these systems distributed in the Dry Diagonal and how do these distributions vary across ecoregions and countries?

2. Data and methods

2.1. Study area

We focus on four ecoregions in South America: the Caatinga, Cerrado, Chaco, and Chiquitano, which together cover 4.2 million km^2 (Olson et al., 2001) (Fig. 1). We refer to these regions as tropical dry

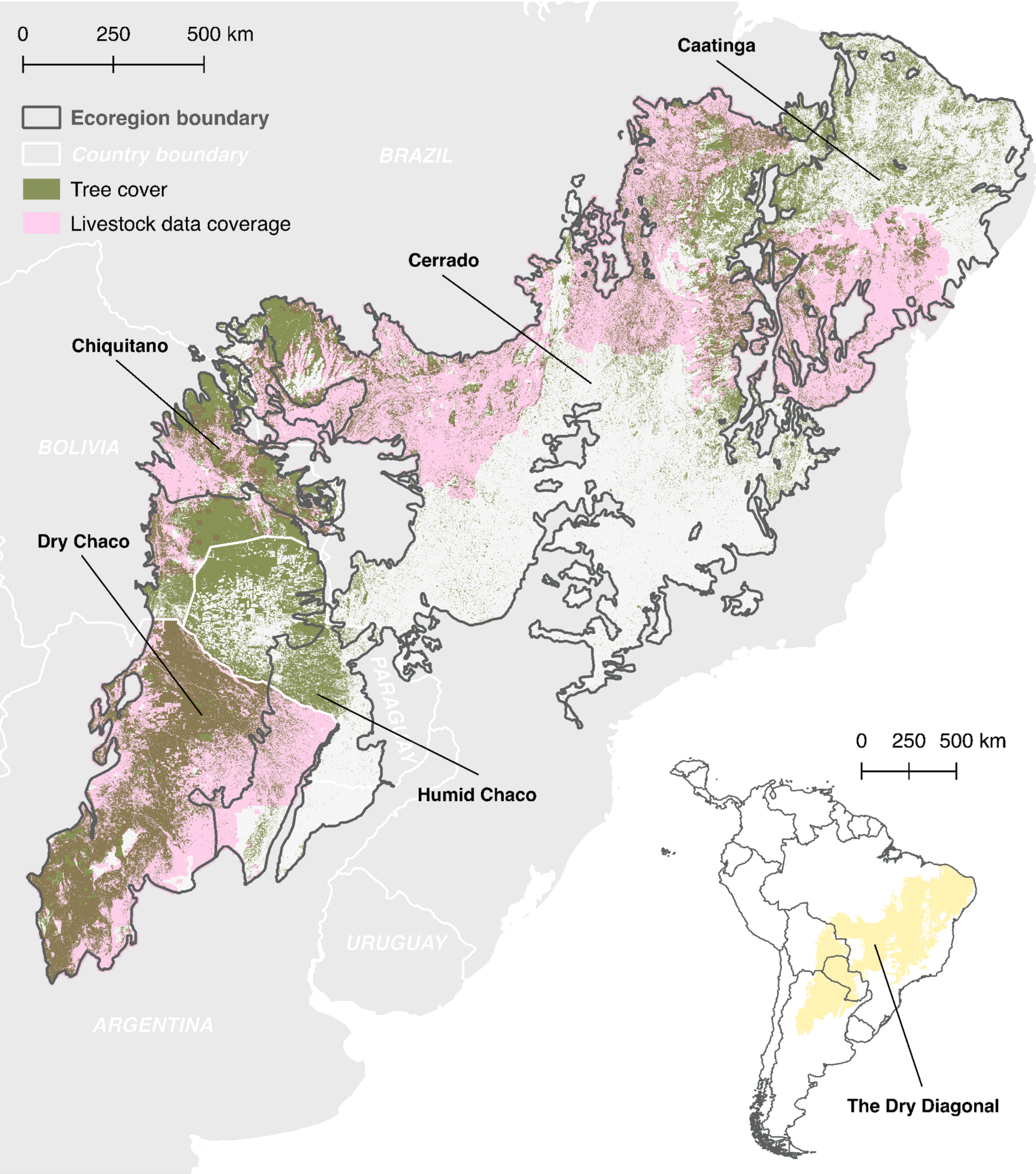

Fig. 1. The study region, South America's Dry Diagonal, with ecoregion boundaries taken from Olson et al. (2001), showing the livestock data coverage (pink shading) representing the spatial extent from which the input livestock datasets (vaccination, register, and transaction data) were sourced (see Table 1 for more details), overlayed with tree cover (green shading) from the MapBiomas project. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

woodlands, encompassing all forests, shrublands, and savannas that fall within their ecoregion boundaries (Buchadas et al., 2022). The Chaco and Caatinga are mostly flat, averaging around 400–500 m above sea level, whereas the Cerrado and Chiquitano are more undulating, ranging between 300–1600 m and 200–900 m above sea level, respectively. Mean monthly temperatures range between 18°C and 28°C across these ecoregions, characterized by a semi-arid climate with a diverse landscape of xerophytic forests, open woodlands, scrubs, and grasslands (Verga and López Lauenstein, 2021). The region’s soils are heterogeneous, ranging from the highly weathered, nutrient-poor *Oxisols* (*Latosols*) that dominate the Cerrado (Batlle-Bayer et al., 2010), to the diverse, often sandy soils of the Caatinga and Chiquitano (Mostacedo et al., 2022; Pontes et al., 2022), and the nutrient-rich *Mollisols* and *Alfisols* of the Chaco (Rubio et al., 2019). The region’s woodlands and extensive wetland areas serve as important carbon stores (Baumann et al., 2017a; Maillard et al., 2024). Additionally, these woodlands are rich in cultural heritage, and inhabited by many Indigenous Peoples, including groups who choose voluntary isolation (Bessire, 2014; Camino et al., 2023; de la Vega-Leinert, 2020).

The Dry Diagonal is a global hotspot for livestock production, characterized by a diverse mosaic of systems ranging from small-scale farms (e.g., mixed crop-livestock operations on small plots of land), pastoralism (e.g., rearing sheep and goats extensively), to large-scale, capitalized ranching (Camino, 2018; Fernández et al., 2020; Jamelli et al., 2021; Lanari et al., 2020). Historically, extensive cattle ranching, such as cattle breeding and rearing (where calves are weaned and young cattle are raised for sale), has been most widespread. More recently, capital investment has accelerated the rise of industrial systems, including intensive fattening (e.g., preparing cattle, typically steers, for slaughter) and whole-cycle operations (i.e., combining breeding, rearing, and fattening) (Adelman, 1994; Fernández et al., 2020; Pratzer et al., 2025).

2.2. Livestock data

We used three large, broad-scale datasets concerning livestock, each containing information on livestock herd composition and size at specific points in time and location (Table 1). Details on the preparation and standardization of these datasets are provided in Supplementary Information S1. For all systems, these points represent the farm or registered property where the herd is administered, rather than the animals' real-time location. The first dataset, covering the entire Argentinian Chaco, was derived from the foot-and-mouth disease vaccination program by *Servicio Nacional de Sanidad y Calidad Agroalimentaria* (SENASA), providing counts of livestock head per group and farm. As vaccination is compulsory to maintain Argentina's official health status, this dataset provides a high degree of coverage and confidence for the formal livestock sector. We used the 2019 data, representing the most recent livestock systems. For the second dataset, from the Bolivian Chaco and Chiquitano, we used the official national livestock register (DSA, 2011). The third dataset, acquired and processed by the *University of Wisconsin-Madison* and covering the Brazilian Cerrado and Caatinga, comprised a census of livestock movements between farms and to slaughterhouses from the Guide to Animal Transport (GTA), namely in the states of Bahia, Goiás, Maranhão, Mato Grosso, and Tocantins. The coverage of this dataset is limited to producers who sell to official markets. We focused on farms that had at least one transaction falling between 2019–2024, differing across states due to data collection efforts (Table 1 and S1), and analysed transactions over the four years prior to the last transaction.

2.3. Analytical framework

2.3.1. Classifying livestock systems

Our first step involved identifying livestock systems in the Dry Diagonal to label and map our data. We drew on a typology process documented in detail in Pratzer et al. (2024), which incorporated global and regional definitions of land systems, cross-checked by regional experts of tropical dry woodlands. Globally, ranching systems were characterized into several categories; the relevant ones here were *Capitalized ranching, Pastoralism* and *Smallholder farming.* We used the data from the three sources (Table 1) to classify the scale of livestock production. For the Argentinian and Bolivian data, the *number of registered livestock* provided a direct measure of herd size. For the Brazilian data, where only sale records were available, we used the magnitude of transactions as a proxy for the scale of operation, guided by the extensive expert knowledge of the coauthors on these production systems (the author team has been working for over 13 years on livestock and land use in the region). This allowed us to classify systems into *Capitalized ranching* (medium- and large-scale operations)*, Pastoralism,* and *Smallholder farming systems* (mostly small-scale operations) (Supplementary Information S2).

Next, we further refined definitions of livestock systems relevant to the Dry Diagonal from the regional typology (Pratzer et al., 2024). These were systems distinguishable in our data by herd composition and sale patterns based on different livestock groups (e.g., cows, calves, heifers, bulls, steers, sheep, and goats) (Supplementary Information S1). We combined these classifications and defined *Capitalized ranching* systems as *Medium-scale cattle breeding-rearing, Large-scale cattle breeding-rearing, Cattle fattening, Cattle whole-cycle* (a mix of *Cattle breeding-rearing* and *Cattle fattening*), and *Cattle dairy.* We categorized *Pastoralism* systems typically found in woodlands in our study region as *Small-scale goat rearing, Large-scale goat rearing, Small-scale sheep rearing, and Large-scale sheep rearing.* There were two *Smallholder farming* systems: *Small-scale cattle dairy*; and *Small-scale cattle breeding-rearing.* While the latter two also occur in pastoral contexts, we classify them here under *Smallholder farming* to specifically represent the common, more sedentary crop-livestock systems where cattle are integrated into a fixed farm property, which occurs throughout our study region (de la Vega-Leinert, 2017; Lima et al., 2022; Meira et al., 2021; Vigroux et al., 2023).

To classify these systems, we implemented two active learning models, each using an ensemble of random forests: one focused on the vaccination and register data (count-based model) and one on livestock sales (transaction-based model), as detailed in Supplementary Information S2. We manually created training labels for each model—leveraging the author team's expertise—based on herd composition, livestock fluxes, and their respective magnitudes, and validated these against a stratified subset of data checked using high-resolution satellite

Table 1
Description of the livestock datasets.

Dataset	Country / regions	Years	Data description	Metric	Source / Reference	Number of unique points
Livestock vaccination data	Argentinian Dry and Humid Chaco	2010–2019	A geo-referenced database with points located within farm boundaries, gathered by the foot-and-mouth disease vaccination program of the *Servicio Nacional de Sanidad y Calidad Agroalimentaria* (SENASA).	Count of livestock head per livestock group (see Supplementary Information S1.1 for details about livestock groups) and per farm, considering only data from 2019 to reflect the most recently registered farms.	*National Registry of Agriculture Producers Health* (*Registro Nacional de Sanidad de Productores Pecuarios* in Spanish; hereafter RENSPA) (Fernández et al., 2020)	44,089
Livestock register data	Bolivian Dry Chaco and Chiquitano	2009–2012	Livestock register (*Catastro Ganadero*) georeferenced as points within individual farm boundaries.	Count of livestock head per livestock group (S1.1) and per farm, with one data point recorded for each farm between 2009 and 2012.	(DSA, 2011)	17,567
Livestock transaction data	Brazilian Cerrado and Caatinga	2010–2024	*Animal Transport Permits* (*Guia de Transporte Animal* in Portuguese), public records of livestock movements between farms or to slaughterhouses, were downloaded as individual transactions and linked to property boundaries according to the methodology described in Skidmore et al. (2021). The centroid of each property boundary was used to ensure consistency with other datasets.	*Sold transactions* (outgoing livestock) per livestock group (Table S1) per farm, including only farms with at least one transaction between 2019 and 2024 to ensure representation of recent activity. To track livestock flow, transaction data from the past four years were averaged (e.g., accounting for all transactions since 2016 for farms with activity in 2019).	("ADAPEC," 2024; "ADEPARA," 2019; "AGED," 2024; "Agrodefensa," 2024; "Consulta pública de GTA," 2019; "IDARON," 2019; "INDEA," 2019)	52,015

imagery (Fig. 2). The validation datasets (a fixed sample of 500 points per model; Table S2) were excluded from the training process to ensure unbiased, fully independent evaluation. Our training set size was dynamic, growing iteratively until model accuracy plateaued (Fig. S1). Thus, our models iteratively improved as uncertain samples were reviewed, re-labelled, and incorporated into subsequent training rounds, a process designed to actively minimize misclassifications by focusing expert review on the most ambiguous cases. The final, optimized models, selected based on overall accuracy and per-system precision and recall, were applied to all respective livestock vaccination, register, and transaction data across the study area, assigning each data point to one of the defined systems.

2.3.2. Modelling the spatial determinants of livestock systems

Based on the initial identification of livestock systems, we then, in a separate step, employed Boosted Regression Trees to predict the spatial distribution of these systems. Boosted Regression Trees was selected for this step as it is a top-performing algorithm for predicting the probability of occurrence of features (analogous to Species Distribution Models, in our case the features were livestock systems), capable of fitting complex non-linear responses to environmental variables to maximize predictive accuracy (Elith et al., 2008; Elith* et al., 2006). To identify the spatial determinants per livestock system, we collected variables relevant to livestock ranching, including environmental and agricultural suitability factors (e.g., soil organic carbon content, soil water content, aridity, and distance to water), and natural vegetation to account for available forage (e.g., woodlands and grasslands cover). Variables such as cropland and pasture cover were excluded to avoid causal circularity, treating these as potential outcomes rather than drivers of livestock ranching. Other factors considered were related to accessibility (e.g., travel time to towns or cities with a minimum population of 20,000, and distance to slaughterhouses), and terrain suitability (e.g., ruggedness). We calculated the predictors for the period relevant to each livestock dataset (Table 1) and aggregated them by calculating the mean within a 2.5 km radius buffer around each livestock data point. This buffer size was chosen to account for the largest farms in our area (Knox, 2019). Detailed explanations of the variables' relevance to livestock ranching, data sources, and calculation methods can be found in Table S5 in the Supporting Information.

To model the spatial determinants of each system, we first aligned the predictor variables with the specific time period of each livestock dataset. Specifically, we used the data from 2009 to 2012 for the Bolivian livestock registers, 2019 for the Argentinian vaccination data, and a four-year moving window corresponding to the livestock transaction dates for the Brazilian data. These temporally aligned predictors were aggregated within a 2.5 km radius buffer around each livestock data point. We then fitted separate Boosted Regression Tree models for the livestock systems and their respective spatial determinants data in the 2.5 km radius buffers. As the response variable, buffers representing a particular system were assigned a value of 1, and 0 otherwise. Because we modelled each system independently in this binary fashion, there was no issue of double-counting in areas where buffers overlapped. Instead, an overlapping area was treated as a “presence” point in the training data for each of the respective models. Our approach thus allows for the coexistence of different systems, which reflects the real-world situation of livestock systems in our study region (le Polain de Waroux, 2024; Pratzer et al., 2025; Vigroux et al., 2023). To account for spatial autocorrelation, which can inflate model performance metrics, we calculated the autocorrelation range for our variables (Fig. S7). We then used this range to define the size of our spatial blocks for a robust spatial cross-validation, ensuring that training and testing sets were independent. This approach is critical for minimizing the over-optimistic error estimates common in random cross-validation and provides a reliable assessment of how well the model predicts to new, spatially distinct locations (Roberts et al., 2017). We chose the final models and parameters based on the optimized F1-score (balance between precision and recall).

Finally, to gain deeper insights into the effects of individual spatial determinants on livestock system probability, we analysed, first, variable importance, which represents the relative contribution of each variable to the predictive accuracy of the final model, indicating how strongly a given social-ecological determinant influences the predicted distribution of a livestock system. Second, we assessed the trend derived from the partial dependence plots of the Boosted Regression Trees,

Fig. 2. Examples of livestock systems in the South American Dry Diagonal. Photos were taken in the Dry Chaco in Argentina in 2023 (Photos J. Burton). Satellite images are from Bing Satellite and were used to help validate the identified livestock systems.

which summarizes the average direction and strength of the relationship between a given social-ecological determinant and the predicted probability of a livestock system's occurrence. This helped us understand whether the probability of a given livestock system increased or decreased in response to the spatial determinants, thereby identifying the main factors influencing livestock system distribution.

2.3.3. *Mapping the distribution of livestock systems*

The final stage involved mapping the distribution of each livestock system. Using the Boosted Regression Trees trained on the temporally-specific data (i.e., the spatial determinants), we then predicted the probability of occurrence for each livestock system onto 2.5 km^2 grid cells throughout the entire Dry Diagonal using a consistent and recent set of spatial determinants for the period 2020–2023. This two-step predictive process allows the model to interpolate the learnt relationships into data-sparse areas, ensuring our final output is an up-to-date map of current livestock system distributions. To ensure predictions remained ecologically and contextually appropriate, we applied three post-prediction measures: (1) multivariate environmental similarity surfaces analysis (Mesgaran et al., 2014) to avoid overextrapolation into areas outside our data coverage (Fig. 1 and S9); (2) a land-cover based masking process; and (3) calibration of predictions with official livestock density data (Gilbert et al., 2018; Robinson et al., 2014). Specifically, the masking process excluded areas with 100% cropland (as identified by MapBiomas) and areas with a mean travel time from urban settlements of less than three minutes. Protected areas were left unmasked, as livestock are known to occur within them (Candino et al., 2024; Marás et al., 2022; West et al., 2022). Lastly, we calibrated the predictions outside of the livestock data coverage (Fig. 1) using official livestock density data from the most recent global livestock censuses, categorized by livestock type (cattle, sheep, or goats), as compiled by Gilbert et al. (2018) and Robinson et al. (2014). To assess the potential for system overlap, we calculated a system dominance metric for each pixel as the difference between the highest and second-highest system probabilities. High values indicate a single dominant system, while low values suggest high niche overlap where the probabilities of competing systems are similar. Our final categorical map showed the livestock system with the highest predicted probability.

3. Results

3.1. *Characterizing the livestock systems of the Dry Diagonal*

Our analyses identified a total of eleven livestock systems (Fig. 3). Overall, the livestock composition of each system, showing the proportions of different livestock types and mean head, was classified consistently between the count-based and transaction-based models (Fig. 3; a comparison across ecoregions is found in Fig. S4). This

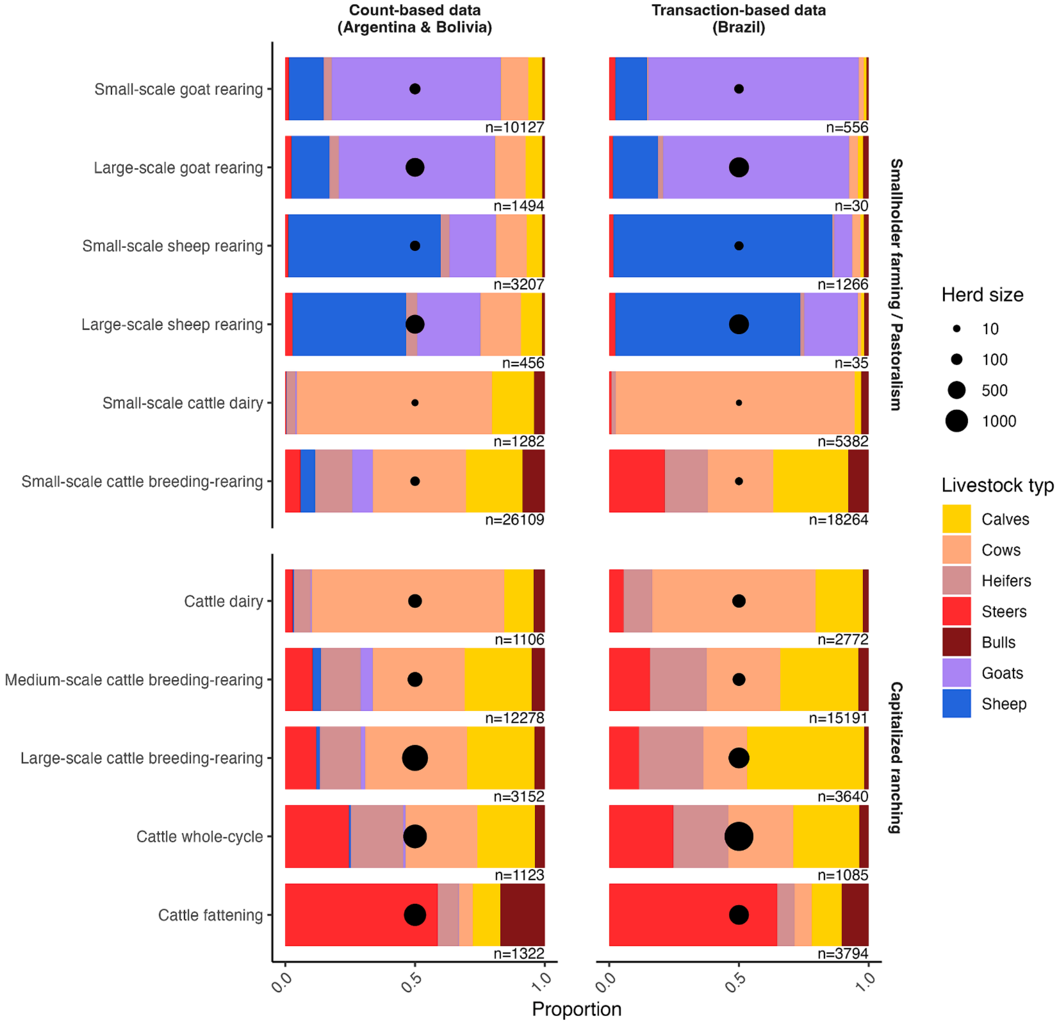

Fig. 3. Average herd composition and herd size (i.e., *mean head* of livestock) for the eleven livestock systems identified in both the count-based and transaction-based data, with bars representing livestock proportions and black dots indicating herd size. The number of observations (n) for each system is listed below the corresponding bar.

demonstrates that, despite using fundamentally different metrics (a stock vs. a flow), our two models resulted in a comparable internal definition for each livestock system.

Two of our classified systems were *Smallholder farming* systems. The most widespread system across all regions, *Small-scale cattle breeding-rearing*, had a mixed composition of cattle with a mean of about 34 livestock head (Table S4). *Small-scale cattle dairy*, consisted primarily of adult female cows, occasionally accompanied by calves, with a mean of 6 head, and was found primarily in the transaction-based data (Fig. 3), particularly the Caatinga (Fig. S4). *Pastoralism* systems included *Small-scale goat rearing* (86 head) and *Small-scale sheep rearing* (60 head) systems, as well as *Large-scale goat rearing* (591 head) and *Large-scale sheep rearing* (625 head) and were prominent in the count-based data but also partially in the transaction-based data (Fig. 3), mainly found in the Dry and Humid Chaco, as well as the Caatinga (Fig. S4). Seven livestock systems can best be described as *Capitalized* (i.e., market-oriented, commodity-based systems; Pratzer et al., 2024). The second most widespread system overall, *Medium-scale cattle breeding and rearing*, fell into this group and included cows, calves, some bulls, and occasionally heifers and steers, with a mean of 217 head, while *Large-scale cattle breeding-rearing* contained an average of 1068 head. *Cattle fattening* predominantly comprised steers and was most common in the transaction-based data and the Cerrado, with an average of 827 head. The *Cattle whole-cycle* system, which integrates breeding, rearing, and fattening, had a mean of 1530 head. The *Cattle dairy* system (216 heads) was identified mainly in the Dry Chaco and Cerrado (Fig. S4).

The overall accuracy of the active-learning models reached > 90% in both cases (Fig. S1), and a detailed per-class breakdown of their performance is provided in the Supporting Information (Fig. S2, S3, and Table S3). Most systems were classified with very high accuracy, with several classes exceeding 90% in both precision and recall. The most common misclassifications occurred between systems of the same type but different operational scales (e.g., the most common false positive for *Small-scale cattle breeding-rearing* in both models was *Medium-scale cattle breeding-rearing*, Table S3). Notably, with the exception of *Cattle whole-cycle*, most livestock system classes were robustly classified in at least one of the two, independent active learning models we fitted (i.e., one based on the livestock count data for Argentina and Bolivia and one based on the transaction data for Brazil dataset). The primary misclassification for *Cattle whole-cycle* was as *Large-scale cattle breeding-rearing*, likely due to similarities in herd size and composition (Fig. 3). Given the good performance of these models, we proceeded with them for the subsequent mapping steps.

Classifying the observational data (i.e., points with information on livestock) into the eleven livestock systems we identified revealed heterogeneous geographic patterns of these systems across the Caatinga, Cerrado, Chiquitano, and Dry and Humid Chaco regions (Fig. S5). To assess potential spatial autocorrelation in the classification errors, we mapped the locations of both correctly and incorrectly identified, independent validation points (Fig. S6). Misclassified points appear to be randomly distributed throughout the study area, suggesting that model performance was not systematically biased towards any particular geographic region.

3.2. Spatial determinants of livestock distribution

Modelling the occurrence of a specific system at the locations where livestock data was available provided insights into the spatial

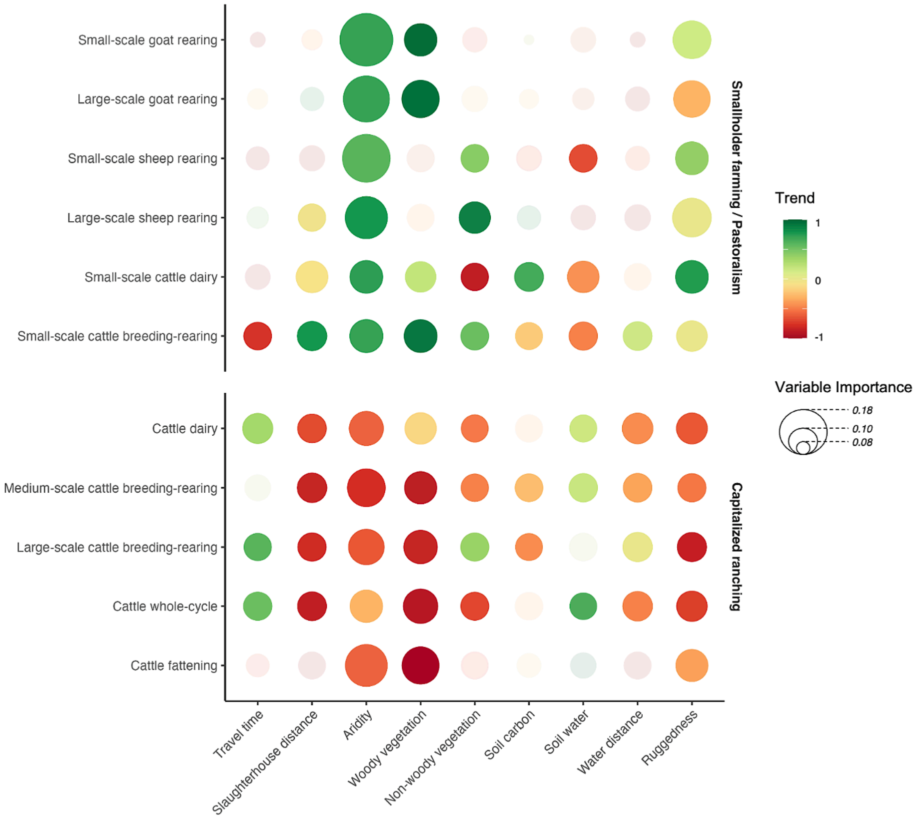

Fig. 4. Trend and variable importance of spatial determinants for different livestock systems. The circle size represents variable importance (faded circles have variable importance < 0.1), where a larger circle represents a higher variable importance, signifying that the variable is a more critical determinant of that system's occurrence. The color indicates the strength and direction of the trend. Trends taken from full partial dependence plots are found in Fig. S8. A value close to + 1 (deep green) indicates a strong positive association (i.e., a higher probability of the system as the determinant value increases), a value near −1 (deep red) indicates a strong negative association, and a value near 0 (yellow/white) indicates a weak or non-linear relationship. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

determinants of each system. Our spatial cross-validation showed that all Boosted Regression Tree models linking individual systems with their spatial determinants fitted the data well (Table S6), with the majority of models achieving over 90% f1-score (*Small-scale cattle breeding-rearing* and *Cattle breeding-rearing* achieved f1-scores of 71% and 76%, respectively). The partial dependence plots and trends (Fig. 4 and Fig. S8) revealed clear distinctions between the pastoralist systems (i.e., rearing small ruminants like sheep and goats) and cattle-based systems (i.e., all other systems), as well as between small-scale and medium-to-large capitalized systems. For *Smallholder farming* and *Pastoralism* systems, the probability of occurrence increased in more arid conditions (Fig. 4). Moreover, natural woody vegetation was strongly and positively associated with *Small-scale cattle breeding-rearing*, *Small-scale goat rearing* and *Large-scale goat farming* in our analyses. *Large-scale breeding-rearing* was the only *Capitalized ranching* system positively associated with natural non-woody vegetation. Generally, the largest *Capitalized ranching* systems (e.g., *Large-scale breeding-rearing*, *Cattle fattening*, and *Cattle whole-cycle* operations) were negatively associated with aridity and were positively associated with soil water content. In contrast, all *Smallholder farming* and *Pastoralism* systems were negatively associated with soil water content. Soil organic carbon content and distance to water were less influential (with variable importance generally < 0.1), although *Cattle dairy*, *Cattle breeding-rearing*, and *Cattle whole-cycle* systems were slightly negatively associated with distance to water. Travel time to urban settlements was negatively associated with all small-scale systems, whereas most *Capitalized ranching* systems showed a positive association. Slaughterhouse distance demonstrated a consistently negative relationship with *Capitalized ranching* systems. Terrain ruggedness also emerged as a key factor (variable importance ≥0.1 for all systems), with *Small-scale cattle dairy* systems exhibiting a pronounced positive association.

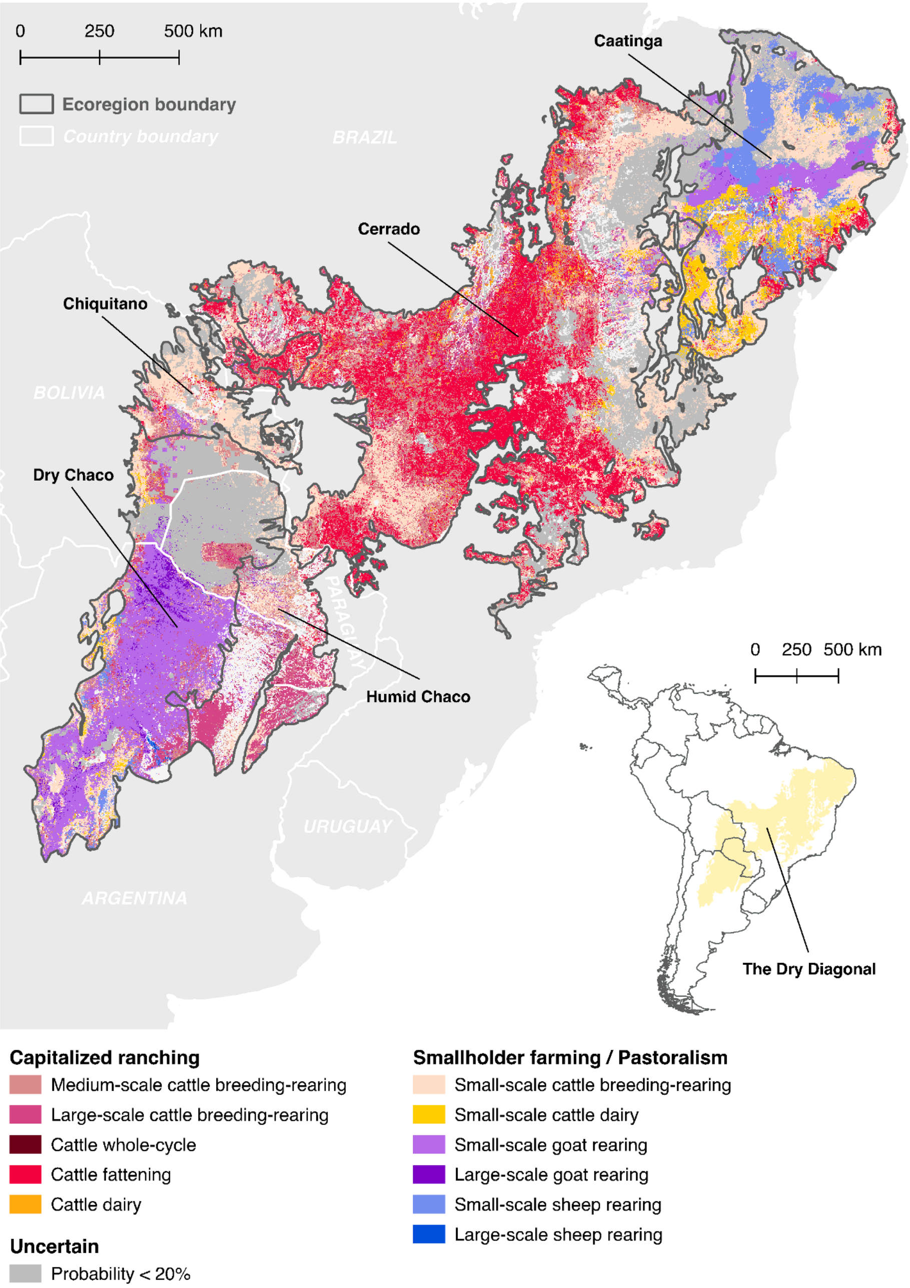

Fig. 5. Categorical map of livestock system distribution in South American tropical dry woodlands, based on the maximum probability of livestock systems in 2.5 km^2 grids. The colors scale represents the different livestock systems identified in this study.

3.3. *The geography of livestock production*

Our final maps (Fig. 5; see Figs. S10 and S11 for the individual and unmasked probability maps, respectively) revealed notable regional variations and transitions between *Smallholder farming* and *Pastoralism* systems with *Capitalized ranching* systems (Fig. 5, Fig. 6a and 6b). Generally, *Smallholder farming* and *Pastoralism* systems were widespread across the Caatinga, Chiquitano, and Dry Chaco, with a notable presence along the eastern border of the Cerrado (Fig. 6a). In contrast, *Capitalized ranching* systems were concentrated in the Cerrado and Humid Chaco, with distinct pockets in the Dry Chaco, Chiquitano, and coastal regions of the Caatinga (Fig. 6b). Histograms of maximum prediction probability reveal that the Chiquitano, Dry Chaco, and Caatinga ecoregions were characterized by bimodal distributions (Fig. S12). A prominent first peak occurred in the low probability range (0.15–0.25), aligning with spatial patterns in our data coverage (Fig. 1, Fig. 6c). Crucially, these ecoregions also exhibit a second, broader peak at moderate probabilities (around 0.40–0.55). We calculated a system dominance metric for each grid cell, defined as the difference between the highest and second-highest system probabilities. This metric revealed a landscape characterized by low dominance and widespread overlap between competing livestock systems (Fig. 6d, Fig. S13). The few areas where one system was strongly dominant were geographically concentrated (Fig. 6d). In the Dry Chaco of Argentina, these areas were associated with *Small-scale goat rearing*, while in the Caatinga, they corresponded to *Small-scale cattle dairy*. Capitalized cattle systems, such as *Large-scale cattle breeding-rearing,* dominated in the northern belt of the Cerrado. In the Chiquitano, areas of high dominance primarily aligned with *Small-scale cattle breeding-rearing* zones. Overall, *Small-scale goat rearing* dominated the Dry Chaco, while the Cerrado was largely covered by *Medium-scale cattle breeding-rearing,* mixed with *Cattle fattening* (Fig. 5). Notably, *Cattle dairy*, *Cattle whole-cycle* and *Large-scale cattle breeding-rearing* systems were predicted around the Araguaia river basin of the Cerrado (Fig. 7a). *Cattle whole-cycle* and *Large-scale cattle breeding-rearing* systems were

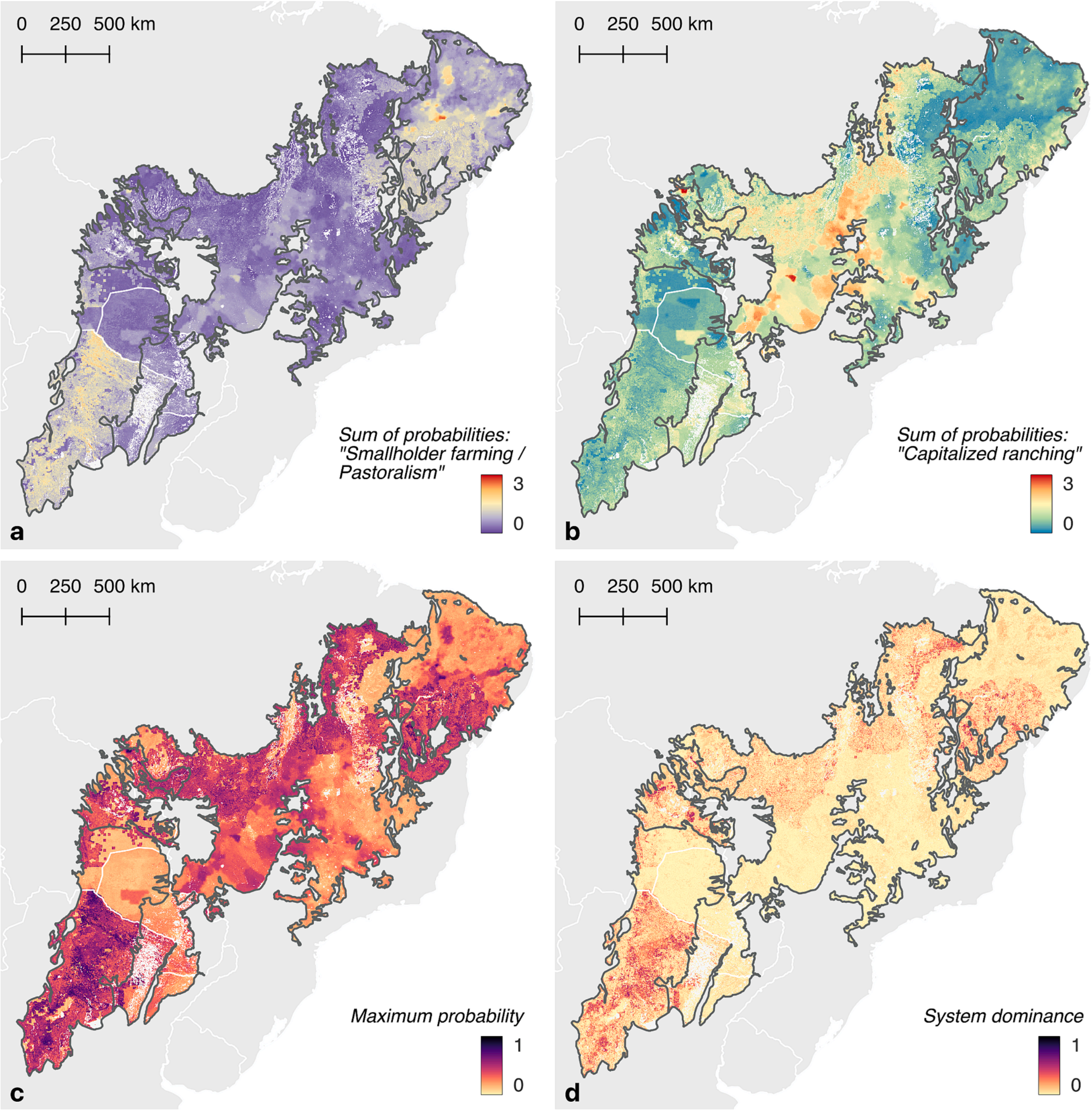

Fig. 6. Overlayed with tree cover: a) the probability of smallholder systems throughout the study region; and b) the probability of capitalized livestock systems in the study region. Across all systems: c) the maximum probability; and d) system dominance, calculated as the difference between the highest and second-highest probability. Low values indicate areas where the top two systems have similar likelihoods, reflecting high spatial overlap between competing systems.

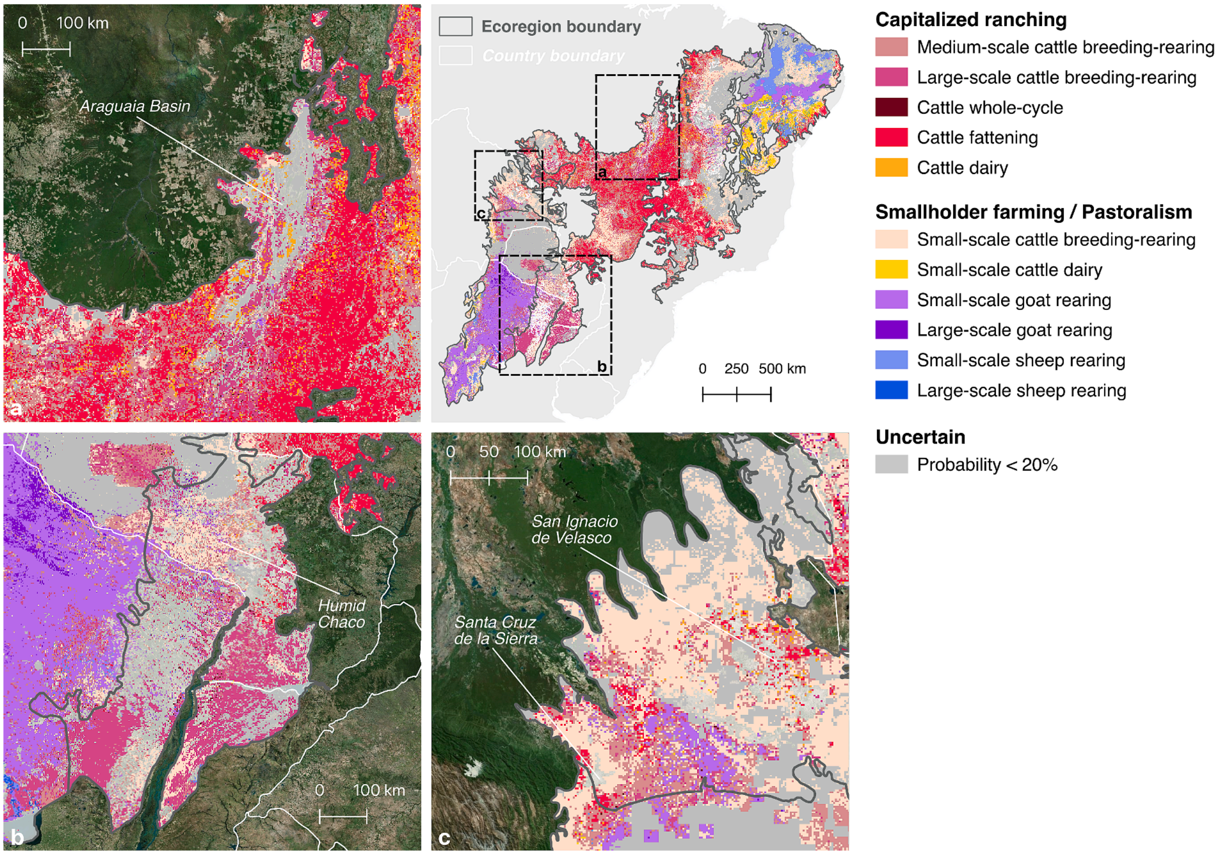

Fig. 7. An example of *Capitalized ranching* systems concentrated in areas such as: a) the Araguaia Basin in the Brazilian Cerrado; b) the Humid Chaco in Argentina and Paraguay; and c) the surroundings of Santa Cruz de la Sierra and San Ignacio de Velasco in the Bolivian Chaco and Chiquitano.

distributed throughout the Humid Chaco (Fig. 7b). The eastern Cerrado showed a mix of *Small-scale cattle breeding-rearing* and *Small-scale goat rearing* (Fig. 5). In the Caatinga, *Smallholder farming* and *Pastoralism* systems were ubiquitous, with *Small-scale cattle dairy* widespread in the south and *Small-scale sheep rearing* and *Small-scale goat rearing* interspersed with *Small-scale cattle breeding-rearing* throughout the region (Fig. 5). In the Chiquitano, *Small-scale cattle breeding-rearing* was prevalent, but we also found *Medium-scale cattle breeding-rearing*, *Cattle fattening*, and *Cattle dairy*, with some *Cattle whole-cycle* and *Large-scale breeding-rearing* systems surrounding key livestock ranching hubs such as Santa Cruz and San Ignacio de Velasco (Fig. 7c).

4. Discussion

Livestock ranching is stitched into the social-ecological fabric of South America (Ficek, 2019; Norton, 2024). In many regions, livestock ranching generates major environmental degradation and social tensions (Cáceres et al., 2020; Garrett and Rausch, 2016; Gerber et al., 2015), but is also central to national economies as well as the livelihoods of many local communities (Altrichter, 2006; Camino, 2018; CIRAD, 2020). Data on livestock is often local, partial (e.g., only livestock numbers) or coarse (e.g., only administrative units). This hinders sustainability assessments and planning to transition to more sustainable livestock production in many regions. Our work makes four primary scientific contributions to better understanding the geography of livestock systems in the Dry Diagonal and beyond. First, we identified eleven distinct livestock systems across the South American Dry Diagonal, encompassing pastoralists, small-scale, and capitalized systems. We also demonstrate that diverse datasets on livestock herd composition and fluxes effectively capture the diversity of these systems. Second, analysing the spatial determinants of these systems, we reveal an association of pastoralist and small-scale systems with the driest and least favourable regions. This points to the potential marginalization of these systems in the Dry Diagonal, but also to a defining feature of pastoralist systems in drylands: their adaptive capacity. Third, predicting the spatial distribution of livestock systems uncovered distinct geographies of livestock production, shaped by historical land-use dynamics. This enhances our understanding of the actors operating within the landscape, their potential interactions, and their roles in driving social-ecological change in the Dry Diagonal. Finally, we provide a novel and replicable methodology, demonstrating that underused datasets, such as livestock vaccination records, registers, and transaction data, can be highly useful and relatively easily integrated within a machine-learning framework to map livestock systems across vast regions at an unprecedented scale.

Our classification identified a wide variety of livestock systems in the Dry Diagonal. This first highlights the prevalence and diversity of *Smallholder farming* and *Pastoralism* systems. Considered together, they were the most widespread system in the Dry Diagonal, accounting for 60% of all farms we identified (Fig. 3; calculated from the n values per system across both data types). These systems are often crucial for local and regional food security, directly supporting household and community needs in ways that market-oriented commodity production does not (Banda and Tanganyika, 2021). The *Small-scale cattle dairy* system, for example, reflects the family-based units common in the Caatinga that supply milk directly to local communities (Burney et al., 2014; Meira et al., 2021). The *Small-scale cattle breeding-rearing* system, in turn, aligns with the diversified silvopastoral systems found in the Chiquitano, where cattle function as savings and are integrated with small-scale agriculture (de la Vega-Leinert, 2017).

Our classification also identified several *Capitalized ranching* systems, which reflect the industrial, market-oriented side of livestock production. From a production standpoint, these capitalized systems are generally characterized by higher productivity and economic efficiency, supplying national and international commodity chains rather than local markets (le Polain de Waroux et al., 2018; Levy et al., 2023). The prominence of capitalized cattle systems in our data, aligning closely with previous studies (Fernández et al., 2020; Milán and González, 2023), highlights the outsized influence of commercial extensive and intensive livestock production in the region. The largest extensive system, *Large-scale cattle breeding-rearing*, accounted for 29% of total livestock head (Fig. 3 and Table S4; calculated using the mean head and *n* values per system across both data types), which leads them to have a profound influence on the livestock landscape, not only socio-economically, but also ecologically. Extensive livestock systems typically require vast tracts of land, exerting substantial pressure on natural resources. This is particularly evident in regions like the South American Dry Diagonal, where concerns about deforestation and habitat conversion are prominent. In the Paraguayan Chaco, for example, extensive cattle ranching has been a major driver of deforestation, transforming tropical dry forests into pastures (Baumann et al., 2017b; Milán and González, 2023).

To understand the factors shaping livestock systems' distributions, we analysed their relationships with spatial determinants, capturing a wide range of social-ecological conditions. Our analysis revealed that *Smallholder farming* and *Pastoralism* systems were consistently associated with higher aridity, ruggedness, and less productive conditions (Fig. 4). This pattern was particularly clear for soil water content—which as an integrated measure of climate and soil properties, is a direct indicator for agricultural viability for growing pastures and crops (Zabel et al., 2014)—with which pastoralist and small-scale systems were negatively associated, while capitalized systems were positively associated.

This finding highlights a critical duality. On one hand, the association with arid conditions is ecologically consistent and reflects the adaptive capacity for which pastoralist systems are renowned (Krätli and Schareika, 2010). They make productive use of spatial and temporal variability to navigate uncertainty (Krätli and Schareika, 2010; Scoones, 2023), for example by rearing more drought-resistant species like sheep and goats (CIRAD, 2020; Guevara et al., 2017; Jamelli et al., 2021) or by engaging in complementary activities, including hunting and harvesting forest resources such as timber for fuel, charcoal, and construction, along with non-timber products, like honey and medicinal plants (Altrichter, 2006). Similarly, the strong, positive association of *Small-scale cattle breeding-rearing* and *goat rearing* systems with natural woody vegetation reflects their adaptability towards this type of forage in dry regions; for instance, *Criollo* cattle, locally-adapted breeds used by pastoralists in the Chaco, are known to browse heavily on woody plants and leaf litter during the dry season, relying less on grasses than the commercial cattle crossbreeds typical of capitalized systems (Marquardt et al., 2018).

On the other hand, this essential adaptability is directly threatened by pressures of displacement, land grabbing, and loss of access to key resources that push smallholders and pastoralists into increasingly marginalized areas (Cáceres, 2015; de la Vega-Leinert, 2020; del Giorgio et al., 2021; Vigroux et al., 2023), often facilitated by corrupt government actors and mechanisms (Blum et al., 2022; Camino et al., 2023). The expansion of capitalized agriculture—which imposes fixed boundaries and privatizes resources in a logic of control and enclosure (del Giorgio, 2024; Lima et al., 2022)—fragments previously communal rangelands, curtails movement, and undermines the very flexibility that is core to pastoral resilience (Scoones, 2023). These dynamics generate places of "friction" (Meyfroidt et al., 2024; Tsing, 2005), where diverse worldviews, cultural practices, ways of relating to nature, patterns of resource exploitation, and sociopolitical systems collide. In such contexts, less powerful actors are overshadowed or dominated by hegemonic powers, exacerbating inequalities and marginalization.

Our final maps (Fig. 5) provide the first detailed geography of livestock systems across the entire Dry Diagonal, one of the most important regions for livestock production globally (Williams and Anderson, 2019). These maps confirm the ubiquity of goat systems in the Dry Chaco and Caatinga (Fig. 5 and Fig. S4), reflecting their historical and ecological adaptation to arid conditions and shrubland environments (Cáceres, 2015; Lopes et al., 2012). Woody vegetation, identified as a key determinant of goat farming, exemplifies the dependence of these systems on natural forage resources (Fig. 4). In contrast, large-scale cattle systems dominate parts of the Cerrado, including the Araguaia river basin (Fig. 7a), and the grasslands of the Humid Chaco (Fig. 7b) where agricultural frontiers have historically expanded through favorable sociopolitical and ecological conditions (Adelman, 1994; Ficek, 2019; Pacheco, 2009). Since the late 20th century, cattle ranching has encroached into the Cerrado and Chaco (Piquer-Rodríguez et al., 2018; Vigroux et al., 2023), and more recently into the Chiquitano (de la Vega-Leinert, 2020). This expansion, driven by state incentives, foreign investments, and infrastructure developments, has seen old agricultural frontiers—established by settlers centuries ago—supplanted by commodity frontiers dominated by capitalized farmers, creating the very landscapes of concentrated production we identify today (Ficek, 2019; le Polain de Waroux et al., 2018; Pacheco, 2009, 2005). These findings align well with previous studies (Milán and González, 2023; Pacheco, 2009), which document the prominence of cattle ranching in these regions, further bolstering trust in our model predictions. Importantly, our findings also reveal a high degree of spatial overlap between *Smallholder farming* and *Pastoralism*, and *Capitalized ranching* systems. This is highlighted by the low system dominance values in many regions (Fig. 6d), which indicate that multiple systems often have similar probabilities of occurrence. While this demonstrates their potential coexistence, we note that the interactions between systems are often marked by highly unequal power dynamics, which likely constrains co-existence in practice (le Polain de Waroux, 2024; Pratzer et al., 2025; Vigroux et al., 2023). Overall, our results allude to a deep entanglement of livestock production with specific social-ecological conditions across the Dry Diagonal, shaped by distinct land-use histories and the dynamic interactions of livestock within and beyond human systems since European colonization (Ficek, 2019; Norton, 2024). The geographical awareness gained is critical for developing policies that promote sustainable livestock practices while recognizing the historical patterns, inequities, and structural disparities that shape resource access, environmental impacts, and livelihoods in the Dry Diagonal.

More generally, our systems mapping contributes to knowledge identifying major patterns and archetypes of human-nature interactions (Oberlack et al., 2019; Václavík et al., 2016); in our case recurring, high-level livestock systems associated with distinct land management, actors, and spatial determinants. In terms of presenting the spatial patterns of livestock production, our classification and maps provide a conceptual and spatial detail far beyond other studies, including the global livestock system maps by the Food and Agricultural Organization (FAO) (Gilbert et al., 2018; Robinson et al., 2014; Wint and Robinson, 2007). At the same time, we map a relatively small number (11) of systems, and these can be grouped meaningfully further into *Smallholder farming*, *Pastoralism* and *Capitalized ranching* systems. This classification not only captures the social-ecological complexity of land systems but also provides a practical framework for policymakers to design targeted interventions, balancing the need for localized strategies with broader, scalable insights, and comparisons across large geographies (Kuemmerle, 2024; Pratzer et al., 2024; Verburg et al., 2019). Such insights can inform sustainable development initiatives and policy interventions that suit the unique needs, and address the vulnerability, of different livestock systems, whilst addressing regional social and environmental concerns. For instance, they can support efforts to curb illegal land accumulation by agribusiness (Cáceres, 2015; del Giorgio et al., 2021; Vigroux et al., 2023), particularly in dry woodlands where deforestation frontiers are widespread, repeatedly intersecting with vulnerable ecosystems and livelihoods of rural pastoralists and smallholders (Buchadas et al., 2022; del Giorgio et al., 2022; Pratzer et al., 2025). They can also help mitigate the environmental consequences of intensified livestock ranching (Naylor et al., 2005), promoting more sustainable and equitable outcomes in these complex landscapes.

By integrating diverse data streams–including livestock vaccination records, farm registers, transactions, and environmental variables from remote sensing–we provide a comprehensive framework for understanding livestock system distribution across vast regions, specifically the tropical dry woodlands of the South American Dry Diagonal, an understudied yet culturally and ecologically vital region (Kuemmerle et al., 2017; Miles et al., 2006; Pennington et al., 2018). These datasets are likely available in many regions where reliable livestock data are scarce, offering opportunities to address persistent data gaps in global livestock research. For the first time, we use transaction data, describing the flow of livestock between farms, to identify livestock systems. Building on Fernández et al. (2020), which used vaccination data for livestock system identification, we advance this approach by applying it at a finer spatial scale (from 20 km^2 to 2.5 km^2 grids) and incorporating a broader range of systems. Our method thus provides a replicable framework to improve our understanding of livestock systems in other tropical dry forests globally and even in other agricultural contexts, paving the way for more effective and context-sensitive policy interventions. By linking this work to spatial determinants, we further highlight the ecological marginalization of pastoralists and smallholders, raising environmental justice concerns (Cáceres, 2015; de la Vega-Leinert, 2020; del Giorgio et al., 2021; Vigroux et al., 2023).

Our system identification based on active learning, as well as our models linking systems with spatial determinants, demonstrated strong model performance, and our results are highly plausible and align with prior knowledge on the geography of livestock production in the Dry Diagonal. Still, some limitations of our study are worth highlighting. First, while we validated our predictive models using a rigorous spatial cross-validation approach designed to account for spatial autocorrelation (Roberts et al., 2017) (Table S6, Fig. S7), a direct on-the-ground validation of our final maps was not feasible given the vast 4.2 million km^2 study area. However, by blocking our validation points in space, we effectively simulated the model's ability to extrapolate to unseen data, ensuring our error estimates are realistic, rather than optimistically biased. Our maps thus represent a robust, large-scale prediction of livestock system distribution, providing a critical baseline to guide more localized future research that can incorporate on-the-ground data and local actor knowledge. Second, our study's temporal scope has limitations. We relied on livestock datasets from varying time periods (2009–2024) due to data availability. As detailed in our methods, we addressed this by first training our models on temporally aligned data before predicting onto a consistent, recent timeframe (2020–2023), an approach which assumes a degree of stability in the fundamental type of livestock system over the past decade. Furthermore, our analysis is static, lacks a temporal component to capture system evolution or seasonal movements, which would be beneficial for assessing how systems compete and evolve over time in response to policies or market forces. Third, including cropland and pasture in our models could improve the prediction of some cattle systems, particularly the intensive ones. Indeed, we detected patterns of Cattle fattening in the central Cerrado (Fig. 5), particularly in cropland areas, a sign of potential decoupling of livestock from land. Fourth, our study is constrained by the nature of the input data. We harmonized different data metrics (herd counts vs. sales transactions) and acknowledge that our reliance on official records may under-represent remote or unregistered producers across all datasets. We also lacked detailed farm-level data, such as paddock boundaries or capital history, that could improve classification precision (Milán and González, 2023). However, our analytical framework is designed to mitigate these gaps. Our spatial models predict system occurrence based on underlying social-ecological conditions, allowing them to interpolate into data-sparse regions where specific systems may be present but unrecorded. Furthermore, the final calibration against regional livestock census data helps correct for any systematic under-representation of certain systems in our source data, thus ensuring the reliability of our final maps (Gilbert et al., 2018; Robinson et al., 2014).

In conclusion, our work illustrates the importance of combining underused data sources and machine-learning approaches to address the challenges of mapping livestock systems in complex social-ecological landscapes. Livestock husbandry is important in most of the world's tropical dry woodlands, yet adequate spatial data on livestock systems is missing and this hinders planning for and implementing sustainable livestock management, and balancing conservation goals with socio-economic and cultural realities. Our approach, here demonstrated for the South American Dry Diagonal, could be adopted and transferred to other dry woodland regions to support such initiatives.

5. Declaration of the use of generative AI and AI-assisted technologies

During the preparation of this work, the author(s) used ChatGPT to improve the readability and language of the manuscript. AI tools were not used for substantive scientific analysis, argumentation, or data interpretation. After using AI tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank A. Romero-Muñoz and P. Villalva for their assistance with the Bolivian livestock data and for providing contextual insights into the Bolivian Chaco and Chiquitano, and R. Butzer for help in hosting the livestock maps online. JB also thanks S.Nanni and H. Correa for accompanying him during fieldwork and for the insights gained, and M. Candido for editorial comments that improved the manuscript. JB acknowledges financial support from the Conservation Biogeography lab in Berlin, the IRI-THESys, and the Elsa Neumann Foundation. HKG, JM, and LR acknowledge financial support from the Gordon and Betty Moore Foundation. Finally, we thank the journal editors and the four anonymous reviewers for their constructive comments, which helped improve this manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloenvcha.2026.103156.

Data availability

The livestock system maps can be explored here: https://hu.berlin/LivestockDryDiagonal. They are available from the authors for non-commercial use upon reasonable request.

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