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1. Introduction

The livestock sector and its environmental impacts have been a subject of growing global concern, reflected in intensive public and scientific discussions. Since the publication of ‘Livestock’s Long Shadow’ by the FAO (Food and Agriculture Organization of the United Nations) in 2006, livestock has been universally criticized for its large contribution to greenhouse gas (GHG) emissions, land use change, soil degradation, water use and loss of biodiversity (Steinfeld *et al* 2006, Herrero *et al* 2015, Hilborn *et al* 2018). Widely publicized recent reports, such as the EAT-Lancet report (Willett *et al* 2019), prompted a wave of media outreach arguing that one of the main solutions to the climate change and human health crises, globally, is to eat no or little animal source foods (ASFs). Global media continues to be dominated by concerns about adverse environmental and health impacts of livestock, while the coverage of livestock’s contribution to livelihoods has been declining (Marchmont Communications 2019). These negative narratives, mostly rooted in industrial livestock production systems and overconsumption of ASF in Western countries, overshadow the various complex and often positive roles livestock plays in low- and middle-income countries (LMICs) in Africa, South America and South(-East) Asia. A singular focus on livestock-associated environmental impacts ignores livestock’s crucial livelihood functions in smallholder systems such as nutrition, income, asset provision, insurance, and nutrient cycling (Herrero *et al* 2013a). Institutions such as the FAO have been working towards higher awareness of the contributions of the livestock sector to the sustainable development goals, including

economic growth, poverty reduction, ending malnutrition, gender equality and ecosystem service provision (FAO 2018). For example, the cereal-based diets of poor people in LMICs regularly lack bioavailable (micro)nutrients, which are highly concentrated in livestock products. Vulnerable groups in LMICs, such as pregnant and lactating women, and children, would benefit from more, and not less, ASF consumption to improve physical and cognitive health, and reduce stunting (Gupta 2016, Adesogan *et al* 2020, Shapiro *et al* 2019). In this perspective paper, we present results from novel analysis that demonstrate the urgent need for LMIC-specific evidence on livestock and the environment to inform a more nuanced global discussion and decision-making supporting sustainable livestock development.

2. Research into sustainable livestock development in LMICs is scarce

We conducted a systematic literature search in the Web of Science to take stock of the global distribution of research on livestock and the environment (figure 1). We complemented this with an expert survey with 260 respondents to explore global perceptions of environmental impacts of livestock, and available solutions (figure 2). Please see supplementary information for a detailed description of data collection and analysis methods of the literature search and expert survey (available online at (stacks.iop.org/ERL/16/011001/mmedia)). While we acknowledge that the livestock sector has complex interactions with more than half of the UN sustainable development goals (Mehrabi *et al* 2020),

our analysis focusses on the environmental dimensions of sustainability. Results suggest that the existing body of published articles from LMICs is limited. For example, only 12.7% of all global published livestock papers since 1945 cover Africa (figure 1), although Africa is home to 20%, 27% and 32% of the global cattle, sheep and goat populations (Gilbert *et al* 2018). After an upsurge of publications in the late 1960s, likely influenced by the green revolution and the subsequent belief that new animal research in Africa could produce gains like those achieved in rice and wheat (McIntire and Grace 2020), the annual number of published livestock papers in Africa has dropped again since the 1990s (figure 1(a)). This drop coincided with the Rio Earth Summit in 1992 and the publication of the FAO's Livestock's Long Shadow in 2006 that both put environmental impacts of agriculture, and especially livestock, at the center of attention. Eight of the top ten lead institutions of publications on livestock in Africa since 1945 are based in the USA, France, UK and the Netherlands, with only two institutions (ILRI and University of Pretoria) having headquarters in Africa (figure 1(b)). Moreover, a comparison of the number of livestock papers per country in relation to the importance of livestock for the respective national economies reveals a crucial disconnect. Countries such as USA and Canada, Germany, France and South Africa have relatively more publications than countries like Chad, Mali and Somalia, where the livestock sector is the backbone of the economy (figure 1(c)). At the same time, livestock research receives only about 0.1% of all overseas development assistance, compared to the 4% that agricultural research receives (ILRI unpublished analysis from <http://stats.oecd.org>).

Thus, livestock production is a driver of climate change but also contributes to other environmental impacts such as changes in water availability and quality, soil and land degradation and biodiversity loss (Herrero *et al* 2015). 91% of responding livestock experts acknowledged such environmental impacts of livestock as crucial. Yet, only a comparably small fraction (15.8%) of the total global livestock literature published since 1945 is devoted to environmental aspects (figure 1(d)). In Africa, the overall percentage is even lower at 13.8%, although a trend is visible with the percentage of environmental publications at its lowest in 1966 (6.4%) and peaking in 2018 (31.9%) (figure 1(a)). Of the global literature covering livestock, 6% cover water, 5.9% soil and land degradation, and 3.6% each biodiversity and climate change issues (figure 1(d)). These percentages are only slightly lower within Africa (water 5.8%, soil and land degradation 5.9%, biodiversity 3.5%, GHG 2.7%) but higher in Latin America and the Caribbean (water 9.2%, soil and land degradation 13%, biodiversity 7%, GHG 4.4%). The surveyed experts agreed with the importance of these multiple environmental dimensions, with the most emphasis overall given to

land degradation and land use, water use, and GHG emissions, but regional differences were striking (figure 2(a)). In Africa, soil and land degradation, followed by land use, ranked highest, closely followed by competition for water and attributing only a smaller importance to GHG emissions. Experts working in Europe prioritized GHG emissions, and after that water pollution, as the most crucial environmental impacts of livestock. In South America, land-related impacts including land degradation, land use and soil organic carbon loss were ranked highest (figure 2(a)). These results point to the need for context-specific research that is driven by local priorities.

As shown, only a small part of the global research on livestock and the environment covers LMICs, or comes from LMICs directly (figure 1). A recently growing interest in agroecological livestock farming and circularity in high income countries (HICs) (e.g. Dumont *et al* 2018) might trigger interest in transferring insights from diversified mixed crop-livestock systems in LMICs to HICs. However, currently research relies on data, approaches and models that originate from industrialized systems in HICs, where agroecological conditions are different and agricultural systems are typically input- and resource-intensive and well connected to global supply chains. This may lead to incorrect conclusions on current environmental impacts as well as recommendations for improvements that do not match local demands and conditions in LMICs. We illustrate this with four examples across the environmental dimensions.

Global modeling studies estimate that the GHG intensities of livestock products in LMICs are one to two magnitudes higher than those of livestock products produced in OECD countries due to lower productivity (Herrero *et al* 2013b). Despite inherent uncertainties of such global assessments, amplified by the lack of LMIC-specific data, the conclusion that GHG emissions from livestock systems in LMICs are higher remains unchallenged. Empirically measured and experimental data on livestock's GHG emissions for Africa has only recently started to become available (e.g. Du Toit *et al* 2013a, 2013b, Pelster *et al* 2016, Goopy *et al* 2018, 2020, Ndung'u *et al* 2019, Zhu *et al* 2019, 2020). The intensities measured in these studies vary significantly from the global model results due to the diversity of production systems. Missing experimental data on feed quality and quantity effects on ruminant methane emissions and uncertainties around GHG emissions associated with manure management and excreta droppings on rangeland further hamper the identification and quantification of opportunities to mitigate GHG emission from livestock production strategies, e.g. by improved feeding strategies (Goopy *et al* 2020) or manure management (Teenstra *et al* 2015). LMICs still offer greater opportunities for synergies between much-needed productivity increases, efficiency gains and GHG emission mitigation than in industrialized systems where

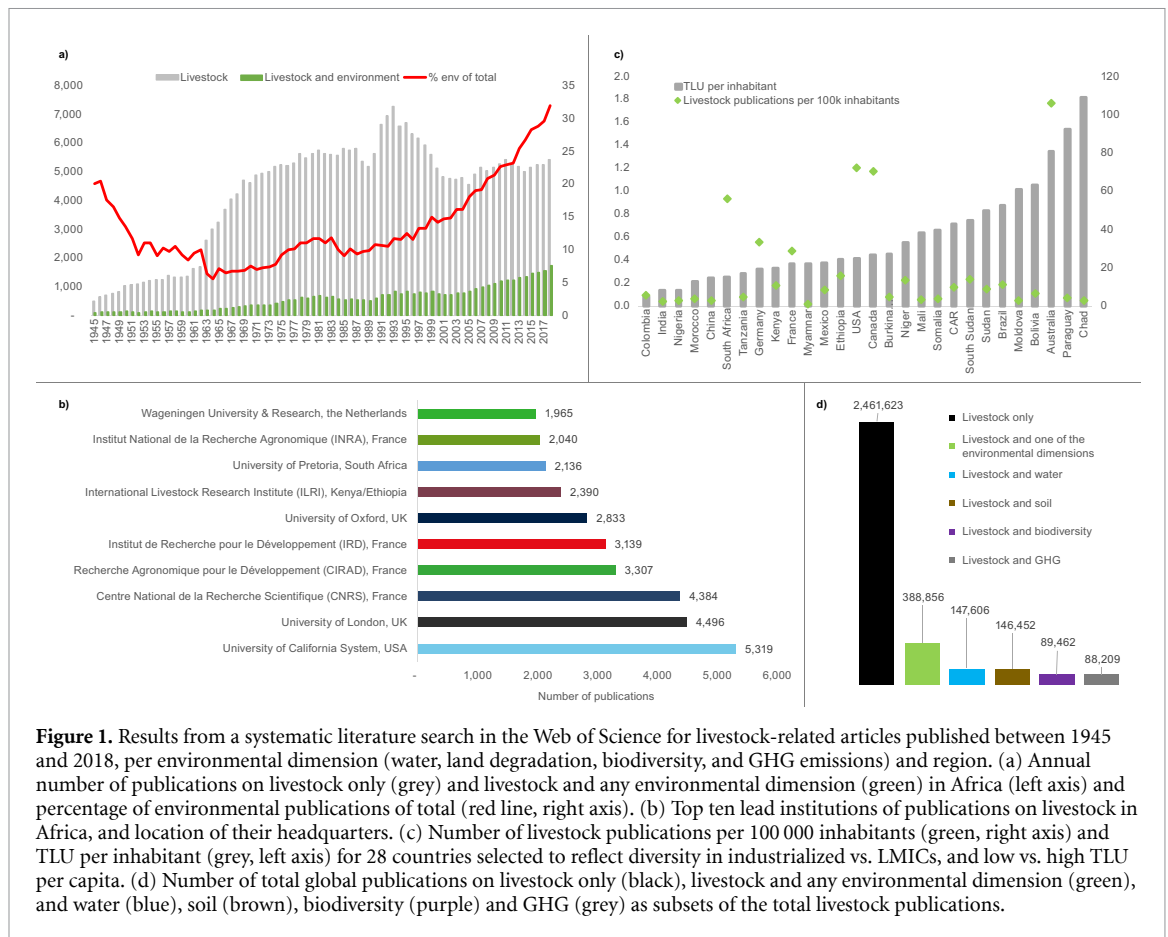


Figure 1. Results from a systematic literature search in the Web of Science for livestock-related articles published between 1945 and 2018, per environmental dimension (water, land degradation, biodiversity, and GHG emissions) and region. (a) Annual number of publications on livestock only (grey) and livestock and any environmental dimension (green) in Africa (left axis) and percentage of environmental publications of total (red line, right axis). (b) Top ten lead institutions of publications on livestock in Africa. (c) Number of livestock publications per 100 000 inhabitants (green, right axis) and TLU per inhabitant (grey, left axis) for 28 countries selected to reflect diversity in industrialized vs. LMICs, and low vs. high TLU per capita. (d) Number of total global publications on livestock only (black), livestock and any environmental dimension (green), and water (blue), soil (brown), biodiversity (purple) and GHG (grey) as subsets of the total livestock publications.

additional measures often result in trade-offs (FAO 2017), but the lack of LMIC-specific data and models hinder the quantification and subsequent leveraging of such opportunities.

Global research on livestock often focuses on the negative impacts on soil, land, water and climate. One of the most prominent impacts of livestock production on the environment in industrialized systems is increased losses of reactive nitrogen (N_r) compounds to the environment, especially through manure management and application. These have multiple negative impacts on human health (aerosol formation due to NH_3 volatilization), soils (acidification due to N_r deposition of NH_3), terrestrial and aquatic ecosystems (eutrophication through N_r leaching, and N_r volatilization and redeposition) (e.g. Heathwaite *et al* 2000, Liu *et al* 2017), tropospheric O_3 (oxidized N compounds in form of NO_x) and GHG emissions (atmospheric N_2O) (e.g. Liu *et al* 2017). The complexity of N_r effects on the global environment has only recently started to be assessed from a holistic point of view in Europe (Sutton *et al* 2011), California (Tomich *et al* 2015) and India (Abrol *et al* 2017), with other countries and regions starting to follow. However, again it is important to consider the farming context: while in industrialized agriculture, high nutrient inputs to soils, including from manure application, are driving water pollution and GHG emissions, undersupply of nutrients through

scarcity of manure and unaffordability of mineral fertilizer is often the bigger problem in LMICs. LMIC-relevant research from China suggests that management is key to minimizing this impact (e.g. Zhao *et al* 2019). While (over)grazing and feed/biomass removal can indeed deplete soil stocks (Mcsherry and Ritchie 2013), manure application to soils is a missed opportunity to improve soil fertility and health and to mitigate these potentially negative impacts. Overgrazing can result in structural and chemical soil degradation, but well-managed grazing can stimulate ecosystem service delivery through vegetation growth and preserve carbon stocks (FAO 2018, Godde *et al* 2018).

Experts' water-related concerns differ strongly by region, with water pollution ranked second in importance by European experts, and competition for water ranked highly by African, Latin American and Caribbean experts (figure 2). Water-related livestock literature often emphasizes the water-intensity of the sector. Heinke *et al* (2020), for example, estimate that annually 4670 km³ of water is used for the production of livestock, and state that this equals about 44% of total water use for agriculture, with agriculture being responsible for 70% of global water use. Most of the total livestock water footprint (98%) is used to produce feed for the animals (Mekonnen and Hoekstra 2010). Water use, however, differs significantly by production system.

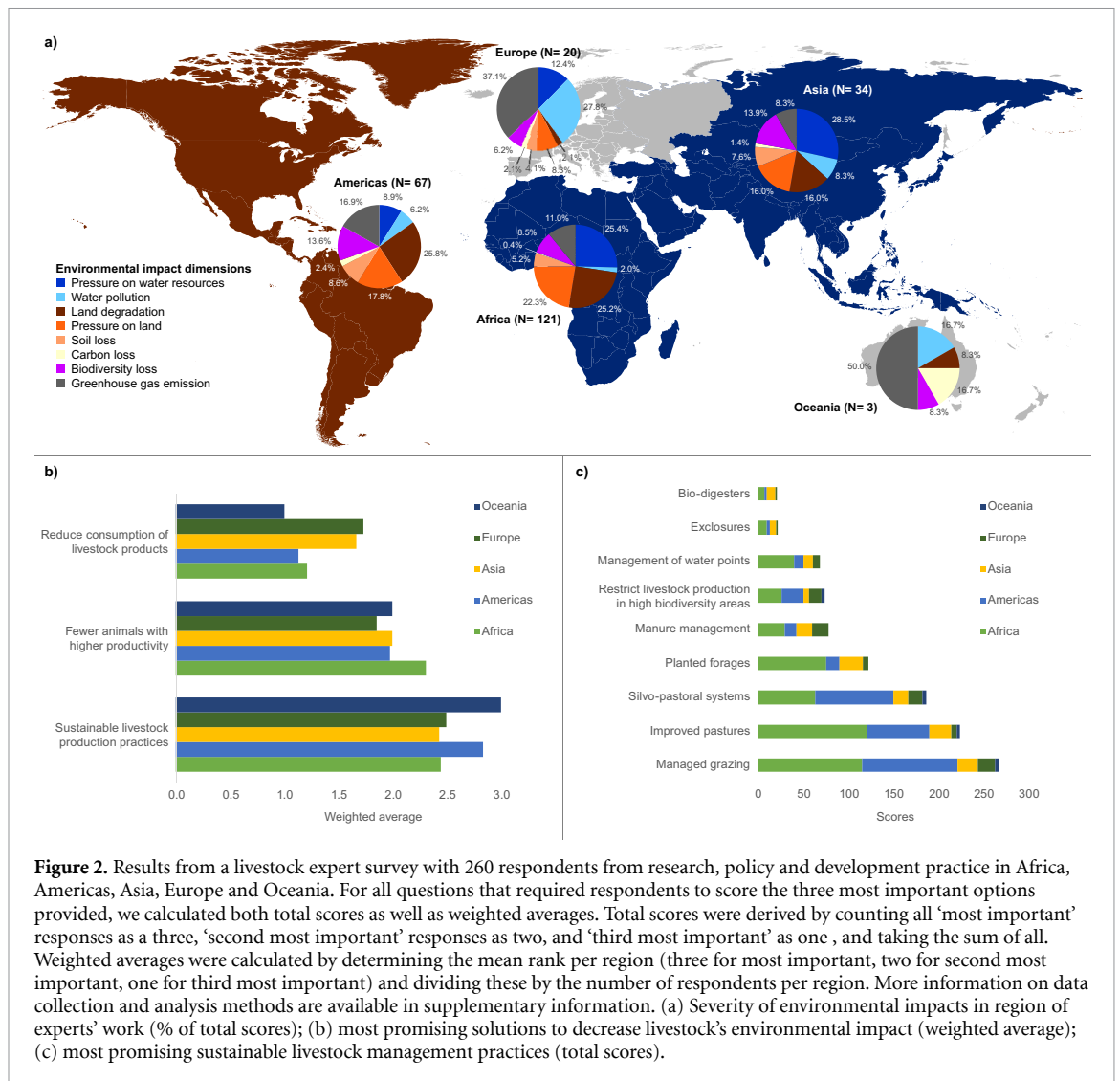


Figure 2. Results from a livestock expert survey with 260 respondents from research, policy and development practice in Africa, Americas, Asia, Europe and Oceania. For all questions that required respondents to score the three most important options provided, we calculated both total scores as well as weighted averages. Total scores were derived by counting all 'most important' responses as a three, 'second most important' responses as two, and 'third most important' as one, and taking the sum of all. Weighted averages were calculated by determining the mean rank per region (three for most important, two for second most important, one for third most important) and dividing these by the number of respondents per region. More information on data collection and analysis methods are available in supplementary information. (a) Severity of environmental impacts in region of experts' work (% of total scores); (b) most promising solutions to decrease livestock's environmental impact (weighted average); (c) most promising sustainable livestock management practices (total scores).

Due to the larger share of concentrate feed in industrial systems, animal products from these systems generally consume and pollute more ground- and surface-water resources than animal products from grazing or mixed systems (Mekonnen and Hoekstra 2012). Moreover, in mixed crop-livestock production systems, which are very prominent in LMICs, the majority of water use is embedded in crop residues of food crops (Zonderland-Thomassen *et al* 2014). Animal farming puts the lowest pressure on freshwater systems when dominantly based on crop residues, waste and roughages (Mekonnen and Hoekstra 2012). Blümmel *et al* (2014) further advice to combine feed resource databases with crop-soil meteorological data to calculate more precise water use efficiency at the smallest possible spatial scale as a basis for mainstream locally relevant recommendations.

In some contexts, livestock production is jeopardizing biodiversity not only due to the conversion of forest to pastures or arable land for feed production (Gordon 2018, IPBES 2019, Creutzig *et al* 2019), but

also due to indirect effects caused by environmental losses of N and P via hydrological and gaseous pathways. These losses drive ecosystem eutrophication and thus large scale changes in ecosystem functioning and biodiversity not only in temperate regions but also in the tropics (e.g. Bleeker *et al* 2014). However, in tropical rangelands livestock production can be compatible with vegetative and wildlife diversity (Russell, 2018), if supportive institutions and incentives are in place to protect mobility and avoid fragmentation (Reid *et al* 2016). In savanna systems, pastoralists are penning their herds at night. That lead to nutrient and biodiversity hotspots, which contributed significantly to the enrichment and diversification of African savanna landscapes (Marshall *et al* 2018). Moderate grazing is important for vegetation diversity, for example (Godde *et al* 2018). More detailed research and experience sharing is required to improve our understanding of the conditions under which these 'pastoralism and biodiversity' synergies can be practically realized on the ground (Notenbaert *et al* 2012).

3. Solutions exist but their implementation at scale is hampered

The majority of experts (63%) believed more sustainable livestock production practices (see examples below) were the most promising area of solutions to reducing livestock's environmental impact, much more than, for example, reducing consumption of ASF. These perceptions had remarkably few regional differences (figure 2(b)). Preferred technologies centered around improved grazing and feeding practices, including managed grazing, improved pastures, silvopastoral systems and planted forages (figure 2(c)). Solutions and innovations exist, but these have yet to go to scale due to constraints such as poor governance, lack of access to knowledge and funding, and lack of institutional cooperation. A less cited reason was high resource demands including labour requirements, high costs and access to inputs (data not shown).

Three examples across LMICs illustrate the availability of solutions but highlight the factors that hamper them going to scale.

Community-based rangeland management in East Africa has been piloted and promoted across Kenya, Tanzania and Ethiopia during the past decade (Flintan *et al* 2019). Central to the approach is the participation of community members in agreeing on governance and management plans for communally managed lands, to avoid conflicts and ensure that livestock have sufficient feed and water resources during the dry season or droughts. Just ensuring community agreement is not enough, however, as rangelands extend beyond community boundaries. Thus, it is important for the community agreements to be embedded in higher level (district, county, national) agreements (Nganga *et al* 2019). In Kenya, community land use plans are now part of county spatial planning processes; in Ethiopia and Tanzania similar processes are underway. Once the governance arrangements are set, then small experiments with setting aside grazing areas or reseeded degraded pastures can begin.

Intensification of the dairy sector in East Africa, e.g. by improved livestock management including feeding, feed preservation, breeding or herd management, provides many opportunities to significantly reduce the GHG footprint of livestock products (e.g. Goopy *et al* 2020). However, only a few of these solutions have been explored or promoted extensively. With experimental data on potential GHG emission reductions due to intensification only becoming available now (see section 2), country-specific emission factors (IPCC Tier 2 approach) can be calculated and used to plan and report on potential and actual GHG reduction gains, which can in turn leverage increased investment (e.g. through NDCs) in the large-scale promotion of such technologies. For example, in Kenya, a nationally appropriate

mitigation action for the dairy sector has been under development for several years, with support from the agricultural research community. Countries such as Colombia and Costa Rica have made progress with livestock-related initiatives to reduce emissions, also due to the availability of data from research partners (e.g. De Pinto *et al* 2018). These examples point to the need for embedding research in local development and capacity building processes, and provide appropriate finance mechanisms, in order to be institutionalized and have long-lasting impacts.

Over the last decade, participatory research in South-East Asia resulted in the identification of promising species and varieties of improved planted forages (Stür *et al* 2013). Such improved forages do not only increase livestock productivity, but also improve nutrient management and cycling (Epper *et al* 2020) and reduce GHG intensities when compared to commercial concentrates often produced abroad and imported (Birnholtz *et al* 2017). However, a lack of investment in scaling these technologies provides no counterweight to a rapidly developing livestock sector in the region that by now heavily relies on feed imports, for example in Vietnam. Concentrate feeds, such as those produced from soybean from the Amazon, result in serious environmental problems due to changes in local and global nutrient cycles in both the livestock and feed producing countries. For improved forages to go to scale, stakeholders need to work together to make seeds commercially available, which requires policy regulation and private sector investment.

4. Conclusions

In many LMICs, there is still an opportunity to develop sustainable livestock development pathways that avoid the pitfalls of the industrial model. Such pathways can support positive nutritional and livelihood outcomes for the global poor while reducing environmental impacts and supporting ecosystem service delivery.

The prevailing narrative on livestock with its singular focus on the negative environmental impacts of the livestock sector, however, fails to take livestock's crucial livelihood functions into account, nor does it highlight the myriad of locally-adapted options for improving its environmental performance. More nuanced global discussion and decision-making, supported with rigorous evidence from LMICs, is urgently needed. Current levels of investment in research for sustainable livestock development in LMICs are insufficient.

We specifically call for locally-adapted, multidisciplinary and people-centered research that is embedded in local development processes. Solutions, such as improved feed production, utilization and storage, and integrated manure management, are emerging and provide a promising avenue to reduce

environmental impacts, but need context-specific research to tailor them to the agroecological and socioeconomic environments. Moreover, research needs to be accompanied by appropriate financial incentives, institutional settings and capacity building of involved stakeholders. It is only when all these factors are in place that we will be able to support sustainable and resilient livestock development pathways and reach long term impact at scale.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: (<https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/CDVOJ1>) (Paul et al 2020)

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