Advanced Review

Re-framing the climate change debate in the livestock sector: mitigation and adaptation options

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Livestock play a key role in the climate change debate. As with crop-based agriculture, the sector is both a net greenhouse gas emitter and vulnerable to climate change. At the same time, it is an essential food source for millions of people worldwide, with other functions apart from food security such as savings and insurance. By comparison with crop-based agriculture, the interactions of livestock and climate change have been much less studied. The debate around livestock is confusing due to the coexistence of multiple livestock farming systems with differing functions for humans, greenhouse gas (GHG) emission profiles and different characteristics and boundary issues in their measurement, which are often pooled together. Consequently, the diversity of livestock farming systems and their functions to human systems are poorly represented and the role of the livestock sector in the climate change debate has not been adequately addressed. In this article, building upon the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 5AR) findings, we review recent literature on livestock and climate change so as better to include this diversity in the adaptation and mitigation debate around livestock systems. For comparative purposes we use the same categories of managerial, technical, behavioral and policy-related action to organize both mitigation and adaptation options. We conclude that different livestock systems provide different functions to different human systems and require different strategies, so they cannot readily be pooled together. We also observe that, for the different livestock systems, several win-win strategies exist that effectively tackle both mitigation and adaptation options as well as food security.

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INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report deals with the role of livestock in delivering food security in future food systems and sustainable livelihoods (through its Working Group 2 on Impacts, Adaptation and Vulnerability), and in the degree that it contributes to climate change via net emissions (through its Working Group 3 on Mitigation). Livestock farming and climate change interact in several domains: livestock emit greenhouse gases (GHGs), farming practices can also contribute to GHG sequestration, livestock farming can generate products that substitute for fossil fuels, and livestock systems are impacted by climate change, are vulnerable to it and will need to adapt to it, all to different degrees. However, the

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IPCC Fifth Assessment clearly states that the different intersections of climate change with livestock systems, despite being crucial, are still relatively understudied research areas.[1]

Agreement exists on the multiple functions of livestock in different contexts. The livestock sector plays a crucial role in global food security, supplying between 13% and 17% of calories and between 28% and 33% of protein consumption, globally.[2,3] Livestock farming in developing countries, especially that of small-scale farmers, is characterized by the provision of multiple benefits, such as improving livelihoods for the rural poor, being a source of direct nutrition, draught power, fertilization, household fuel, fibre, wealth storage, social status, cultural identity, control of insects and weeds, and as a buffer against crop failure.[4–8] The benefits of animal-sourced protein to poor people are particularly relevant.[9–12] In industrialized countries by contrast, livestock production is more likely to be carried out by large-scale enterprises structured to produce single commodities, generally meat or milk.

The supply of goods and services provided by livestock has been accompanied by the ongoing use and in some cases degradation of natural resources. It is estimated that 26% of the world's ice-free terrestrial area is devoted to pasture and 33% of cropland is used for feed crop production.[5] The livestock sector accounts for 80% of the agricultural land[13] and 8% of human water use, mostly for irrigation of feed crops.[14] Also, humans appropriate 24% of world's potential net primary productivity[15] of which 58% is devoted to livestock farming.[16] This high level of global activity is particularly reflected in high levels of GHG emissions. A total of 80% of the agricultural non-CO_2 emissions are due to livestock[17] while the livestock sector has been estimated to contribute between 9 and 25% of anthropogenic emissions.[13,18–23] Assuming that GHG emissions are expected to increase worldwide in the years to come,[18,24] it is of crucial importance to examine under what conditions the livestock sector can best contribute to reduce net emissions. In addition, we need to consider that the livestock sector is vulnerable to climate changes and will need to adapt to them. In examples of vulnerable human groups in rural areas highlighted in IPCC AR5 WGII, two were livestock dependent—pastoralists and mountain farmers.[25] Potential adaptation strategies have been identified, but even if fully implemented, there is likely to be considerable residual vulnerability and so further adaptations will need to be developed.

Thus, the livestock sector will be bound up in a nexus of augmented shocks and uncertainties, and acts both as a driver and recipient of these, with uncertain implications. Responses to these reflect sometimes polarised value systems (e.g., in relation to meat consumption), leading to significant public debates as to the best pathway forward (e.g., Refs 26,27). This is made more complex by the coexistence of multiple systems of livestock farming with differing GHG emissions and different characteristics and boundary issues in their measurement, which, however, are often pooled together. Consequently, the diversity of livestock farming systems is poorly represented and the role of the livestock sector in the climate change debate has not been adequately addressed, which is a major omission since distinct livestock systems involve diverse interactions between livestock, population, climate and natural resources.

A large body of work[28–33] already notes the importance of differentiating between livestock production systems, suggesting that this differentiation is a necessity in the evaluation of different technology and policy options. It is important to consider that the existence of different livestock systems is the outcome of the different functions played by livestock in different human systems in a variety of contexts. For instance, large industrial systems are in play in the United States because the function of livestock production is mainly as a competitive corporate business activity, and there is little demand today for livestock in the United States to play the same role as they do in Africa (as repositories of savings, providers of unspoiled milk to the family, a source of income in the non-cropping season, etc.). It is important to consider this in addressing strategies for action in different regions.

In order to illustrate the need to consider the existing diversity of livestock farming systems and shed light on the interactions between climate change, livestock and human systems, we employ the broad classification proposed by Thornton et al.[28] and Kurska et al.,[29] based on Seré and Steinfeld.[34] This classification system has been used widely for poverty mapping[28]; animal health targeting[35]; climate change impacts and vulnerability[30,36]; and the assessment of environmental impacts[22,32,37–41] amongst others.[33] It comprises three general types of livestock system, namely: grazing, mixed crop-livestock, and industrial systems (Table 1). Even though these systems grossly simplify the existing diversity, the use of this accepted classification allows us to maximize data availability and reframe recent findings. We will show in this paper that distinctions between the systems entail radically different interactions with people and climate change.

TABLE 1 | Characterization of Livestock Farming Systems

	Grazing System	Mixed Crop-Livestock System	Industrial System
People	Pastoralism engages 120/190 million people[42,43]	Involves ~2/3 of the world population. Main system for smallholder farmers in developing countries[44]	Relatively small numbers of people, often highly skilled
Purpose	Traditional grazing systems are sources of food, income, waste recycling, fibre, lending, status, social and cultural identity, and insurance against hard times. Large-scale private ranching systems are geared to extensive meat production for sale.	Source of food, income, fertilization and manure, and draught power.	Source of food, income. 90% of the value of livestock attributed to marketed outputs[45]
Modalities	• Mobile systems on communal grasslands • Sedentary systems on communal grasslands • Ranching and grassland farming	• Mixed, communal grazing • Mixed, crop residues • Mixed, cut and carry • Mixed, feed from farm • Mixed, external feed	• Intensive poultry production • Intensive pig production • Ruminant feedlot meat production • Large-scale dairy production often in grain-producing regions or near to urban centers
Location	In lands that are too wet, dry, mountainous, distant or stony for cultivation, and where grassland and fodder production sustain large herds. In Arid, Semi-Arid, Sub-Humid zones and Temperate and Tropical Highlands	Near sources of crops and by-products. In nearly all Agro Ecological Zones: from rainforests to oases in arid zones.	Often near large urban centers or transport systems. More or less independent of the agro-ecological zone, of special relevance in Europe, North America, and some parts of Latin America, the Near East, and East and Southeast Asia
Feed Source	Dependent on the natural productivity of grasslands. Convert human-inedible forage and rangelands into edible animal source food.	Use of crop residues and permanent crop cultivation. Scarce reliance on external feed (if any). Convert human-inedible self-produced residues into edible animal source food.	Concentrated animal feeding operations. Depend on external feed (grains, industrial by-products). Can convert human-edible purchased products into edible animal source food.
Human edible protein Output/ Input	Some examples: Kenya, 21.16; Mongolia, 14.60[3]	An example: New Zealand, 10.06[3]	Some examples: Brazil, 1.17; Germany, 0.62; USA, 0.53[3]
Land and tenure	Rangelands including communal and open-access grasslands. Low infrastructure.	Communal and private high-quality grasslands and fodder crops and crop residues. Moderate infrastructure.	Relatively small areas. Large infrastructure development.
Input nature	Little or minimal dependence from purchased feed and external inputs. In usual conditions, 0 kg of external feed per kg of meat.[46] 12,000 l of water per kg of edible beef in ranching[14]	Dependent on system and land tenure. Inputs range from small to significant. 42 l water per pig/day (drinking and service)[46]	Dependent on purchased feedstuffs. Estimate 8 kg of feed per kg of beef, 4 kg for pork, 1 kg for broiler[46] 53,200 l of water per kg of edible beef.[14] 142 l water pig/ day (drinking and service)[46]
World food production	24% beef, 32% sheep & goat meat, 1% pork, 2% poultry meat and 1% of eggs.[32] Provides 9% global meat[47]	69% milk & 61% of meat from ruminants,[40] 38% of eggs.[32] Provides 54% global meat.[47]	Provides 76% pork & 79% of poultry meat,[40] 61% eggs, 6% beef, 1% of sheep & goat meat[32]
Genetic diversity	86% (6536) and 7% (523) of the 7616 recorded breeds are local and regional transboundary breeds, respectively[45]		7% (557) of the breeds are international transboundary[45]

LIVESTOCK SYSTEMS AND CLIMATE CHANGE MITIGATION

Livestock and GHG Emission Metrics

The livestock sector contributes to GHG emissions through the emission of methane (CH_4), largely from enteric fermentation; nitrous oxide (N_2O), from manure and the use of nitrogenous fertilizers in growing feed; and carbon dioxide (CO_2), from fossil fuel burning, land use change driven by agricultural expansion and reductions in soil carbon in some circumstances. Estimates of the GHG emissions from livestock differ according to the system boundaries established for calculation. Emissions can be classified as direct, if they are produced on- farm by the animal (e.g., enteric fermentation), or during the rearing process (e.g., manure), and indirect, if they are produced pre-farm by associated industries (e.g., nitrogenous fertilizers in growing feed or associated land use changes). The range of estimates of global GHG emissions attributable to livestock is large, ranging from 9 to 25% of total emissions,[13,18–23] with differences mainly due to different calculation methods and whether or not indirect emissions are considered in the equations. In presenting emissions we also need to differentiate between absolute and efficiency measures as these can lead to different outcomes. For example, a livestock system might improve its efficiency parameter (e.g., emissions per unit product), even though its absolute parameter (total emissions) increases. Absolute emission metrics are important in terms of addressing the global commons issue of mitigating GHG emissions whereas efficiency metrics are most relevant to financial and other livestock system performance measures.

The most common method to determine GHG emission relates to the volume of CO_2-equivalents which integrates the effects of the multiple greenhouse gases which may be produced (or removed) by livestock systems (e.g., Ref 48). This absolute measure is fundamental to setting emission limits and emission-reduction goals for the UNFCCC and national policies, as it links livestock activities to the change in composition and function of the atmosphere. But other efficiency-based or rate metrics exist, which can be used to plot pathways to efficient and/or equitable achievement of these goals. These include emissions per hectare, per unit value or per unit livestock product[19,49] or per unit of protein.[50] When expressed in these efficiency terms (e.g., GHG per edible output), the confined operations of industrial livestock systems can appear to directly emit less than grazing and mixed systems, and intensive grazing less than extensive grazing.[51] In contrast, when the method of calculation takes into consideration the direct and indirect amounts of resources used as inputs by the livestock system (e.g., land, kg of fossil fuels), mixed systems, through livestock and cropland integration, and extensive grazing systems, through moving the herd opportunistically and benefiting from the natural productivity of grasslands, can show smaller GHG emissions than the confined and sedentary operations of 'industrial' livestock systems.[52] The different metrics employed therefore affect the outcome of the analysis and the GHG emission responsibility attributed to diverse livestock systems and thus, they provide different data to inform policy-makers and the broader pubic debate.

Nonetheless, several general omissions are identified in the literature. Firstly, to give the clearest picture, the measurement of the GHG emissions should relate to the whole life cycle of the livestock product, including the feed footprint, since obviously emissions occur throughout the production and distribution phases of feed inputs.[23,27,53] Secondly, not only the quantity but also the quality of the resources used by livestock farming should be integrated into the calculation. The same quantity of GHG emissions from using human-edible grain to feed the animals, or from wastes and pastures of marginal lands, should be accounted for in a consistent way but differentiated so as to deal with it explicitly in nutrition security policy design and implementation. Also, other environmental and social costs and benefits can be included in the calculation, such as the value of the non-monetized economic activities, the subsistence function of grazing and mixed systems, which provide valuable nutrition to the poor as well as of unique livelihood in areas characterized by pastoralism and extensive grazing where a lack of alternative livelihood opportunities exist, and the value of preserving the health of ecosystems.[54,55] According to Ripoll-Bosch et al.[56] when accounting for the multifunctionality of livestock systems, considering multiple-outputs and allocating the GHG emissions to the diverse outputs on their relative economic value, grazing systems emit less GHG emissions per unit of livestock product (CO_2-eq/kg of lamb live weight in that case) than mixed-grazing systems, and those in turn have lower emissions than industrial systems. There are additional grounds for speculation over whether grazing areas without domestic livestock might be repopulated with methane-producing wild ungulates.[52,57] A useful change would be to see GHG mitigation as one variable in considering policy and management in changes to livestock systems.

Livestock and Mitigation Potential

The main strategies described to reduce GHG emission and to increase GHG sequestration by the livestock sector can be divided into supply- and demand-side strategies. While the former have been better studied than the latter[58] clearly no measure in isolation will encompass the full emission reduction potential (e.g., Ref 27). Instead, a combination will be required, selected from the full range of existing options, as adapted to different livestock systems and their functions according to geographical, social and institutional contexts. In this article, we sub-divide supply and demand-driven mitigation strategies into managerial, technological, policy-related and behavioral (Table 2).

SUPPLY-SIDE Mitigation Strategies

Supply-side strategies refer to the actions directly related to animal production at the farming level. These include managerial, technological and policy-related options. **Managerial** mitigation strategies in the livestock sector fundamentally comprise (1) improved energy and nutrient utilization on land, through management of land, grazing, vegetation, water, and fire; (2) improved productivity, through capital and labor intensification; and (3) improved energy conversion in livestock, through appropriate breeding, health and feeding, which also include **technological** strategies; **Policy-related** options include both (4) market mechanisms, through GHG emission trading systems and GHG footprint labeling (including sequestration activities); and (5) enhancing the production and use of alternative fuels, through recycling livestock waste into biogas.[58–63]

Improved Nutrient and Carbon Cycling on Land

The control of land degradation and deforestation, and regulating the use of fertilizer inputs for feed production, are the main issues when dealing with the enhancing of nutrient cycling on land. Deforestation prevention is one of the most developed GHG mitigation policies.[64] Land degradation and deforestation are associated with overgrazing,[65] with conversion of forests into pastures for ranching in grazing systems,[60] and with land clearing for feed production in industrial systems.[66,67] Conversion of forests into croplands and pastures, and grassland degradation, result in carbon losses which work against any mitigation from soil carbon sequestration.[68,69] Soil carbon is often lost more rapidly than it is gained.[70] In fact, deforestation, either to open new pasture or to create new cropland for feed production, is calculated to release more CO_2 than any other livestock-related activity.[60] A total of 4% of anthropogenic

TABLE 2 | Livestock Farming Systems and Climate Change Mitigation

	Grazing System	Mixed Crop-Livestock System	Industrial System
GHG emissions (examples)	27–31 kg of CH_4 per animal per year in grazing cattle in Africa and India[46] 12% total non-CO_2 emissions[40]	53–60 kg of CH_4 per animal per year in beef & dairy cattle in USA and Europe; 45–58 kg of CH_4 per animal per year in dairy cattle in Africa and India.[46] 77% emissions from cattle (not all mixed crop-livestock)[40]	117–128 kg of CH_4 per animal per year in dairy cattle in USA and Europe[46] 10% total non-CO_2 emissions from monogastric (not all industrial)[40]
GHG emission metrics giving the most favorable outcome	Area (kg CO_2eq/area of land); resource based (kg CO_2eq/kg of fossil fuel based inputs; kg edible output/quantity of ecosystem services provided; kg CO_2eq. avoided by use of marginal land).[52]	Quantity based (e.g., kg CO_2eq./kg food and non-food goods—leather, wool, manure, traction, etc.)[52]	Quantity based (e.g., kg CO_2eq/kg produce)[52]
Mitigation assets	Grazing responsive to environmental variation and low dependence on fossil-fuel-based practices and external inputs. Enhanced animal husbandry, GHG sequestration.	Maintenance of soil fertility, low dependence on fossil-fuel based practices and external inputs. Enhanced animal husbandry and herd/flock management, supplements, feed budgets.	Increased productivity and efficiency through better nutrition and genetics, adjusting the growing environment, animal health.

emissions are attributed to land use change and deforestation for livestock production.[32]

Land and soil management is a key mitigation strategy[22] since there is twice as much carbon in the top meter of soil globally as there is in the entire atmosphere.[71] Soil is one of the largest carbon stores globally that can be increased through management.[62] Grasslands are estimated to store up to 30% of the world's soil carbon.[72,73] The carbon sequestration capacity through soil erosion control and soil restoration has been estimated to be between 5 and 15% of global emissions.[74] Soil carbon sequestration potential in global agriculture is estimated to contribute to 89% of the technical mitigation potential.[59] However, the costs of mitigation substantially limit that potential, such that economic potentials are only around one-third of technical mitigation potentials.[59] In both grazing and mixed systems, improved grassland management and appropriate stocking density can help to increase soil C stocks.[75] Other strategies include limiting grazing on seasonally wet soils and adequate management of irrigation in pastures.[20,62,76,77]

The need to efficiently apply fertilizer inputs is widely accepted due to the multiple benefits that accrue. However, this is often driven by an interest in tailoring fertilizer input with a focus on economic benefit, rather than for GHG mitigation. Livestock excreta contain more nutrients than the inorganic fertilizer used annually[32] so consideration of this seems germane. The separation of livestock from land, mainly via the livestock housing of industrial systems, interrupts nutrient flows which triggers soil organic matter depletion in the location of the food source, and often pollution at the point of the housed livestock,[60] while entailing feed production on large areas of cropland with the associated application of inorganic fertilizers and GHG emissions. While the manure from these types of systems deposited on fields and pastures does not usually generate significant amounts of CH_4,[78] the confined rearing and feedlots of the industrial systems release an estimated 18 million tons of CH_4 annually.[32] To further reduce in-house emissions of CH_4 and N_2O in industrial systems, deep cooling of slurry can be a feasible option.[79] In addition to this mitigation potential, and despite the existence of transport, storage and odor issues, it should also be noted that smallholders cannot usually afford inorganic fertilizers.

Improved Nutrient and Energy Cycling in Livestock

The different degrees of inefficiency of animals in nutrient and feed conversion are the main issues when tackling improvement of nutrient cycling in livestock. Both plants and animals are particularly inefficient in nitrogen uptake.[80,81] Practices to reduce N_2O emissions include animal and herd management to improve energy and nutrient balances, such as: (1) reducing the number of unproductive animals; (2) genetic manipulation or animal breeding to improve the N conversion efficiency in the rumen, (3) changes in feed quality and composition, and (4) use of feeding additives, such as condensed tannins, to improve the digestion of amino acids and reducing N excretion, or salt supplementation to induce more frequent urination events and thus a more even spreading of urine across pastures.[20,76,77]

Livestock also show differential performance in feed conversion and associated CH_4 emissions, with the largest difference between ruminants and monogastrics. Thus, given the higher feed conversion efficiency of monogastrics, some GHG mitigation can be achieved by shifting production from ruminants to monogastrics, e.g., chicken, pigs[23,82] or from large to small ruminants. Additionally, taking into account the large potential of ruminants to generate CH_4 emissions *via* enteric fermentation, the following are specific GHG mitigation measures focused on ruminants: (1) improving forage quality, such as forage with lower fibre and higher soluble carbohydrates—changing from C_4 to C_3 grasses; (2) dietary supplements to improve ruminant fibre digestion and productivity and reducing methanogenesis, such as dietary lipids, probiotics, proprionate precursors, enzymes in the form of cellulases or hemicellulases, or condensed tannins and saponins; and (3) manipulations of microbial populations in the rumen to reduce CH_4 production, such as CH_4 inhibitory vaccinations against methanogens or chemical defaunation to eliminate rumen protozoa,[83] although these techniques are still in their infancy or are subeconomic to use.[20,76,84–87] It must be acknowledged too the higher potential of ruminants for non-competition with human food production, since they are able to utilize non-human-edible feedstuff (e.g., grass, shrubs), whereas monogastrics often compete for human-edible food[19] unless they use by-products or waste products, which makes the comparison complex.

Improving Input Capital and Labor Productivity

Enhancing capital and labor productivity to increase yields at the same time as reducing GHG emissions and natural resource use per unit of produce is a goal that is widely being advocated to tackle both food security and climate change.[46,88] Several studies suggest the potential to improve the environmental performance of livestock systems can stem from capital and labor intensification that reduce inputs and GHG emissions per unit of livestock product.[89] For instance, in Europe (EU-12) livestock production increased slightly during the 1990–2002 period, while CH_4 and N_2O emissions were reduced by 8% due to intensification.[90] Similar linkages have been long-established elsewhere (e.g., Australia[91]). However, it is also important to consider other trade-offs. For instance, though it is assumed that the adoption of more productive breeds will result in the keeping of fewer animals and reduced GHG emissions, there may be negative environmental impacts from using more productive breeds, even in lower numbers, for example via an increased use of concentrate feeds rather than the use of crop residues or grazing on nonarable land.[92] Strategies in this category can be implemented for all types of livestock system.

Market Mechanisms

Mitigation strategies based on market mechanisms fundamentally comprise schemes of payment for environmental services for carbon storage and sequestration, such as REDD+, the Joint Implementation or the Clean Development Mechanism under the United Nations Framework Convention on Climate Change. These are mechanisms to provide market-based incentives to manage ecosystems, in this case livestock systems, to reduce GHG emissions. These systems can be used to provide monetary alternatives to GHG emissions. They aim at promoting the protection of the environment, as well as GHG mitigation, while alleviating poverty.[93] Institutional factors are crucial to determine who is involved and who benefits from these schemes.[94] Some studies show that these mechanisms can promote GHG mitigation and improve the livelihood of service providers, *via* the provision of institutional frameworks for management and regulation and through incentives for behavioral change.[95,96] Critics question the appropriateness of these mechanisms for GHG mitigation in relation to: the large transaction costs associated with identifying and working with potential project partners, and ensuring parties accomplish their obligations that might constrain the participation of the communities[97]; the existence of unclear property rights[98]; or the potential alteration of culturally-based conservation values and land development aspirations.[93] These critics are linked to the complexity surrounding diverse stakeholders acting at multiple scales, and being exposed to drivers operating across multiple scales too. The different scales of demand create a complex market, where small and large landowners deal with different costs and interests. For instance, the interests of international businesses can collide with local communities seeking to secure food sovereignty.[99] For an effective implementation of payment for environmental services, it is thus necessary to understand the local institutional context in terms of the characteristics of buyers, sellers, and their relationship.[100] It should also be considered that collecting the required data to calculate the emissions is unlikely to be feasible for most smallholders.[101] It is also important to note that in livestock systems, informational, cultural and institutional drivers can substantially affect the balancing of the grass/forage available with animal intake, and thus become additional costs or barriers to the implementation of mitigation strategies for carbon sequestration. Specifically in rangelands, the low sequestration capacity per unit of area, the consequent large monitoring costs, and unclear or communal land tenure entail costs for carbon sequestration additional to those derived from assessing technical feasibility alone.

Given the increasing importance of international trade of animal products, which accounted for 22% of total livestock-related carbon emissions in 2004,[102] there is an increasing concern regarding the trade-offs inherent in these market mechanisms, if not addressed from a food system perspective. For instance, industrialized countries promoted the REDD+ initiative to reduce forest loss in developing countries, some of which are associated with indirect GHG emissions allocated to livestock for feed production. But as they pay to protect forests, they indirectly drive deforestation *via* consumption of livestock.[103] That is, global drivers, such as consumption and international trade, contribute to deforestation in particular countries, suggesting that market mechanisms targeting the supply-side need to be accompanied by market mechanisms targeting the demand-side if they are to be more efficient, as well as both coherent and fairer. Other market mechanisms linked to demand-side strategies will be discussed below.

Alternative Fuels

The use of alternative fuels, such as recycling livestock waste into biogas by means of anaerobic digesters, is both a policy-related strategy and a technological strategy, aiming to reduce the climate impact of livestock from manure management, while increasing profit and reducing fossil fuel use.[104,105] In industrialized contexts, biogas production through anaerobic digestion can achieve between 50 and 75% reduction in emissions in manure storage systems.[32] In the EU, using manure to produce methane can potentially reduce 57% of supply chain energy use in pig farming.[106] At present, only 1% of global manure is being used to produce biogas.[107] This offers a mitigation opportunity, particularly for the high-livestock-density operations, which can reduce GHG emissions while reducing the cost of waste disposal. Anaerobic digesters, now in use at some large intensive farms, may not always be economically viable for small-scale farms.[108] However, recovering the methane and using it as an energy source alternative to wood, charcoal or fossil fuel could become an option to improve the welfare of smallholder livestock farmers with co-benefits for soil fertility and health while favoring GHG mitigation.[105,109] Flexi-biogas, as developed by IFAD, could be an option.[110]

Oils such as canola and cottonseed can be used to reduce methane emissions from ruminants (while also enhancing production) or for conversion into biofuel (thus substituting for fossil fuels). A recent analysis of which of these two options is the most beneficial in terms of GHG emissions across the production chain suggests that conversion into biofuel reduces net GHG most.[63]

DEMAND-SIDE Strategies

Although most mitigation strategies focus on supply-side and technical solutions, the need to focus on the demand-side is being increasingly recognized.[27,58,62,111,112] That is, if we are to achieve substantial reduction in GHG emissions in the livestock sector, we need to address not only how we raise livestock, but also what, where and how much livestock produce is consumed, in order to develop low-GHG emission diets.[26,27] Demand-side strategies are more general and do not refer to specific production systems but rather to consumption options. Thus, there is a need to take a food systems approach in order to combine the best mitigation options for different livestock systems in different contexts. At the same time, it is important to note that, as currently addressed in the literature, there is more emphasis on industrialized contexts given the overconsumption of animal products and their role in driving deforestation in developing countries. However, we need to consider that most of the present day and likely future changes in consumption patterns occur in developing countries[113] that present completely different issues not well addressed yet. Here, the increased consumption of animal source foods will be beneficial to poor people, involving large numbers of people with very different nutritional issues,[114] so the scope for such solutions may be limited. The **behavioral** modifications of the demand-side mitigation strategies include dietary choices, such as (1) reduction in meat consumption, consumption of animal products with lower net emissions, or a dietary shift from meat to plant-based protein[115,116]; (2) avoidance of food wastage where possible; and (3) reduction of life cycle emissions. Most of these mechanisms require supportive policies to facilitate changes in behavior.

Reduction of Meat Consumption

A number of authors have estimated the mitigation potential of dietary choices.[117,118] For instance, Popp et al.[119] estimate a 24% reduction in global soil N_2O emissions by 2055, if per capita calorific intake increases as a function of increases in GDP, but the share of animal-source foods in this intake is reduced by 25% every 10 years between 2005 and 2055. However, while reduction of livestock consumption may be an acceptable form of mitigation for those in developed countries, or wealthier people elsewhere, it may well be deleterious for the poor. Animal-sourced food offers valuable nutrition for rural poor, both in protein and in micronutrients, particularly for those suffering from malnutrition and during periods of climate stress.[4,10,12] This is why some authors[9,120] suggest that a redistribution of livestock consumption from food surplus to food deficit regions would trigger coupled health and environmental benefits, as well as mitigation gains, although the mechanisms to do this are challenging. To illustrate the potential benefits associated with a reduction in livestock consumption, Westhoek et al.[121] estimated that halving the consumption of animal products in the European Union, which at present consumes 70% more animal protein than recommended by the WHO, would deliver a 40% reduction in nitrogen emissions, 25–40% reduction in GHG emissions and 23% per capita less use of cropland for food production, while at the same time would lead to a reduction in cardiovascular diseases and some cancers. The environmental, health and food security benefits of healthy diets, with reduced livestock content, were also emphasized by Tilman and Clark.[116] In addressing the nutritional contributions of meat to food security, it must be considered that grazing animals often provide higher nutritional quality products than animals raised industrially.[122,123] Taxes and subsidies to favor behavioral modification have recently been proposed[124] and in that manner, mitigation through the promotion of low-emission diets could offer good opportunities for boosting the role of smallholders in the mitigation of climate change.

Food Wastage Reduction

Reduction in food wastage is another behavioral modification that can trigger mitigation gains, particularly concerning GHG-intensive foodstuffs.[125,126] In the United States, food losses contribute 1.4 kg carbon dioxide equivalents (CO_2-eq) per capita per day, that is, 28% of the overall carbon footprint of the average U.S. diet.[127] Similarly, the avoidance of food losses in the consumer phase of milk, poultry meat, pig meat, sheep meat and potatoes in United Kingdom would reduce annual N_2O emissions by at least 2 Gg N_2O-N per year.[117]

Reduction of Life Cycle Emissions

Most strategies in this category look for the reduction of large travel distances and energy costs of refrigeration/preservation.[27,46,120,128–130] The consideration of the indirect GHG emissions associated with grain-based feed production,[131] mostly due to land use change strongly associated with confined ruminant and monogastric operations, can neutralize the difference in GHG emission between monogastric and ruminant livestock when calculated with only feed-conversion efficiency. In line with this, some authors suggest a shift toward the local consumption of livestock produce from grazing and mixed systems as a mitigation option.[132] In contrast with the land-sparing strategy, mixed and grazing systems seek to integrate cropping and grasslands with livestock, reducing GHG emissions through a decrease in nitrogen-fertilizer use and enhancing soil fertility by partially closing nutrient loops, while local consumption of the livestock produce reduces fossil fuel use for transport.[133–135] These strategies fit well with the production conditions of small farmers both in industrialized and developing countries.

Market Mechanisms: Voluntary Standards and Labeling

Market-based mechanisms on the demand-side can mitigate GHG through the development of livestock product standards and labeling, such as the Carbon Reduction Label in United Kingdom, ClimaTop label in Switzerland, or the Carbon Label in France. Product carbon footprint standards are also being increasingly integrated within labels of organic food, such as the Swedish label KRAV. Based on the lessons learned from the development of organic farming, it is suggested that GHG footprint labeling might become a good option for the benefit of smallholders in developed countries.[135] Besides the issue of calculating the emissions, which is likely to be difficult particularly for smallholders and developing countries, there are not only technological issues to be overcome, but also equity and social justice issues between industrialized and impoverished countries.[136]

IMPACTS, VULNERABILITY AND ADAPTATION OF LIVESTOCK SYSTEMS TO CLIMATE CHANGE: THE HUMAN DIMENSION

Climate-change impacts, vulnerability and adaptation options of the livestock sector are multiple, varied and complex[137,138] but in the IPCC 5AR Working Group 2 they were under-represented when compared with cropping systems (Figure 1). In large part, this reflects the relativities of the size of the literature on livestock and climate versus the expansive literature on crops, but it also reflects the lack at the time of global livestock modeling analyses which are only now coming available (e.g., Ref 22) and the paucity of synthetic reviews of the issue. Addressing the impacts, vulnerability and potential adaptation capacity of diverse livestock systems is an important part of global analysis of the risks of climate changes. For instance, grazing and mixed systems involve large numbers of poor people and people at risk of poverty worldwide (Table 1), for whom livestock production accounts directly or indirectly for a significant share of household income and consumption, and for whom there are often no practical alternative livelihoods.[139] Impacts of climate change on these production systems are likely to therefore have more severe impacts on more people than impacts on industrial systems, and possible in these contexts, the only potential adaptation under climate change is to raise livestock.[140]

Observed and Projected Impacts of Climate Change on Livestock Systems

Considering the different dimensions of climate change, impacts can be distinguished between those related to (1) extreme events, such as floods, storms, hurricanes, droughts, and heat waves, and (2) the more gradual changes in the averages of climate-related variables, such as local temperature, rainfall, and its seasonality, sea level rise, and higher atmospheric concentrations of CO_2. Considering causality, impacts can be grouped as (a) direct impacts on animals, such as heat and cold stress, water stress, physical damage during extremes, and (b) indirect impacts, such as modification in the geographical distribution of vector-borne diseases, location, quality

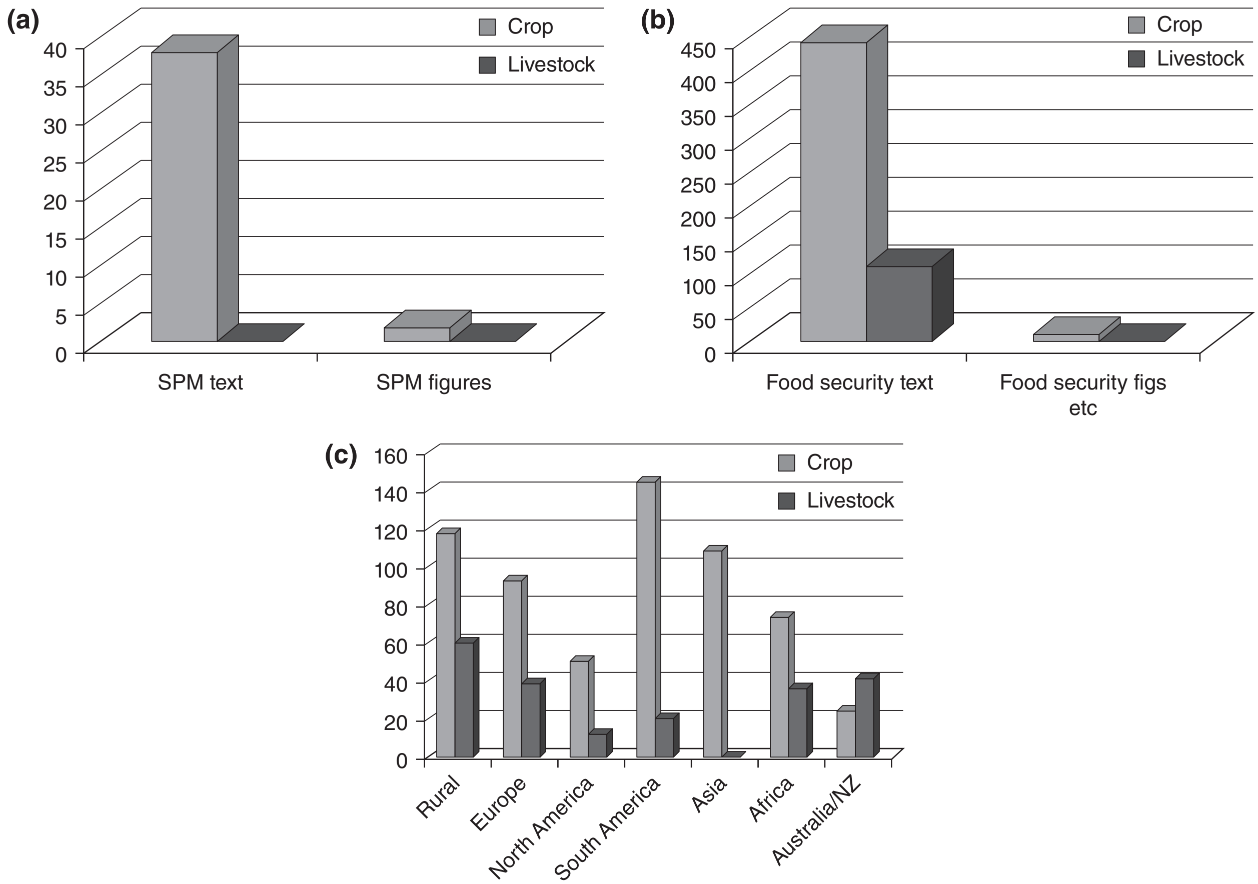

FIGURE 1 | Frequency of appearance of the word and phrases relating to livestock versus cropping systems and their outputs in (a) the Summary for Policymakers, (b) the Food Security chapter and (c) the regional chapters of the IPPC Fifth Assessment Report.

and quantity of feed and water and destruction of livestock farming infrastructures[141] (Table 3). In terms of observed and projected impacts in the literature, they mostly relate to animal feed, whether through impacts on grassland and pastures, or impacts via grain-feed production.[138] From a food systems perspective, other impacts on livestock systems will affect storage infrastructures (both of animal feed and animal products, e.g., milk), processing operations, transport facilities and retailing.[142]

In industrial livestock systems, the most important impacts are expected to be indirect, leading to rises in the costs of water, feeding, housing,[143] transport and the destruction of infrastructure due to extreme events, as well as an increasing volatility of the price of feedstuff which increases the level of uncertainty in production. Given the high costs involved in moving the associated infrastructure, climate change will likely result in increasing effort to isolate the animals from climate influences. When financial returns pass below a context-specific threshold, transformational change via relocation may occur.[144]

The most important direct impacts on mixed livestock systems are linked to increased water and temperature stress on the animals, while indirect impacts are mostly the result of impacts on the feed base, whether pastures or crops, leading to increased variability and sometimes reductions in availability and quality of the feed for the animals. Changes toward breeds with higher heat resistance but lower productivity potential and to fodder bases which are more able to cope with difficult climate conditions may be needed. This may require changes in knowledge base and practice changes. Those mixed systems which are dependent on external infrastructures, such as irrigation infrastructure, may be exposed to increased risk of damage from extreme weather events.

Extensive grazing systems will be more affected by those impacts which significantly alter ecosystem processes, such as changes in the feed base or increased risk of animal diseases.[145,146] As for mixed-systems, direct impacts result from water and temperature stress to the animals potentially leading

TABLE 3 | Some Direct and Indirect Impacts of Climate Change on Livestock in Different Livestock Systems

		Grazing System	Mixed Crop-Livestock System	Industrial System
Direct impact	**Mean climate changes**	• Chronic temperature stress • Water stress • Reduced feed intakes • Decreased production and reproduction of livestock	• Chronic temperature stress • Water stress • Reduced feed intakes • Decreased production and reproduction of livestock	• Decreased production and reproduction of livestock
	Extreme events	• Temperature stress events • Livestock mortality and distress sales	• Temperature stress events • Lowered productivity	• Increased likelihood and severity of heat stress events • Animal morbidity and mortality • Lowered productivity
Indirect impact	**Mean climate changes**	• Variation of the quality, quantity, seasonality and distribution of pasture • Changes in grass/browse cover in rangelands • Increased incidence of livestock pests and disease • Change in disease distributions • Decreased productivity of livestock • Moving to smaller breeds • Increased conflict in pastoral regions	• Variation of the quality and quantity of fodder (stover, pastures) • Increased incidence of livestock pests and disease • Change in disease distributions • Move to lower productivity but higher heat stress resistance breeds • Better conditions for crop weeds and pests • Cropping often favored financially • In dry margins, grazing may increase overcropping	• Increased cost of animal housing • Increased risk of disease epidemics • Increased cost of feed and water • Moving to lower productivity but higher heat stress resistance breeds • Changing enterprise viability due to extra costs • Moving location
	Extreme events	• Pasture shortage • Increased variability in ground-cover • Altered distributions of livestock vectors • Soil erosion and vegetation damage	• Fodder shortage • Damage to standing feed • Negative impacts on livestock managers • Increased costs through insurance • Soil erosion • Destruction of infrastructure	• Increased transport cost • Increased cost of feed and water • Increased volatility of feed supplies and their price • Increased costs through additional insurance • Destruction of infrastructure

Source: Adapted from Refs 31,138,141.

to animal morbidity, mortality and distress sales. Indirect impacts presumably will be more linked to decreasing or changing rangeland productivity[138] and may entail systemic changes such as moves toward smaller breeds or species more tolerant of emerging climate conditions, noting that this often has cultural dimensions as well as financial and knowledge investment implications. Although the effects of CO_2 fertilization on grassland and forage production and quality need to be better quantified under conditions of water stress and high temperature, when considered along with projected climate changes, in many regions, forage availability and quality will be reduced and become more variable. This is likely to lead toward overgrazing and land degradation if farmers are not able to adjust stocking rates[147] due to economic or cultural pressures or relocate or alter seasonal migratory patterns. The capacity to address the non-climate-related stressors that threaten the capacity to change is crucial[101] as shown later, to reduce the vulnerability of these farming systems.[25]

Vulnerability of Livestock Systems to Climate Change

Different livestock farming systems have clearly differentiated vulnerabilities and adaptive capacity to climate change (Table 4). Following the IPCC WG2, we highlight here contextual vulnerability, in which not only climate-related drivers are considered, but also non-climate drivers, to give a more complete picture of systems' vulnerability and to understand adaptation capacities with respect to observed and projected impacts. Here, we divide these drivers into internal and external drivers. In general terms, grazing and mixed systems' vulnerabilities derive both from external and internal drivers, while industrial systems' vulnerability arise mainly from internal drivers, particularly the high dependence on

TABLE 4 | Vulnerability of Livestock Farming Systems and Climate Change Adaptation Capacity

	Grazing System	Mixed Crop-Livestock System	Industrial System
Vulnerabilities	• Marginalization • Land encroachment • Land degradation • Land fragmentation • Remoteness • Lack of financial capital and alternative economic options	• Limited mobility • Land degradation • Land scarcity especially from urban expansion • Rising food safety standards • Population growth • Economic margins often small and financial capital often low, resulting in lock-in • Economic relativities favoring cropping • Co-managing price and climate variability • Learning and capital demands from having multiple farm components • Labor supply for peak periods of activity • Shrinking farm sizes	• Dependence on fossil-fuel-based practices, external inputs and hired labor • Difficulties in re-locating • Narrow gene pools in livestock and input crops • Challenges in waste disposal and animal welfare impacting on social licence to operate • Susceptibility to disease outbreaks • Low economic margins • Operating close to or at maximum physiological and financial limits
Adaptation capacity	• Mobility to adapt to spatial climate variability • Family labor • Communal land and social collaboration • Local knowledge of diverse resources • Capacity to add value to marginal land • Wide livestock gene pool • Recycling plant nutrients • Transformation to mixed systems • Off farm income	• Integration of agriculture and livestock • Capacity to use crop residues • Often private land, hence have agency • Flexibility in crop-:livestock allocation and other decisions • Diversification • Family labor • Wide livestock and forage gene pool • Recycling plant nutrients • Flexibility in allocating produce to subsistence or market • Off farm income	• Access to global feed and input supply chains • Access to credit and modern technology • Access to global consumer market • Capital mobility and exploiting economies of scale. • Control of many aspects of the system • Good information systems (climate, financial, supply) allowing rapid responses

fossil-fuel-based and external inputs, the current narrow livestock gene pool, limitations on waste disposal and constraints on relocation.[141]

Grazing systems' external vulnerability mainly arises from being a remote, often marginal economic activity with relatively low value in export or economic development terms, and a range of constraints on improvement including the high cost and often low supply of basic services.[101,148] This and the '*distant voice*' characteristic of extensive grazing communities—geographical and political distance from the decision-makers[149]—tend to limit investment by government and business. Also, land encroachment through expansion of crop-only land use can increase this vulnerability for the livestock activities. These conditions also result in a lack of other economic options to the people depending on these farming systems, further increasing their vulnerability to climate change. Non-climate stressors increasing grazing systems' and smallholders' vulnerability[8,101] can be grouped into: (1) demographic growth and rising competition for the use of rangelands, (2) disregard of traditional knowledge, institutions and customary practices in policy-making, and (3) increasing but unequal and precarious integration within the market economy resulting in increased risk of market failures. For instance, recent findings show that while efforts to enhance access to markets and alleviate constraints to mobility may have some positive effects, further benefits would arise if current inequities in market development were addressed. Indeed, poor and middle-income pastoralists are shown to participate very little in high-value export trade and thus market-based benefits for them will be greater in relatively low-value market chains, such as domestic and cross-border trade.[150] Overall, these drivers are causing gradual dismissal of local knowledge, abandonment of communal planning and institutions, increase in social differentiation, and overexploitation of natural resources.

Mixed systems' vulnerabilities arise from different sources. In contrast to grazing systems, the limited mobility of mixed livestock systems increases their vulnerability to climate change, which is augmented by the seasonal scarcity of available land to graze and use for animal feed. External drivers of vulnerability of mixed livestock systems are linked to the rise of food safety standards, population growth, land competition, capital constraints, degradation of resources and more limited economic opportunities as compared to cropping options.[60]

Adaptation Options

Numerous adaptation strategies in the livestock sector have been described,[8,55,101,151–154] that could individually and collectively improve food security under climate change.[138] For analytical purposes we focus on adaptation strategies of livestock systems. Considering that livestock systems have different functions to different human systems, the nature of how these systems contribute to livelihoods resilience, mostly to poor people in developing countries, is of major importance and needs to be considered.[139]

Like mitigation strategies, we classify adaptation options as managerial, technological, policy-related, and behavioral (Table 5). **Managerial** options include (1) production adjustments, such as intensification, integration of livestock, and crop production, altering the timing of the farming practices, shifting from grazing to browsing species, herd mobility, soil and nutrient management, water management, pasture management, control of livestock (e.g., corralling), feed and food storage including processing of animal products (e.g., fermented, salted), multispecies herds, farm diversification or cooling systems (e.g., in livestock housing); and (2) alterations in labor allocation, such as diversifying livelihoods, shifting to irrigated farming, and labor flexibility. **Technological** options include (3) breeding strategies, such as adoption of high-yield breeds, selecting breeds with improved feed-conversion efficiency, and cross-breeding with heat- and disease-tolerant breeds; (4) information and communication technology research to provide greater understanding of climate and livestock interactions, such as fenceless grazing using GPS or improved short-term weather and seasonal climate forecasts. **Policy-related** options include (5) institutional and policy plans, such as schemes of sedentarization, access to resources to reduce vulnerability, such as early-warning systems, food relief and national safety programs, weather-indexed insurance for impacts of climate extremes or development and maintenance of supportive infrastructure (roads, rail, harbors, storage, processing, etc); (6) modifications in market integration and wealth storage, such as supporting different market access, credit schemes, promotion of interregional trading, bartering, herd accumulation, food preservation, and cash and asset management. **Behavioral** options are linked to cultural patterns such as (7) boosting social collaboration and reciprocity, e.g., livestock loans, friendly collaboration, communal planning, communal ownership and food exchange; and (8) information exchange.[155]

Some of these strategies can be considered as deriving from local traditional knowledge that promotes endogenous adaptation and to be easier to implement, others require exogenous knowledge and more inputs to be implemented, but all may have some utility in different contexts and livestock systems. Access to technologically-advanced breeding strategies, cooling systems, insurance, credit or veterinary services, which allow industrial, intensive systems to reduce the impact of local climate variability, are beyond the means of most smallholders, particularly in developing countries. In contrast, farmers in developing countries are highly experienced in managing livestock in marginal situations including managing variable and sometimes extreme climatic conditions.[101] Their sometimes ambiguous institutions,[156,157] knowledge, and customary practices which are often highly adapted to the local conditions and developed over centuries of co-evolution with changing environments, can be of great value in adapting the whole livestock sector to changes in climate means and variability. But adaptation to a variable and changing climate is an ongoing process, since vulnerabilities and impacts are permanently evolving, which means that some forms of adaptation that have proved to be appropriate in the past or at present, may became inappropriate or inadequate in the future[138] and vice versa. Also, as previously mentioned, diverse non-climate-related stressors can severely hinder the adaptive capacity of smallholders.

INTEGRATED ADAPTATION AND MITIGATION OPTIONS

In looking at the potential mitigation and adaptation strategies discussed in this paper, and facilitated by the use of the same categories for both, we can

TABLE 5 | Qualitative Integrated Assessment of Adaptation and Mitigation Strategies and Its Potential Applicability by Livestock Farming System, Including the Type of Knowledge Associated to Develop the Strategies

Category	Sub-category	Practices	GRAZING SYSTEM	MIXED SYSTEM	INDUSTRIAL SYSTEM	Co-benefits	Knowledge type
		MITIGATION				**Adaptation**	
Managerial	Land management	Avoid deforestation	++	++	++	++	LTK/STK
		Control land degradation (soil erosion, restoration)	++	++	++	++	LTK/STK
		Grassland management, stocking density	++	++	0	++	LTK/STK
		Limited grazing on wet soils, pastures irrigation management	+	++	0	++	STK
	Farm nutrient cycling	Efficient use of fertilizers for feed	0	++	++	+	STK
		Organic manure	0	++	0	+	LTK
		Integration livestock-crop	++	0	+	+	
	Livestock nutrient cycling	Breeding to improve rumen N conversion efficiency	++	++	+	+	STK
		Reducing the number of unproductive animals	++	++	0	++	LTK
		Change species: ruminant to monogastric; large to small	++	++	++	+	LTK/STK
		Changes in feed quality and composition	+	++	++	++	LTK/STK
	Capital-labour intensification	Capital intensification	0	+	++	0	STK
		Labour intensification	++	++	++	+	LTK/STK
Technological	Farm nutrient cycling	Urease or Nitrification inhibitors	0	+	0	0	STK
	Livestock nutrient cycling & reduction of CH4 emissions	Feeding additives (eg. condensed tannins)	0	++	+	0	STK
		Salt supplementation	++	++	0	+	STK
		Improving forage quality	++	++	0	++	LTK/ STK
		Manipulations of microbial populations	0	++	++	0	STK
		Deep cooling slurry	0	0	++	0	STK
Policy-related	Market mechanisms	Policy schemes (REDD++, CDM)	++	++	++	+	P
	Alternative fuels	Anaerobic digesters	0	0	++	++	STK
		Flexi-biogas systems	++	++	0	++	STK
Behavioural (Demand-driven)		Reduction in meat consumption	+	++	++	+	P
		Food waste reduction	++	++	++	++	LTK/STK/P
		Reduction of life cycle emissions (local food, low energy)	++	++	+/-	++	LTK/P
		Labelling products	+	+	+	0	P

TABLE 5 | Continued

Category	Sub-category	Practices	GRAZING SYSTEM	MIXED SYSTEM	INDUSTRIAL SYSTEM	Co-benefits	Knowledge type
		ADAPTATION				**Mitigation**	
Managerial	Farm management	Integration crop-livestock	++	0	0	++	LTK
		Altering timing of farming practices	++	++	0	0	LTK
		Shifting species (grazer to browser) and/or breeds	++	++	++	++	LTK
		Herd mobility	++	+	-	+	LTK
		Soil management (composting, crop residues, legumes)	+	++	0	++	LTK/STK
		Water management (irrigation, traditional storage, etc.)	++	++	++	0	LTK/STK
		Pasture management (enclosure)	++	++	0	++	LTK/STK
		Control of livestock (corralling)	++	++	0	++	LTK
		Feed and food storage	++	++	++	0	LTK/STK
		Food processing	++	++	0	0	LTK/STK
		Multispecies herds	+	++	-	+	LTK
		Farm diversification	+	++	-	+	LTK
		Cooling system	0	0	++	-	STK
	Labour allocation	Diversifying livelihoods	+	++	-	0	LTK
		Shift to irrigated farming	--	+/-	0	0	STK
		Labour flexibility	++	++	++	+	
Technological	Livestock management	Breeding (I): high-yield, good feed-conversion breeds	+	++	++	++	STK
		Breeding (II): Cross-breeding heat, disease-tolerant breeds	++	++	+	0	LTK/STK
	ICT	Weather forecasting	++	++	++	0	LTK/STK
Policy-related	Institutional and policy plans	Early-warning systems	++	++	++	0	P
		Schemes of sedentarization	+	0	0	0	P
		Weather-indexed insurance/ catastrophic coverage	++	++	++	0	P
		Access to resources (land, water)	++	++	0	0	P
		Food relief, National safety programs	++	++	0	0	P
	Market (integration and wealth storage)	Market access (local-regional-global)	++	++	++	++(local) --(global)	P
		Credit schemes	++	++	++	0	LTK/P
		Interregional trading	++	++	++	-	P
		Bartering	++	++	0	0	LTK
		Herd accumulation	++	++	0	-	LTK
		Food preservation	++	++	0	0	LTK/STK
		Cash and asset management (bank savings)	++	++	++	0	

TABLE 5 | Continued

Category	Sub-category	Practices	GRAZING SYSTEM	MIXED SYSTEM	INDUSTRIAL SYSTEM	Co-benefits	Knowledge type
		ADAPTATION				Mitigation	
Behavioural (cultural)	Social collaboration & reciprocity	Livestock loans	++	0	0	0	LTK
		Friends-family collaboration	++	++	0	0	LTK
		Communal planning	++	0	0	0	LTK
		Communal ownership	++	-	0	0	LTK
		Food sharing	++	++	0	0	LTK

Potential refers to relevance for the specific farming system, or capacity of the system to adopt such a strategy (e.g., poor farmers cannot adopt some expensive technologies). 0 can indicate a lack of potential *or* that the strategy is already part of the system (e.g., mixed livestock systems already integrate livestock and crops). + and ++ indicate greater degrees of potential for application. Type of knowledge: LTK, Local and traditional knowledge; STK, Scientific and technological knowledge; P, Policy-driven actions.

identify integrative solutions that provide potential win-win strategies for mitigation and adaptation (and food security) for each livestock system, and even for the livestock sector in general. Similarly, we can identify trade-off (or win-lose) situations. Table 5 qualitatively assess all the mitigation and adaptation strategies collected in this review for each category and farming system, including whether they depend on traditional or/and scientific knowledge, and whether policy actions are required.

Starting with the strategies described in this paper classified as having mitigation potential, we observe that all the strategies under the managerial category also have adaptation potential, and are suitable for at least two of the three farming systems categories. In general terms, these strategies do not require high investments, being more dependent on adequate policy incentives or institutional environments to facilitate changes in management. Thus, their overall potential to contribute to both mitigation and adaptation in all livestock systems is very high, as well as their potential effectiveness (Figure 2). From these, land management strategies offer the greatest options. For instance, avoiding deforestation is a very important strategy to mitigate and adapt to climate change, since in adaptation terms it can also provide other resources (e.g., bush foods, medicinal plants) to livestock keepers, which can buffer climate variations *via* diversification of income and obtaining other food sources.[158,159] These land management strategies are mainly managerial and technological and are often intended to improve the efficiency of livestock systems in a form of sustainable intensification. Strategies linked to sustainable intensification that consider all the other objectives (ethical, health, development, social justice, including concerns around vulnerability and social equity, biodiversity and land use, animal welfare, human nutrition and rural economies[139,160]) can offer promising outcomes in both adaptation and mitigation terms. Indeed, sustainable intensification measures in livestock have also been suggested for adaptation purposes.[161] For instance, changing species or breeds, strategies widely used by grazing and mixed farmers to adapt to changing conditions, can also aid mitigation in certain cases. For example, by improving breeds to obtain more efficient animals and then keeping a lower number of animals, or by changing to non-ruminants (e.g., from cattle to camels) which are more efficient in the use of nutrients. In promoting these strategies, it is very important to look at the system where they will be applied with a complex systems perspective, to consider future potential vulnerability and resilience.[139] Finally, we can observe that demand-driven strategies, linked to changes in behavior, strongly depend on adequate policies to promote these changes.

Mixed-systems appear to present greater opportunities for mitigation strategies than the other systems, consistent with the quantitative estimations of Havlik et al.[22] They showed that transitioning from grazing to mixed systems contributes to reduced GHG emissions, mostly through gain in feed and forage productivity from more intensive inputs and management. This is an attractive mitigation opportunity for reducing CH_4 and N_2O emissions per unit of livestock product, while at the same time increasing productivity.[59,162] It is important to note however, that increased efficiencies by themselves do not necessarily assist meeting global GHG reduction targets if the demand for underlying production increases to a greater extent[27] and where the GHG impacts of the feed production is included. Additionally, not all grazing systems can shift to mixed systems, since many of them are located in marginal areas where cropping is difficult, if not impossible, and in others various constraints operate to limit change, with livestock

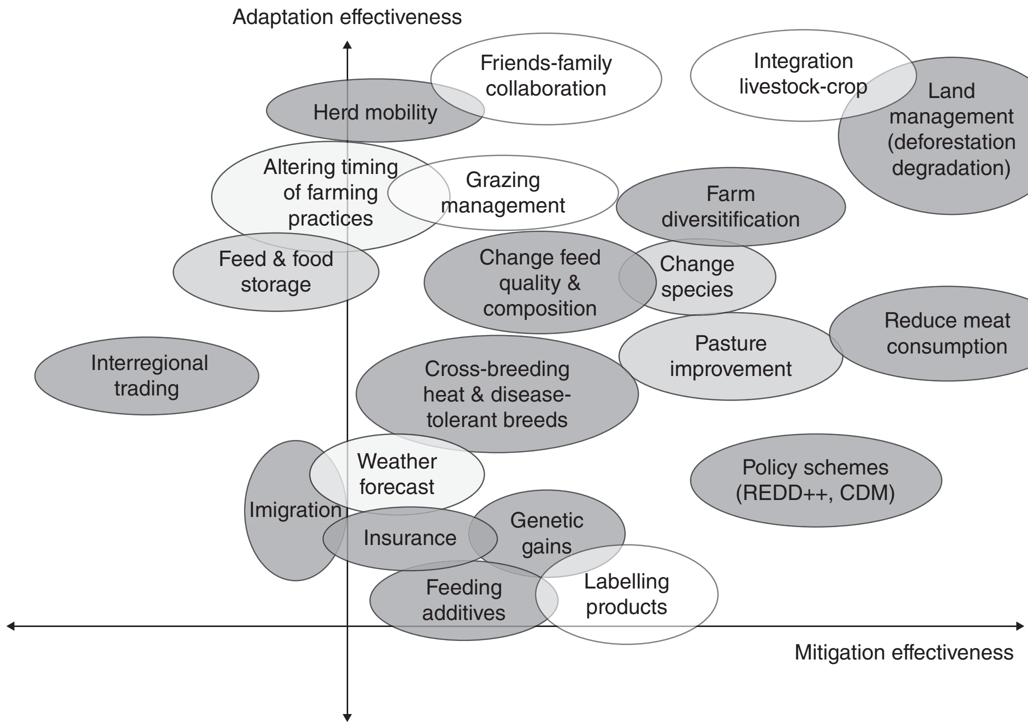

FIGURE 2 | Effectiveness of different adaptation and mitigation options. The intensity of the color implies the difficulty in implementation or cost or trade-off involved. Valorization is qualitative: clear gray, easy implementation, low trade-offs; hard gray, difficult implementation, high trade-offs.

currently being the only viable livelihood.[139] A call for analyzing crop-livestock interactions to increase resilience to global environmental change, including responses of these interactions to climate change, has recently been made.[163]

In terms of adaptation, once again managerial strategies appear to offer the greatest potential to favor both adaptation and mitigation options, many of which (e.g., herd mobility or pasture enclosure) need support from favorable policies and institutions. This suggests a need to focus more research on the role they can play.[164] In terms of farming systems, both grazing and mixed systems have the highest number of adaptation options identified. Industrial systems, as previously stated, have fewer options, resulting from their high dependence on external knowledge, and the need to control the system in order to reduce its internal vulnerability.

If we allocate to each of the described strategies in this article the type of knowledge (broadly categorized into local and traditional knowledge, and scientific and technological knowledge) required to support adaptation and mitigation strategies (Table 5), and which integrated strategies have higher difficulty or cost in implementation (Figure 2), some patterns emerge. In general, we observe that adaptation is more related to management of both the internal and external environment (i.e., market conditions, input availability, finance options, access to knowledge and technology, climate, robust institutions, etc.) with often strong contributions from local and traditional knowledge, whereas mitigation is more about managing just the internal operations, bringing in new technology on an occasional basis, with fewer inputs from local and traditional knowledge. Across farming systems, we observe that options for mitigation in industrial livestock systems are more dependent on scientific and technological knowledge, and are facilitated by increased levels of control within these systems. Policy strategies are important both in mitigation and adaptation strategies, and more research is needed to further develop the potential of different policies (e.g., addressing changes in management and behavior) to both mitigate and adapt to climate change with a relatively low economic cost.

Finally, our analysis reveals relevant information in terms of efficiency, that is, which cost or trade-off is involved in some of the integrated strategies (Figure 2). Crop-livestock integration, land management and reduction of meat consumption offer the greatest advantages as integrated adaptation and mitigation strategies. But each of them has its specificities. For example, crop-livestock integration is a highly efficient strategy with relatively low barriers for implementation except those explained above. In contrast, the cultural changes needed for broad scale implementation of dietary change, with large impact for mitigation, are relatively difficult in the short-term, but possible if we accept that current increasing demand of meat products is also a policy-driven trend.[111] Clearly, more research to develop a complex array of behavioral, policy and technological approaches is needed to facilitate dietary transition. Land management strategies can be relatively easy to implement, depending on the context, being very efficient in terms of adaptation and mitigation. These strategies should be high priorities for policy makers if we consider efficiency and implementation costs. Figure 2 also indicates that in general, adaptation strategies seem to be less difficult to implement, or have fewer barriers and trade-offs than mitigation options. It is important also to highlight that some strategies are context-dependent, and this makes them difficult to evaluate broadly. For instance, inter-regional trading, which can be a valid adaptation strategy, can have mitigation trade-offs given the increasing CO_2 emissions associated with livestock transport.

CONCLUSIONS

The rapid growth of the livestock sector and demands for its products has given rise to unexpected and major implications for the environment and livelihoods, particularly in relation to climate change. Clearly, drawing greater distinctions between different livestock systems is needed. Renewed attention to diversity within the livestock sector and the multiple objectives it meets are required to address the increased demand in ways that contribute to environmental sustainability, poverty reduction, social equity, food security, and human health. To meet these requirements, all livestock systems must improve their performance via combinations of managerial, technological, and policy responses. Particularly, more research is needed to assess the potential of managerial strategies to promote win-win solutions, including their economic cost and their social outcomes. We identify some responses that can improve both climate change adaptation and mitigation and their interaction but in doing so we identify the need for more integrative assessment processes. Notable progress could be made firstly by approaching the issue from a food system perspective, with more attention being paid to the whole food chain, since GHG emissions and use of natural resources occur throughout the entire livestock production, distribution and consumption chains; and secondly by paying attention to social and equity issues and livelihoods, with the aim of addressing more comprehensively the multiple benefits and costs associated with different livestock farming systems in different contexts, and specifically the fundamental contribution of livestock to the livelihoods of the world's poor.

There is great potential for all livestock systems to reduce net GHG emissions, and a combination of different strategies will be required from the full range of existing options, adjusted to different livestock systems and geographical, social, and institutional contexts. Specifically, grazing and mixed systems have strong mitigation potential through practices such as moderate grazing, soil conservation, and use of local resources; whereas most technological and market-oriented mitigation strategies are generally more applicable to large-scale confined operations of some industrial systems. However, mitigation objectives are unlikely to be met only through using these solutions, and changes in the demand side are needed. Here again a more integrated assessment of demand-side strategies linked to changes in consumption that takes into account the needs of the poor is also needed. This could include research into consumer behavior and how policy can provide a supportive environment for improved adaptation and mitigation decisions to different contexts. From a policy perspective, the simultaneous reduction in net GHG emissions, enhancement of carbon sequestration, the sustainable use of natural and world food resources, as well as the maintenance of desirable social systems might be considered as outcomes of appropriate livestock farming practices, rather than goals *per se*, that can favor both mitigation and adaptation strategies. There are critical questions as to why producers and consumers are not adopting these approaches currently, and what policy stances would enhance implementation.

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