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# Priority areas for investment in more sustainable and climate-resilient livestock systems

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Camila Bonilla-Cedrez[1], Peter Steward[2], Todd S. Rosenstock[3], Philip Thornton[4], Jacobo Arango[5], Martin Kropff[6] & Julian Ramirez-Villegas[5,7,8] ✉

Livestock production supports economic growth, jobs and nutrition, but contributes to and is vulnerable to climate change. A transition is thus needed for livestock systems to become more sustainable and climate resilient, with clear positive effects on the Sustainable Development Goals. It is unclear, however, where the global community should invest to support this change. We identified priority geographies for livestock system investments in 132 low- and middle-income countries (LMICs), at mid- and low latitudes. Our results show that adaptation and mitigation goals are inextricably linked for the vast majority of these countries. An equal weighting of adaptation and mitigation indicators suggests that the top five investment priorities are India, Brazil, China, Pakistan and Sudan. Across LMICs, these act as critical control points for the livestock sector's interactions with the climate system, land and livelihoods.

Livestock production supports society and generates nearly 40% of global agricultural gross domestic product (GDP). About 1.3 billion people[1], including almost 930 million poor Africans and South Asians[2], depend on it for their livelihoods. Many rely on livestock as the primary source of revenue, and keeping livestock can also act as insurance, offering some protection when other income streams fail[1]. An important economic asset, livestock symbolize wealth and status across the Global South[3]. Through the provision of draught power and manure and the recycling of agricultural byproducts, livestock underpin crop production and the food system[3–5]. Animal-sourced food also provides nutrient-dense diets that contribute to cognitive development, growth and well-being[6]. Thus, livestock positively affect economics, health and cultural development, all of which are pillars of the Sustainable Development Goals (SDGs). Among others, the livestock sector has substantial potential to contribute to SDG 8.4 (on decoupling economic growth from environmental degradation), SDG 12.1 (on sustainable consumption and production patterns), SDG 13.1 (on strengthening resilience and adaptive capacity), SDG 13.2 (on the integration of climate change measures in national policies) and SDG 13.b (on promoting mechanisms for raising the capacity for effective climate change-related planning and management).

Climate change seriously threatens livestock productivity and those who depend on it. More frequent extreme weather events, irregular precipitation and rising temperatures decrease yields and product quality, increase pest and disease outbreaks, increase mortality, cause price shocks and disrupt supply, with cascading effects on producers and consumers[7,8]. For example, without adaptation, by 2100, the impact of heat stress on cattle alone will probably reach 4–10% of the 2005 production value[9]. Global estimates can, however, mask large regional differences. Reduction in milk and meat production in African and Asian countries may exceed 50 or even 70% under high-emission scenarios (Shared Socioeconomic Pathway 585) by 2100[9]. Despite uncertainties in the impact projections[9], the risk is substantial[10,11]. An analysis of 113 countries in Asia, Africa and Latin America suggested

[1]Animal Production Systems Group, Wageningen University & Research, Wageningen, the Netherlands. [2]International Center for Tropical Agriculture, Nairobi, Kenya. [3]Bioversity International, Montpellier, France. [4]Clim-Eat, Netherlands Food Partnership, Utrecht, the Netherlands. [5]International Center for Tropical Agriculture, Palmira, Colombia. [6]Resilient Agrifood Systems, CGIAR System Organization, Montpellier, France. [7]Plant Production Systems Group, Wageningen University & Research, Wageningen, the Netherlands. [8]Bioversity International, Rome, Italy. ✉e-mail: j.r.villegas@cgiar.org

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BOX 1

## Key concepts and terms on climate change adaptation and mitigation

**Adaptation:** Actions that decrease the vulnerability of farming systems to climate change (for example, farmers implementing water management systems to adapt to short- and long-term rainfall variations).

**Adaptive capacity:** Skills and capacity, such as knowledge, finance and technical capacity, that permit farmers or institutions to adjust their behaviour to mitigate the impact of climate hazards or capture opportunities.

**Exposure:** The degree to which a system is subject to a climate hazard.

**Hazard:** A climate event or process that can harm farmers, such as loss in productivity—a function of exposure and sensitivity.

**Impact:** Hazards' effect on farming systems and farmers, such as loss in productivity—a function of exposure and sensitivity.

**Mitigation:** Actions that decrease the rate of climate change by limiting or preventing GHG emissions and by enhancing activities that remove them from the atmosphere (for example, decreasing herd size to decrease their proportion of national and global GHG emissions).

**Risk:** The combination of exposure and vulnerability to hazards (the potential for adverse consequences).

that US$994 billion per year in livestock value—around 55% of the total value of production (VOP) for five commodities—is exposed to various climate hazards, especially rainfall variability (US$198 billion) and heat stress (US$130 billion)[12]. Adaptation of livestock production systems is imperative to maintain and enhance the benefits they provide.

These benefits, however, must be considered alongside the negative impacts of livestock on the climate system. Feed production, enteric emissions, manure management, grazing and land-use change release methane, nitrous oxide and carbon dioxide into the atmosphere. Livestock production accounts for about 5.8% of global annual greenhouse gas (GHG) emissions and about 31.5% of the food systems' contribution[1,13,14]. The dominant livestock emission source varies by region. Herd size and enteric emissions drive climate impacts, for example, in rangeland systems[15], while land-use change has an influence in mixed grazing systems. The expansion of livestock production systems also threatens tropical forests[16]. Given the impacts, actions to decrease agricultural emissions need to target livestock production systems.

The livestock sector affects 10 of 17 SDGs, but not all in positive ways[17], meaning that the meeting of global goals will require transitioning to climate-resilient and low-emissions livestock production systems[18]. Yet, while nearly 100 countries prioritize livestock in their Nationally Determined Contributions (NDCs), public and private investors hesitate to target the livestock sector due to perceived risks and environmental concerns. Critical questions remain largely unanswered on where and in what to invest. In this study, we quantify countries and livestock production systems that leverage the livestock agri-food systems in low- and middle-income countries (LMICs) to guide future adaptation and mitigation investments (Box 1). We detail proven actions for accelerating the transition to low-emission, climate-resilient systems. We discuss their scalability, enabling factors and constraints.

## Results

### Exposure to climate hazards and emissions by geographies

We found that substantial livestock production value and rural population are exposed to climate hazards (Table 1 and Fig. 1). Across the 132 countries in this analysis, US$660 billion in VOP, 1.04 billion people, 470 million tropical livestock units (TLUs) and 671 million hectares of pasture are exposed to climate hazards (Table 1 and Supplementary Table 1). The most prevalent hazard combinations by percentage of total area were rainfall variability plus heat stress plus drought (33%), heat stress (28%) and rainfall variability plus heat stress (12%) (Fig. 1 and Supplementary Fig. 1). The levels of importance of the various climate hazards differ among countries and livestock production systems (Fig. 1 and Supplementary Figs. 1 and 2). Livestock systems in India, Nigeria and Sudan are the most exposed, with India's exposure exceeding that of other countries at least fivefold (Fig. 1). Within the study area, rainfed arid and humid regions where mixed farming (crops and livestock) systems are prevalent had the highest VOPs (US$405 billion), rural populations (661 million) and TLUs (295 million) exposed to climate hazards (Table 1 and Supplementary Fig. 2). Regions such as the Horn of Africa, which predominantly includes rainfed arid rangelands, and West Africa (with both humid and arid conditions) have 14% of their VOP, 28% of their rural population, 39% of their pasture area and 32% of their TLUs exposed to climate hazards.

GHG emissions from livestock are substantial across the study region. Across the 132 countries included in this analysis, emissions were estimated to be 2,995 megatons ($CO_2$e) (Table 1, Fig. 1 and Supplementary Table 2). Seventy-one percent (2,132 megatons $CO_2$e) were directly from livestock production, including enteric emissions, manure and feeds, while 29% (863 megatons $CO_2$e) related to deforestation for pastures and soy production (Table 1 and Supplementary Table 2). Mixed rainfed systems in humid and arid lands produce the most carbon dioxide equivalents ($CO_2$e) by far, with ruminants representing 66 and 94% of their total emissions (Supplementary Fig. 3). Emissions from Brazil and India far exceed those of the other countries studied, but these emissions result from vastly different dynamics. In Brazil, 64% of total emissions are due to soybean and pasture-driven forest loss. In India, 99% of the emissions are from ruminants, predominantly from bovine milk production associated with mixed systems (Supplementary Fig. 4).

### Priorities for adaptation and mitigation

Our analysis shows that no country or system with appreciable livestock production value and population has zero exposure to climate hazards or zero emissions (Fig. 1). Therefore, using this analysis to obtain a set of geographic priorities requires the identification of target outcomes, their relative importance and the implied trade-offs across scales. An equal weighting of adaptation and mitigation indicators (see Methods) suggests that the top five investment priorities are India, Brazil, China, Pakistan and Sudan (Figs. 1 and 2 and Supplementary Fig. 5). Across LMICs, these act as critical control points for the livestock sector's interactions with the climate system, land and livelihoods. These five countries combined account for 46% of the total VOP, 35% of the total rural population exposed to climate hazards and 51% of emissions. However, differential weighting indicators change the outcomes of investment prioritization. For example, a sole focus on mitigation prioritizes investments in Brazil, China, India, Pakistan and Bangladesh (Fig. 2 and Supplementary Fig. 7). In contrast, focusing only on adaptation prioritizes India, Sudan, South Africa, Nigeria and Chad (Fig. 2 and Supplementary Fig. 8).

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**Table 1 | Totals of GHG emissions and exposure to climate hazards per livestock system within the study area**

| Livestock production system | GHG emissions | | | Climate hazard exposure | | | |
|---|---|---|---|---|---|---|---|
| | Direct emissions (Mt $CO_2$e) | Indirect emissions (Mt $CO_2$e) | Total emissions (Mt $CO_2$e) | VOP (billion US$) | Rural population (million) | Pasture area (million ha) | TLUs (million) |
| Mixed irrigated | | | | | | | |
| MIA | 263 | 1 | 264 | 115.7 | 167.9 | 5.7 | 70.9 |
| MIH | 103 | 3 | 106 | 57.9 | 31.7 | 0.7 | 30.8 |
| MIY | 1 | 0 | 1 | 0 | 0 | 0 | 0 |
| MIT | 58 | 0 | 58 | 18.8 | 10.1 | 4.0 | 3.7 |
| Mixed rainfed | | | | | | | |
| MRA | 379 | 20 | 399 | 132.4 | 285.6 | 150.6 | 132.8 |
| MRH | 440 | 200 | 640 | 99.1 | 175.9 | 28.0 | 60.8 |
| MRY | 0 | 0 | 0 | 0 | 0 | 0 | 0.1 |
| MRT | 148 | 6 | 154 | 31.1 | 37.4 | 10.1 | 22.1 |
| Rangelands | | | | | | | |
| LGA | 250 | 22 | 272 | 50.1 | 108.7 | 326.7 | 71.4 |
| LGH | 99 | 56 | 155 | 21.6 | 46.2 | 49.4 | 14.7 |
| LGY | 4 | 0 | 4 | 0.1 | 0.2 | 3.4 | 0.3 |
| LGT | 77 | 4 | 81 | 24.0 | 11.4 | 38.8 | 8.8 |
| Other | 310 | 551 | 862 | 110 | 167 | 54 | 54 |
| Total | 2,132.3 | 863.2 | 2,995.6 | 660.7 | 1,042.0 | 671.7 | 470.5 |

The category other is as reported by Robinson et al.[41] for systems of varying type (for example, root crop based, root crop mixed, forest based and tree based), with some component of livestock. LGA, rangelands arid; LGH, rangelands humid; LGT, rangelands temperate; LGY, rangelands hyperarid; MIA, mixed irrigated arid; MIH, mixed irrigated humid); MIT, mixed irrigated temperate; MIY, mixed irrigated hyperarid; MRA, mixed rainfed arid; MRH, mixed rainfed humid; MRT, mixed rainfed temperate; MRY, mixed rainfed hyperarid.

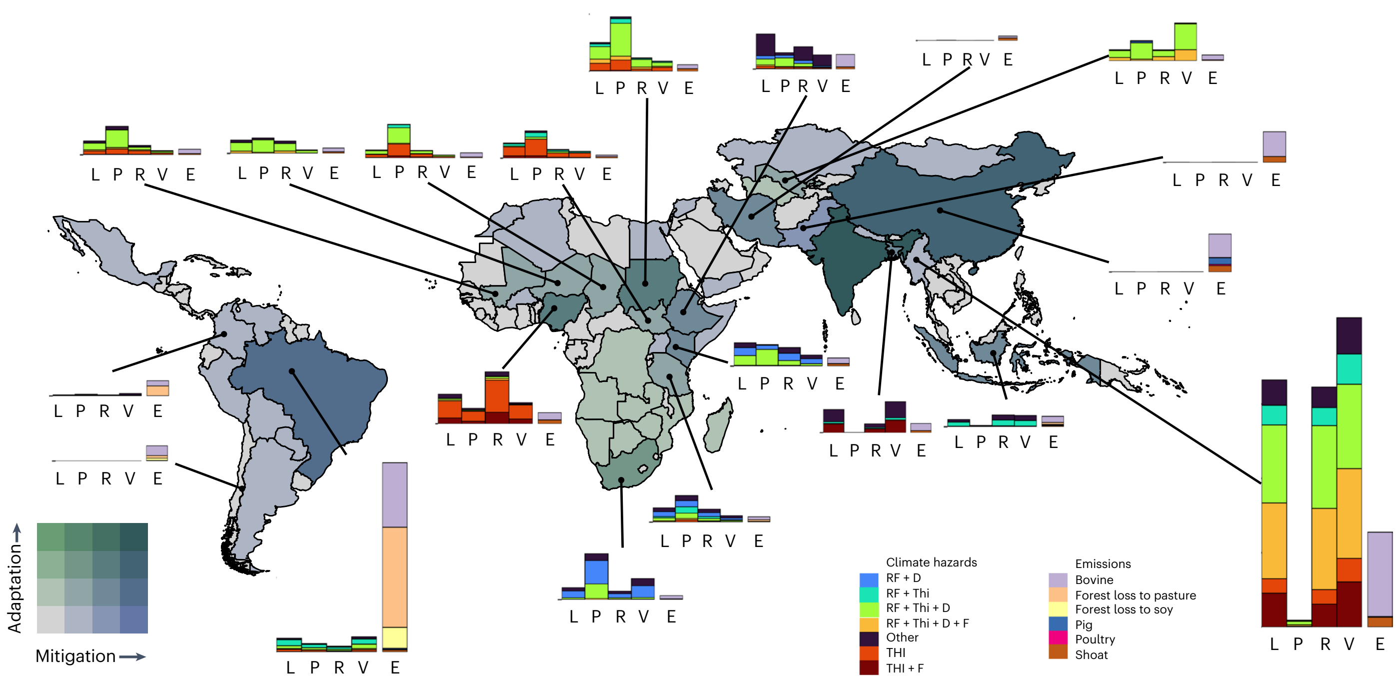


**Fig. 1 | Adaptation and mitigation potential priorities.** Adaptation priorities include areas where TLUs (L), pasture area (P), rural population (R) and VOP (V) are exposed to climate hazards. Mitigation priorities include reducing livestock-direct and deforestation-linked GHG emissions (E). The bottom-left (top-right) corner of the colour scale indicates low (high) adaptation and mitigation potential priorities. Shades of blue show increasing mitigation potential, moving from light to dark blue, over the $x$ axis of the colour scale, whereas shades of green show increasing adaptation potential, moving from light to dark green, over the $y$ axis of the colour scale. The climate hazards include climate variability (RF), heat stress (THI), drought (D) and flooding (F). The following ID codes for the various indicators, hazards and emissions categories reference datasets used in the analysis (see Supplementary Table 3): TLUs (001), VOP (002), pasture area (003), rural population (004), climate hazards (006–009), GHG emissions (011–017), bovine emissions (011 and 012), forest loss to pasture emissions (013–016), forest loss to soy emissions (013–015 and 017), pig emissions (011 and 012) and shoat emissions (011 and 012).

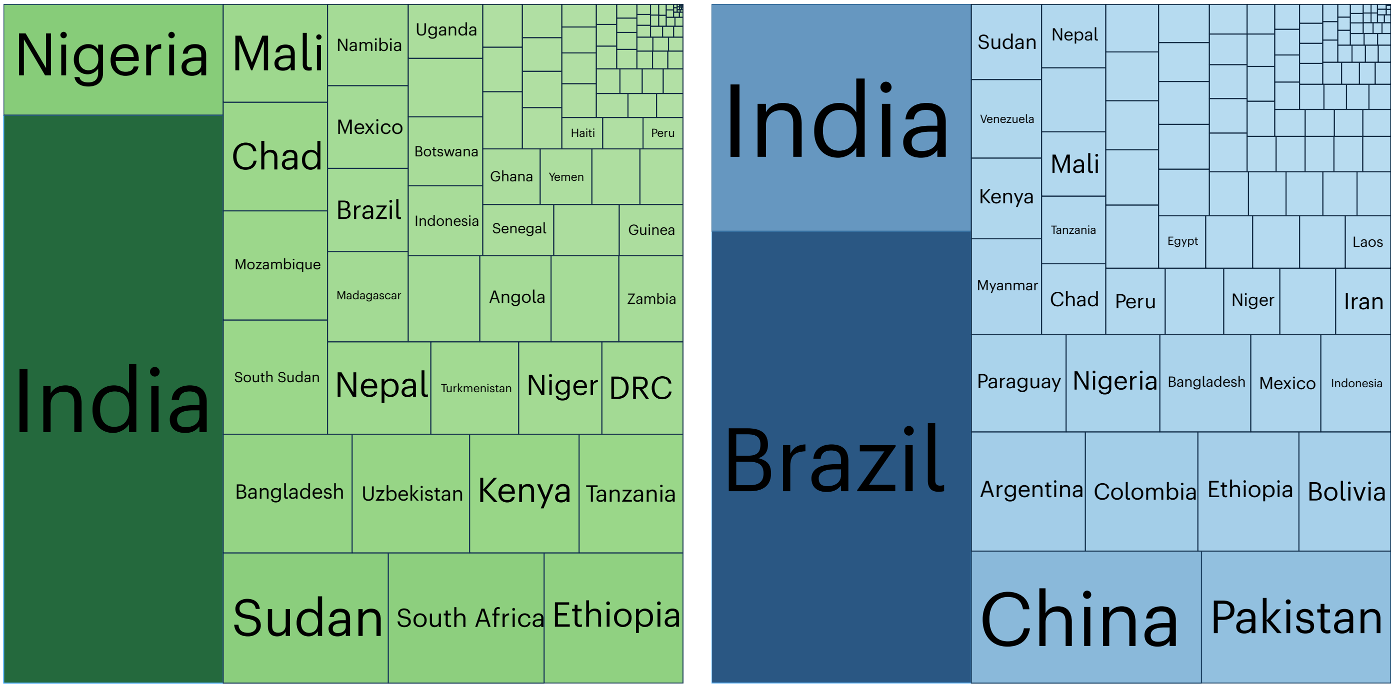


**Fig. 2 | Priority countries for adaptation and mitigation.** Priority countries for adaptation are shown in green (left) and those for mitigation are shown in blue (right). Larger shapes and fonts and more intense colours within each panel represent higher priorities. DRC, Democratic Republic of the Congo.

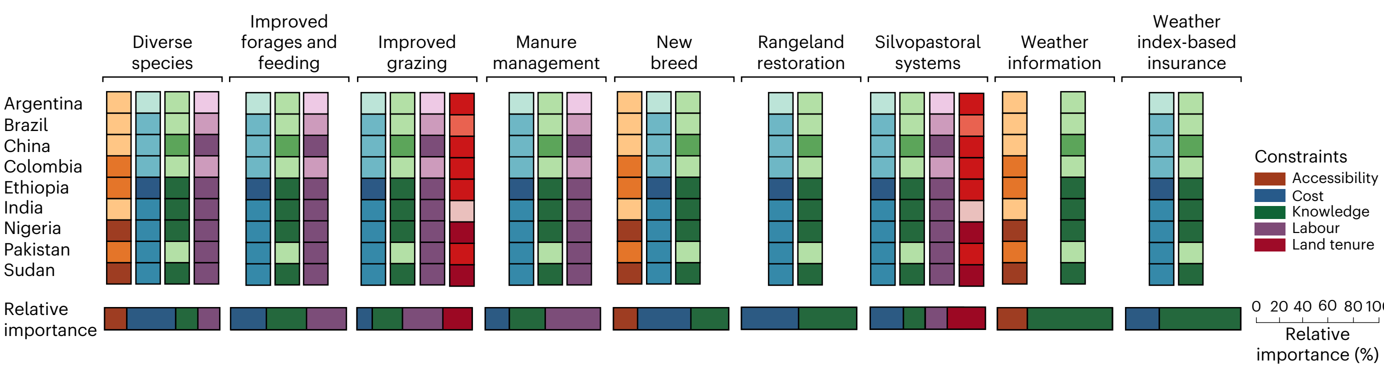


**Fig. 3 | Adaptation and mitigation options available for livestock systems in LMICs, constraints to their adoption in the selected countries and the relative importance of each constraint for the adoption of each option in general.** Darker colours represent a higher constraint for the adoption of a particular option in each country, as determined by the quantile in which the country sits with respect to the global median. Indicators to represent each constraint include accessibility (research and development expenditure (percentage of GDP)), cost (GDP per capita), knowledge (literacy rate in the total adult population), labour (employment in agriculture) and land tenure (Rule of Law). Data from ref. 57.

For most geographies, it is virtually impossible to disentangle the importance and relationship between adaptation and mitigation. More specifically, adaptation and mitigation emerge as joint priorities most clearly in India, in which 32% of the rural population and 41% of the VOP in the study area are exposed to climate hazards, and which produces 13% of the emissions (Fig. 1). Across most of Sub-Saharan Africa, adaptation measures tend to greatly outweigh those of mitigation options (Fig. 1). The converse is true for countries in Latin America, where mitigation concerns are generally greater than adaptation concerns.

### Climate actions and their adoption constraints

Adaptation and mitigation options already exist that would allow the livestock sector to meet its economic, environmental and climate mitigation and resilience goals (Fig. 3). Among other factors, low investment, lack of education and cultural, institutional and political barriers have led to generally low adoption rates for these actions. Constraints to the adoption vary by region, country and options (Fig. 3). For instance, for the selected countries, cost is a barrier to adopting most options, and the relative importance of cost varies between 20 and 50%. In countries such as Argentina, Brazil and China, the main barrier to adopting a technology is the limited labour force due to the lower rural population and fewer people employed in agriculture. This barrier differs in Ethiopia, Nigeria and Sudan, where accessibility and knowledge are the main adoption constraints.

## Discussion

From a global perspective, the weighting of adaptation and mitigation indicators highlights the geographies with the greatest problems, providing a regional focus. At local scales, however, these indicators emerge from farmers' decisions on system management and, as such, are interconnected; any choice of adaptive or mitigating priorities needs understanding of the trade-offs that impact other goals.

Adopting a livestock practice or technology nearly always involves trade-offs between adaptation and mitigation outcomes[19]. Thus, to avoid unintended consequences, actions need to be aligned with local demands and goals. The consideration that adaptation and mitigation need to be addressed jointly is especially important in areas where population growth and/or dietary change are most prominent[20]. Yet, a lack of alignment at the policy level potentially hinders this objective. Roughly 50% of the NDCs that mention livestock note just one of the priorities[21], and only 28 out of 184 countries' NDCs include soil-related targets[22]. This omittance suggests that, as a global community, we are creating institutions and narratives that disincentivize or preclude action on adaptation, mitigation or both.

Our assessment of adaptation and mitigation options suggests that careful consideration of context specificities is needed for the scaling of options due to regional systems dynamics and adoption constraints (Fig. 3). In livestock systems in general, to maximize the benefits of improving and intensifying diets, reductions in herd size are necessary[15–17]. However, reductions in animal numbers may be limited to: (1) humid and temperate mixed systems where feeding grain concentrates are a plausible option[23]; (2) places where an alternative source of both feed and food protein are available[15,23,24]; and (3) where livestock are not enmeshed in cultural identity[25,26]. Manure management is another viable strategy for decreasing emissions, but its applicability is limited for open grazing systems. In the study region, 18% of cattle, 27% of sheep and 43% of goats roam in extensive grazing systems, where most excretion happens in the field; collection occurs after the manure is dry, if at all[15,27]. In East Asian systems with a high concentration of animals, emissions are associated with unregulated manure disposal, and animals produce more manure than can be recycled in the agricultural area[28]. In grasslands and agricultural land, 47% of the total potential mitigation arises from soil organic carbon protection and sequestration[29], as well as the restoration of degraded rangelands[23]. The potential of restoration and improved land management actions to increase carbon storage and/or avoid emissions across global forests, wetlands, grasslands and agricultural lands is 23.8 $GtCO_2e\ yr^{-1}$ (ref. 30). Silvopastoral systems are a viable land management strategy for adaptation and mitigation in Latin America, where livestock is a major driver of deforestation and 11% of people are exposed to heat stress. Silvopastoral systems could increase productivity[31,32], decrease GHG emissions[33], improve carbon storage potential[32] and aid adaptation to heat stress[34]. However, the scalability of silvopastoral systems has been limited by several factors: lack of knowledge, high initial investment requirements and the extended periods before returns on investments are seen.

Climate risk reduction should be essential in transforming livestock systems; according to our analysis, 69% of the VOP is exposed to high levels of climate variability. Climate services and access to credit and insurance are proven climate risk management actions that have demonstrated potential and scalability for crop-based systems[35,36]. In Senegal, where virtually all livestock systems are exposed to high or extreme climate variability, climate services increase farmer income by 10–25%[37]. In the Horn of Africa, where pastoral drylands are regularly affected by drought and its interannual variability (Supplementary Figs. 1 and 2), the Predictive Livestock Early Warning System[38] seeks to improve livestock herd management, migration patterns and livestock health through providing forecasts on water and pasture availability. Likewise, the index-based livestock insurance approach has sold around 90,000 insurance policies in Kenya and Ethiopia, positively impacting policyholders' sales, income and well-being[39,40].

Low levels of investment in the sector and a lack of effective policies, combined with high resource demand and limited information to implement solutions (Fig. 3), reinforce the gap between current livestock systems and their future potential. There is limited evidence regarding the scalability of the actions outlined here. As such, the set of interventions and practices that best protect against the combined hazards and can reliably measure their effectiveness warrants further investigation. The gathering of such evidence must be combined with building the capacities of local and regional organizations, the public sector and producers, to promote and implement adaptation options. Governments need technical support to access finance, implement programmes and report adaptation and mitigation achievements. These challenges apply equally to the private sector and small-scale systems. Large-scale production changes landscapes, and supply and demand shifts can provide major benefits and influence consumer behaviour. In small-scale systems, the value of livestock to livelihoods goes far beyond their productive capacity, and building local knowledge and capacity is vital to achieving transformation.

# Methods

We used multiple spatial datasets (Supplementary Tables 3 and 4) to implement a prioritization approach to identify priority geographies (that is, countries and production systems) for livestock system investments and to identify adoption constraints to adaptation and mitigation options. We selected two main challenges related to climate adaptation and mitigation strategies: (1) livestock production and producer livelihoods are threatened by short- and long-term rainfall and temperature variations and their changing predictability; and (2) livestock are responsible for a substantial proportion of national and global GHG emissions. A fully detailed description of the methods is provided in the Supplementary Information.

We used the livestock production system classification of Robinson et al.[41]. This classification divides livestock production systems into landless, rangeland and mixed systems. Mixed systems are divided into rainfed and irrigated, giving rise to four broad system categories (that is, landless, rangelands, mixed rainfed and mixed irrigated). Each category was then divided into agroecologies according to temperature and whether they were humid, arid or hyperarid[41]. The study area included livestock production systems in all LMICs in mid- and low latitudes identified by The World Bank ($n$ = 132 countries).

## Analysis of adaptation

We performed a geospatial data analysis to characterize livestock production systems and producer livelihoods and to identify threats related to short- and long-term variations in rainfall and temperature. First, we mapped regions projected to experience climatic hazards and masked them by their adaptive capacity within the livestock systems (Supplementary Fig. 8). Second, we assessed the exposure per hazard within each country and livestock system (Supplementary Fig. 9). Exposure was represented by the total VOP[42], total rural population[43], pasture area[44] and TLUs. TLU values were computed following Rothman-Ostrow et al.[45] using data from the Gridded Livestock of the World database (version 3)[46]. VOP data were derived from ref. 42, which used a combination of modelling and FAOSTAT data[13] to produce geospatial datasets of the value of livestock production.

Sixteen climatic hazard classes were identified from the intersection of rainfall variability, heat stress, drought and flood risk. To characterize rainfall variability, we used the coefficient of variation in annual mean rainfall (15–30% = highly variable; >30% = extremely variable) derived from the Climate Hazards Group InfraRed Precipitation with Stations dataset[47]. Areas of heat stress were defined as having thermal stress (projected for 2030 under the Representative Concentration Pathway 8.5 scenario) with a of ≥79 (ref. 48). To define areas at risk of flooding, we used the UN Environment Programme–Division of Early Warning and Assessment–GRID-Europe dataset[49], in which flooding risk is ranked from 0 (no risk) to 5 (extreme). Areas at risk of drought were defined as having more than 25 d without rain per month on average.

We defined three categories of livestock system adaptive capacity to these climate hazards (low ≥ 25%; medium = 10–25%; high ≤ 10%) using the national-level poverty headcount ratio of US\$1.90 $d^{-1}$ (ref. 50) as a proxy. For the exposure analysis, we considered areas with poverty rates above 10% and their climate dimensions (that is, the rainfall coefficient of variation, heat stress, flood hazard risk and drought).

### Analysis of mitigation

We calculated total livestock emissions by geography by summing direct and estimated emissions from deforestation (Supplementary Figs. 10 and 11). We did not include changes in soil carbon stocks due to the difficulty in estimating these reliably at the scale of our study. Across the 132 countries included in this analysis, emissions were estimated to be 2,995 megatons ($CO_2e$), which is lower than other recently published estimates[51]. This difference arises primarily due to the exclusion of direct $CO_2$ emissions from cropland used for feed (see Supplementary Information) and the focus on LMICs only (compared with global estimates). Despite inherent limitations and uncertainties in the input datasets (see the corresponding references), our sources of emissions data are derived well-established sources (refs. 13,42,52,53) and robust for the purposes of our prioritization analysis. Furthermore, because our analysis does not introduce specific equations or parameters, it is unlikely that it introduces new uncertainties or propagates any original uncertainties present in the input datasets, beyond what would be a simple addition of these original uncertainties.

Direct emissions data come from ref. 42 and are for the year 2010. To update these data to 2019, we multiplied 2010 values by the proportional increase in national livestock emissions between 2000 and 2019, as reported by FAOSTAT[13,54]. To estimate livestock emissions linked to deforestation, we first combined above- and below-ground carbon biomass data from 2010[55] and masked these values by areas with tree cover values ≥30%[56], giving a layer of carbon biomass per hectare of forest. Commodity-linked deforestation data are available for subnational administrative areas[52]. For each area, we calculated the average amount of carbon biomass (using the data from ref. 55) and multiplied this by the mean annual rate of commodity-linked (soy and pasture) forest loss for the period 2010–2015 (data from ref. 52) giving the average rate of carbon loss per area per year. Data from ref. 52 are available only at the subnational administration level; thus, our analysis of indirect emissions was conducted at that spatial scale. Carbon was converted to $CO_2$ using a factor of 3.67 to account for its atomic weight. We assume that carbon in below-ground biomass is lost on conversion to pastureland or soybeans. We included deforestation due to soybeans as the majority of soybean production is used for livestock feed, but note that a proportion of this production has other fates.

### Prioritization

All indicators were normalized by dividing the value of each indicator per country by the maximum value across geographies to rank countries and visualize adaptation and mitigation indicators (Fig. 1). For example, TLUs for each country were normalized using India's TLUs, since it has the highest value worldwide. Each normalized exposure indicator was then weighted and summed, creating a unique adaptation index. For the case of mitigation, each indicator corresponding to emissions was normalized by dividing by the maximum value across geographies.

### Constraints for the adoption of climate actions

Based on a literature review[57] and expert opinion, we identified adaptation and mitigation options available for livestock systems (Fig. 3). To represent the constraints for the adoption of these options, we identified key global indicators reported by The World Bank to quantify the relevance of each constraint for each adaptation and mitigation option per country (that is, accessibility, cost, knowledge, labour and land tenure). We represented the constraints as follows: (1) accessibility was measured using research and development expenditure (percentage of GDP); (2) cost was measured by GDP per capita; (3) knowledge was measured by the total adult literature rate; (4) labour was measured by employment in agriculture; and (5) land tenure was measured by the Rule of Law (see Supplementary Table 4). The relative importance of each constraint for each option—not for a specific country but generally—was quantified based on expert opinion. We represent these constraints for the top three countries, by continent, that were identified in the prioritization analysis.

This research was conducted as part of a global research programme on livestock and climate (see https://www.cgiar.org/initiative/34-livestock-climate-and-system-resilience/), which is part of the CGIAR consortium of research centres. No involvement of human participants or animal subjects took place as part of this work. To the best of the authors' knowledge, the findings reported herein do not carry any racial, cultural or gender bias.

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

## Data availability

The datasets analysed during the current study are available from the livestock_prioritization repository https://github.com/CIAT/livestock_prioritization/tree/main/Data. No restrictions on data availability exist other than those related to refs. 42,52, the data from which are not publicly available. For use of these datasets, we strongly recommend contacting the first and/or corresponding authors of the studies. Access links for all datasets are provided in Supplementary Table 3.

## Code availability

An interactive markdown is available at https://github.com/CIAT/livestock_prioritization.

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## Author contributions

T.S.R. and J.R.-V. conceived of the research. C.B.-C., P.S., T.S.R. and J.R.-V. performed the data acquisition and processing. C.B.-C. and P.S. analysed the data. C.B.-C., P.S., T.S.R., P.T., J.A. and J.R.-V. wrote the manuscript. C.B.-C., P.S., T.S.R., P.T., J.A., M.K. and J.R.-V. edited the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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**Correspondence and requests for materials** should be addressed to Julian Ramirez-Villegas.

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Corresponding author(s): Julian Ramirez-Villegas (j.r.villegas@cgiar.org)

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## Software and code

Policy information about availability of computer code

**Data collection**

Data collection was performed manually from the original sources. In two cases data were provided by authors upon direct contact. The R markdown file contains all data transformations performed, with modifiable options. The GitHub repository (https://github.com/CIAT/livestock_prioritization) contains all input datasets (under the folder Data). These datasets will allow reproducing the entire analysis conducted. All datasets are listed in Supplementary Table S3. Below we provide a list of data with the access web addresses:

001 – Gilbert et al. (2018). Exposure: livestock density. Available online at https://dataverse.harvard.edu/dataverse/glw
002 – Herrero et al. (2013). Exposure: value of livestock production. Dataset provided by author.
003 – Ramankutty et al. (2008). Exposure: pasture area. Available at http://www.earthstat.org/cropland-pasture-area-2000/
004 – World Pop. Exposure: total rural population. Available at https://data.worldpop.org/GIS/Population/Global_2000_2020/2020/0_Mosaicked/ppp_2020_1km_Aggregated.tif
005 – Robinson et al. (2014). Exposure: global livestock systems. Available at https://dataverse.harvard.edu/dataverse/GLPS
006 – Funk et al. (2015). Hazards: coefficient of variation in mean rainfall. Calculated from CHIRPS data at https://data.chc.ucsb.edu/products/CHIRPS-2.0/
007 – Funk et al. (2015). Hazards: dry days per months. Calculated from CHIRPS data at https://data.chc.ucsb.edu/products/CHIRPS-2.0/
008 – UNEP/DEWA/GRID-Europe. Hazards: flood risk. https://preview.grid.unep.ch/index.php?preview=data&events=floods&evcat=5&lang=eng
009 – Thornton et al. (2021). Hazards: heat stress index. Dataset provided by author.
010 – World Bank. Adaptive capacity: poverty headcount ratio of US$1.9 per day. Available at https://maps.worldbank.org/projects
011 – Herrero et al. (2013). Emissions: direct GHG emissions. Dataset provided by author.
012 – FAOSTAT (2021) & Tubiello et al. (2022). Emissions: direct GHG emissions. Available at https://fenixservices.fao.org/faostat/static/bulkdownloads/Emissions_Totals_E_All_Data.zip
013 – Soto-Navarro et al. (2020). Emissions: aboveground biomass carbon density. Available at https://datadownload-production.s3.amazonaws.com/WCMC_carbon_tonnes_per_ha.zip
014 – Soto-Navarro et al. (2020). Emissions: belowground biomass carbon density. Available at https://datadownload-

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016 – Goldman et al. (2020). Emissions: pasture-driven forest loss. Dataset provided by author.
017 – Goldman et al. (2020). Emissions: soy-driven forest loss. Dataset provided by author.
018 – Global Administrative Areas (2021). Administrative regions. Available at https://gadm.org/download_world.html.

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The datasets analyzed during the current study are available in the Livestock_Prioritization repository https://github.com/CIAT/livestock_prioritization/tree/main/Data. No restrictions on data availability exist other than related to refs. 42 and 52 (see Main Text), which are not publicly available. For use of these datasets we strongly recommend contacting the first and/or corresponding authors of those studies. Access links for all datasets can be found in Supplementary Table S3.

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| Research sample | We analyzed n=132 countries |
| Sampling strategy | We selected these n=132 countries because they are Low and Middle Income Countries according to the World Bank in mid- and low latitudes. |
| Data collection | Data were downloaded from existing (public) repositories for all datasets except two, which were provided directly by the authors of those datasets. |
| Timing and spatial scale | We analyze a combination of historical and future projected conditions (see Methods and Supplementary Table S3). |
| Data exclusions | No data exclusions were made. |
| Reproducibility | All code and data are freely available in a GitHub repository. See data and code availability statements on the Main Text. |
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| ☒ | ☐ Human research participants |
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## Methods

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| ☒ | ☐ Flow cytometry |
| ☒ | ☐ MRI-based neuroimaging |