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Review

Climate Change and Livestock Production: A Literature Review

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Abstract: Globally, the climate is changing, and this has implications for livestock. Climate affects livestock growth rates, milk and egg production, reproductive performance, morbidity, and mortality, along with feed supply. Simultaneously, livestock is a climate change driver, generating 14.5% of total anthropogenic Greenhouse Gas (GHG) emissions. Herein, we review the literature addressing climate change and livestock, covering impacts, emissions, adaptation possibilities, and mitigation strategies. While the existing literature principally focuses on ruminants, we extended the scope to include non-ruminants. We found that livestock are affected by climate change and do enhance climate change through emissions but that there are adaptation and mitigation actions that can limit the effects of climate change. We also suggest some research directions and especially find the need for work in developing country settings. In the context of climate change, adaptation measures are pivotal to sustaining the growing demand for livestock products, but often their relevance depends on local conditions. Furthermore, mitigation is key to limiting the future extent of climate change and there are a number of possible strategies.

Keywords: livestock production; adaptation; mitigation

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1. Introduction

Livestock products and services play an important role for humans. Globally, livestock occupy about 26% of the ice-free land with one-third of the cropland being used for feed production [1]. Livestock production generates nearly 40% of global agricultural gross domestic product (GDP). Livestock provide 33% of the global protein and 17% of the global calories consumed. Production creates substantial employment opportunities for rural households [2,3]. Additionally, livestock are a major provider of food, nutritional security, livelihood, and income in developing countries [4].

Driven by population and income growth plus urbanization, the demand for livestock products is growing rapidly. Simultaneously, livestock production is facing increasing pressure from climate change effects, such as increasing temperatures, more variable precipitation patterns, more frequent extreme events, and increasing carbon dioxide concentrations [5]. Such changes have been found to impact livestock performance across many regions and are projected to have growing impacts. Predictive models broadly indicate the impact will be negative [6]. Meanwhile, livestock are a direct source of both methane and nitrous oxide and an indirect source of those gases and carbon through land use and feed production. Globally, the livestock emissions share is an estimated 14.5% of total anthropogenic emissions [7].

The interaction between ongoing climate change and demands for increasing livestock production makes it challenging to increase production while lowering climate impacts and Greenhouse Gas (GHG) emissions. Addressing such challenges requires an understanding of climate change effects on livestock production, as well as the effect of both adaptation and mitigation actions. This paper overviews climate change impacts on livestock production, livestock emissions, and possible adaptation and mitigation actions. In constructing this

review, we relied on material from 157 references, with the papers classified as shown in Table1.

Table 1. Counts of papers used in the review by category.

Category	Sub-Category	Number of Papers Cited
By topic	Climate change impacts and adaptation	95
	Livestock emissions and mitigation	27
	Comprehensive treatment	31
By year	Before 2000	12
	2000 to 2010	39
	2011 to 2021	102
By region	North America	42
	Europe	14
	Asia	8
	Africa and Australia	8
	Region not specified	40
	Multi-region/global	41
By livestock species	Ruminants	41
	Hogs	15
	Poultry	18
	Not livestock	32
	Multiple livestock	47

2. Impact of Climate Change on Livestock Production

The climate is changing, exhibiting higher temperatures, increasing precipitation variation, and more frequent extremes. This is driven by increasing carbon dioxide (CO_2) concentrations. Such changes have been found to alter livestock and associated feed production. We will follow Collier [8] and broadly divide the impacts into direct and indirect effects: Direct effects refer to climate and CO_2 impacts on livestock thermoregulation, metabolism, immune system function, and production. Indirect effects derive from the influence of climate on feed production, water availability, and pest/pathogen populations. A brief summary of the impacts appears in Table2. In addition, the impacts are elaborated below.

Table 2. Climate change impacts on livestock production.

Impact Type	Observed Impacts	Major Influential Factors
Direct Impact	Reduced feed intake	Increased temperature (heat stress)
	Decline in animal milk and meat production	
	Decreased reproductive performance	
	Negatively affected immune functions	
	Increased mortality	
Indirect Impact	Changes in feedstuff crop yields	Elevated CO_2 level
	Changes in pasture composition and forage production	
	Changes in forage quality	Increased temperature and elevated CO_2 level
	Shrinking water availability and increasing water use	Increased temperature
	Larger seasonal variation in resource availability	More frequent extreme climate events
	Increased disease, pest, and parasite stress	Increased temperature and changes in the precipitation pattern

2.1. Direct Effects

The thermal environment is the major climatic factor that affects animal production. This involves a combination of air temperature, humidity, and air movement [9]. The relationship describing the best conditions of these is often referred to as the thermal comfort zone. In this zone, animals exhibit optimum performance and minimal energy expenditure [10]. When conditions rise above this zone, extra energy is required to maintain thermoregulation and production processes become less effective [11]. Animals suffer from thermal stress when the environmental temperature deviates outside the thermal comfort zone. The phenotypic response of animals to an individual source of stress can be called acclimation [12,13]. Heat stress is more problematic and has a greater effect than cold stress [14,15]. Climate change is also almost certainly increasing temperatures and, in association, increasing heat stress and lowering cold stress. Therefore, heat stress has been the dominant topic within the discussion of thermal stress.

Heat stress has been found to have negative effects on livestock. The estimated annual U.S. livestock industry loss caused by heat stress falls between $1.7 and $2.4 billion [16]. Heat stress occurs when animals are not able to dissipate sufficient heat to keep homeothermy [17]. This has been found to lead to increased respiration, pulse, and heart rate, along with increased body temperatures [18]. In turn, this can result in reduced feed intake, milk production, and reproduction efficiency, as well as changes in mortality and immune system function. Below, we discuss these impacts in more detail, with emphasis on animal performance rather than underlying biological mechanisms.

2.1.1. Feed Intake

Reduced feed intake is one response to high environmental temperatures. Ruminants experience reduced appetite, gut motility, and rumination under increased heat stress [19,20]. Lactating dairy cows exhibit a reduction in feed intake as ambient temperatures rise above 25–26 °C and show more rapid declines above 30 °C [21]. Goats are less susceptible to heat stress than other ruminants. However, their voluntary feed intake declines when the ambient temperature is more than 10 °C above their thermal comfort zone [22].

Hogs exposed to heat stress exhibit increased body temperature, and their feed intake decreases by 10.9% when temperatures increase from 20 to 35 °C [23]. Such impacts persist beyond the period when the hogs are exposed to heat stress. Hence it is suggested that feeding in early morning hours could help avoid reduced feed intake [24].

Poultry animals also exhibit reduced feed intake when exposed to high temperatures. An increase in ambient temperature from 21.1 to 32.2 °C has been found to lead to a 9.5% drop in feed intake for birds from the post-hatch period to 6 weeks of age [25]. The reduction in feed intake causes decreased feed conversion efficiency and daily weight gain [26–29].

More generally, across all the livestock types, heat-stress-related decreased feed intake leads to decreased milk, meat, and egg production, which in turn leads to further sectoral losses.

2.1.2. Animal Production: Milk and Others

Studies indicate that the dairy industry suffers greater heat-stress-related economic loss than does the other U.S. livestock sectors [16]. Under heat stress, dairy cows reduce feed dry matter intake and this explains approximately 35% of the decrease in milk production [30]. Meanwhile, as high-producing dairy cows are larger and emit more metabolic heat than lower-producing breeds, the most productive breeds exhibit more sensitivity to heat stress [3]. As a consequence, milk production declines as heat-stress-caused metabolic heat production increases [21]. In addition to milk production, hot and humid environments also affect milk composition. Ravagnolo et al. [31] and Gorniak [32] have indicated that lactating cows start to suffer from heat stress at a temperature–humidity index of 72 and above this level, milk protein and milk fat content declines as the index increases.

Similar changes in milk composition have been found for dairy goats [33] and buffaloes [34] but have only been narrowly studied.

Meat production has been found to be affected by heat stress for all major commercial livestock types [35]. Heat-stressed ruminants exhibit reduced body size, carcass weight, and fat thickness and lower meat quality [10,36,37]. Small ruminants, such as goats and sheep, have been found to be more adapted to a hot and humid environment [38]. However, feedlot cattle have been found to be more vulnerable due to their being raised with greater exposure to rough radiant surfaces and fed high-energy diets [35,39].

Similar to ruminants, hogs exhibit reduced carcass weight and meat quality when exposed to a high temperature [40]. Under high ambient temperature, they have also been found to exhibit reduced average daily gain of 9.8% when compared to thermoneutral animals [41].

Chickens exposed to heat stress increase energy expenditure to maintain thermoneutral conditions at the expense of growth [42]. Heat-stressed broilers exhibit reduced weight gain, feed conversion rates, protein concentration, and breast muscle weight [43–45]. For laying hens, egg shell strength, daily feed intake, egg mass, and egg production are more sensitive to heat stress compared to other traits [46]. In addition, significant declines in egg shell quality and egg production are observed in breeders [47]. The reduction in egg quality and production caused by heat stress can be mediated by alterations in dietary calcium [48].

2.1.3. Reproduction

Heat stress affects reproduction for both sexes. For females, heat stress reduces estrous period and fertility while increasing the incidence of anestrous and embryonic death. For males, there are declines in semen quality, testicular volume, and quantity of fertile sperm. Significant seasonal differences in reproductive performance in both sexes have been reported [49].

Although poultry reproduction is also affected by heat stress, birds may exhibit a difference in performance compared to mammals. Male broilers are reported to be more sensitive to heat-related infertility than female broilers [50]. For layers, environmental stress could delay the process of ovulation, reduce yolk quality, and affect hatchability [51].

2.1.4. Disease and Parasite Stress

Many factors, including species, breed, geographical location, disease characteristics, and animal susceptibility, contribute to the effects of climate change on livestock health [52]. In terms of animals themselves, the immune system is their major body defense that protects them from environmental stressors and other noxious insults [53]. Heat stress can negatively affect immune functions via cell-mediated and humoral immune responses [54]. As a result, periods of hot weather can cause livestock to be more vulnerable to diseases and raise the incidence of certain diseases (such as mastitis), leading to an increased potential of morbidity and death [55–57].

In addition, heat stress could affect the health condition of livestock through other functional pathways. For example, growing hogs may suffer from intestinal injuries if exposed to acute heat for several hours [28]. Broilers and laying hens are also reported to experience intestinal microbiota alterations under heat stress [58,59].

Simultaneously, increased temperature and altered precipitation may accelerate the incidence of pathogens and parasites. Although the effect of pathogens and parasites on livestock is generally regarded as an indirect effect, it is covered in this section since it is usually discussed in conjunction with animal health. This would affect the distribution and abundance of vector-borne pests and introduce new diseases [52,60]. These may increase the potential for morbidity/mortality and associated economic loss [61]. Compared to other impacts, climate change effect on livestock disease is more difficult to estimate and predict due to the nature of disease and climate-change-driven alterations to livestock. Such impact assessment is even more challenging in developing countries [52,61].

2.1.5. Mortality

Mortality is an important heat stress impact that has significant associated economic loss. Studies on dairy cows and hogs show that added heat stress increases mortality rates [62–64]. Hot and humid weather has been found to be more life threatening to cows and hogs compared to hot but dry conditions, and a temperature higher than 37.7 °C with over 50% humidity was shown to be detrimental [65].

For poultry, the body temperature of birds is usually higher and more variable than that of mammals and they are more sensitive to rising temperature. Chickens can function normally up to ambient temperature of 27 °C or a body temperature of 41 °C, but an increase of 4 °C in body temperature would be lethal to them [66].

2.2. Indirect Effects

Livestock feed is mostly composed of forages and grain/oilseed crop product. Production of those items is affected by climate, as are water supplies, both through irrigation and soil moisture. Thus climate change indirectly imposes effects, mainly through its impacts on feed supply and water. There exists a huge body of literature focusing on climate change impacts on crop production, and herein we are not trying to cover the details of this research area (for a review, see Reilly et al. [67], Shukla et al. [68], and IPCC [69]). In terms of solely livestock production, crops and forages provide feedstocks consumed by livestock. In this regard, climate change affects the supply of livestock feed but the magnitude of this impact on livestock production while commonly discussed has not been separately evaluated. We discuss the general aspects of this discussion in the remainder of this section.

First, let us introduce some terminology. The International Forage and Grazing Terminology Committee [70] defines forage as "edible parts of plants that can provide feed for grazing animals or that can be harvested for feeding." Forage plants can be roughly divided into two large groups: grasses and legumes. Besides these two groups, forage plants include others, such as woody species. As they are usually not considered as major feed for domestic animals and the impacts of climate change on woody species feed have not been well investigated, we will not cover them in this review. Two relevant studies to refer to are Papanastasis et al. [71] and Hejcman et al. [72]. Legumes can be grouped into cool season (C3) and warm season categories (C4) based on leaf anatomy [73]. Increases in atmospheric CO_2 and temperature are alter forage quantity and quality, with the magnitude dependent on the livestock system [74], location, and species. Precipitation patterns and extreme climate events are also influential, with the main impacts being production variation. Other influential factors include water supplies, which will be discussed in more detail below.

CO_2 contributes to crop growth [75]. C3 crop (soybeans, cotton, and wheat) yields increase under increased CO_2 concentrations, while yields of C4 crops (corn and sorghum) do not directly respond to the elevated CO_2 but may indirectly benefit under drought. Other climatic factors that affect livestock feed supply quantity are precipitation; temperature; and extreme events, such as drought. Increased precipitation is beneficial to corn, sorghum, rice, and soybean [76,77]. As for temperature, C4 species enjoy greater effects from temperature rise, but such effects depend on location, plant species, and production system [52,78]. Drought causes significant crop yield reductions, especially in hot regions [79,80]. A recent study in Europe found that drought stress is the main driver of losses for corn and winter wheat, especially in low-yielding years [81]. These climatic factors are often confounded, and their effects on vegetation growth are not easy to isolate. For example, higher temperatures at lower latitudes may be associated with higher water stress, while higher temperatures at higher latitudes may increase suitability for cropping and expand the length of the growing season.

Grass forage supplies are also affected by climate change. In terms of grassland and pasture, increases in average temperature bring significant changes in pasture composition, patterns, and biome distribution. Changes in precipitation patterns and more frequent droughts may lead to shorter pasture growing periods. Some research has indicated

that changes in temperature, CO_2 levels, and nitrogen deposition decrease the primary production in pasture [82], while some argue that higher temperatures favor grasses over forbs and legumes.

2.2.1. Forage Quality

Adequate nutrition is critical to weight gain, production, and reproduction, and forage is an important nutrition component for ruminants. As forage quality varies greatly within and between forage crops and nutritional needs vary among animal species, providing suitable feed to animals requires a balance. Most forage-quality studies have focused on digestibility, nutritive value, voluntary intake, and effects of anti-quality factors [83]. Forages of higher digestibility supply more energy per unit dry matter (DM) consumed. Nutritive values reported by forage analysis usually include neutral detergent fiber (NDF); acid detergent fiber (ADF); crude protein (CP); and minerals, such as calcium (Ca), phosphorus (P), magnesium (Mg), and potassium (K) [84]. Quality can be affected by climate through increased temperatures and dry conditions, which cause variations in concentrations of water-soluble carbohydrates and nitrogen [82]. Forage quality may also increase due to an increase in nonstructural carbohydrates resulting from elevated CO_2 level [85]. However, quality may also decrease since rising temperatures can increase lignin within plant tissues and therefore reduce digestibility [86]. Lee et al. [87] suggest that increasing temperature reduces forage nutritive values and correspondingly may lead to higher methane production.

2.2.2. Water

Water is scarce worldwide, and the magnitude of water scarcity depends on the supply relative to the demand. Agriculture is the single largest global water user, accounting for 69% of fresh water withdrawals [88]. As human populations, incomes, and livestock product demand increase, water scarcity will likely grow in importance as a constraint on production agriculture. The livestock sector uses water for consumption by animals, growing feed crops, and product processing [52]. It accounts for about 22% of the total evapotranspiration (ET) from global agricultural land and 41% of total consumptive water use [89].

Climate change is projected to change water availability [69,90] and water usage in animal production [3]. Rising temperatures are likely to increase per animal and per land area animal water consumption and irrigation water use [91,92]. Water salination caused by sea-level rise is another concern [93,94]. Competition for water between livestock, crops, and nonagricultural uses will increase in the coming decades, and it requires more efficient production systems to address water scarcity issue [95].

2.2.3. Seasonal Variation and Extreme Climate Events

Climate change may alter the seasonal pattern and variability of resource availability and crop yield [96,97], imposing further impacts on livestock production. As the frequency and duration of heat waves increase, animals will suffer from additional heat stress [62]. Knee et al. [98] found significant seasonal differences in cattle muscle glycogen and also that conditions with nutritious and abundant pastures coincide with better beef quality in spring and that worse pastures coincide with worse beef quality in summer. Moreover, changes in seasonal patterns of forage availability could bring additional challenges for grazing management and livestock management [99]. Increasing risk of extreme drought threatens forage quantity, and adaptation strategies are required to cope with such extreme events [100]. In addition, changes in snow melt timing alter water availability patterns during the year, which affects feed supplies [96,101].

3. Impact of Livestock Production on GHG Emissions

Livestock is a substantial contributor to global GHGs, with emissions estimated at 8.1 gigatons of CO_2-eq per annum or 14.5% of total anthropogenic emissions [7]. The three

main GHGs emitted by livestock are methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2). Their relative incidence has been explored using the FAO Global Livestock Environmental Assessment Model (GLEAM) [102] and are converted to CO_2 equivalents using 100-year global warming potentials from IPCC (2014) (298 for N_2O and 34 for CH_4).

The GLEAM results indicate that emissions from livestock supply chains consist of 50% methane (CH_4), 24% nitrous oxide (N_2O), and 26% carbon dioxide (CO_2), with emissions by category shown in Figure1. In terms of species, cattle are the major contributor, with about 62% of total livestock emissions. Other species (hogs, poultry, buffaloes, and small ruminants) each represent between 7 and 11% of the sector's emissions. Within cattle, beef and dairy animals generate similar amounts of total emissions. Figure2shows the global estimates of livestock emissions by species.

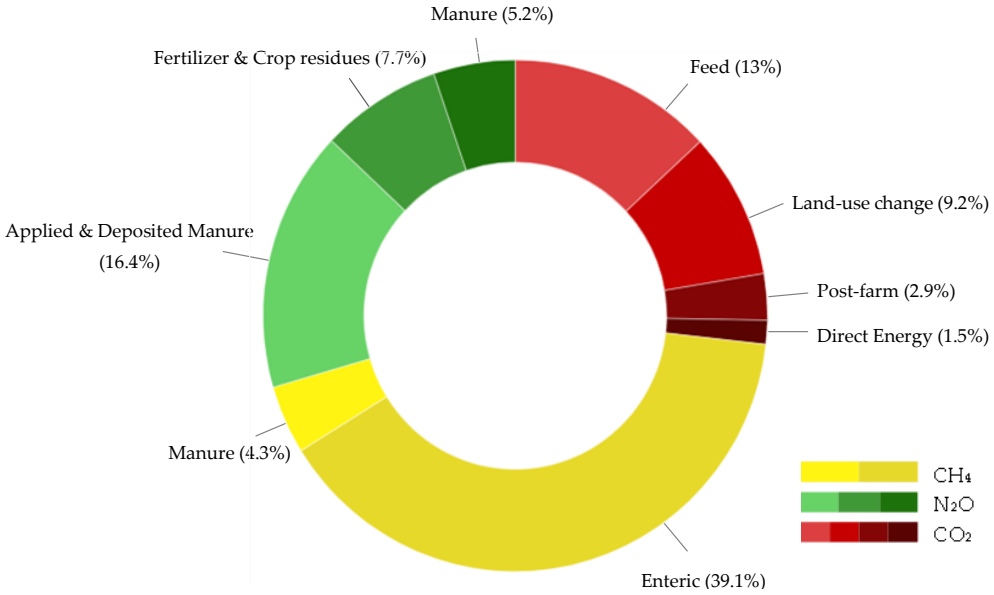

Figure 1. Emissions from livestock (by category), where methane (CH_4) emissions are portrayed in yellow, nitrous oxide (N_2O) in green, and carbon dioxide (CO_2) in red. Figure drawn by authors with data source from [7].

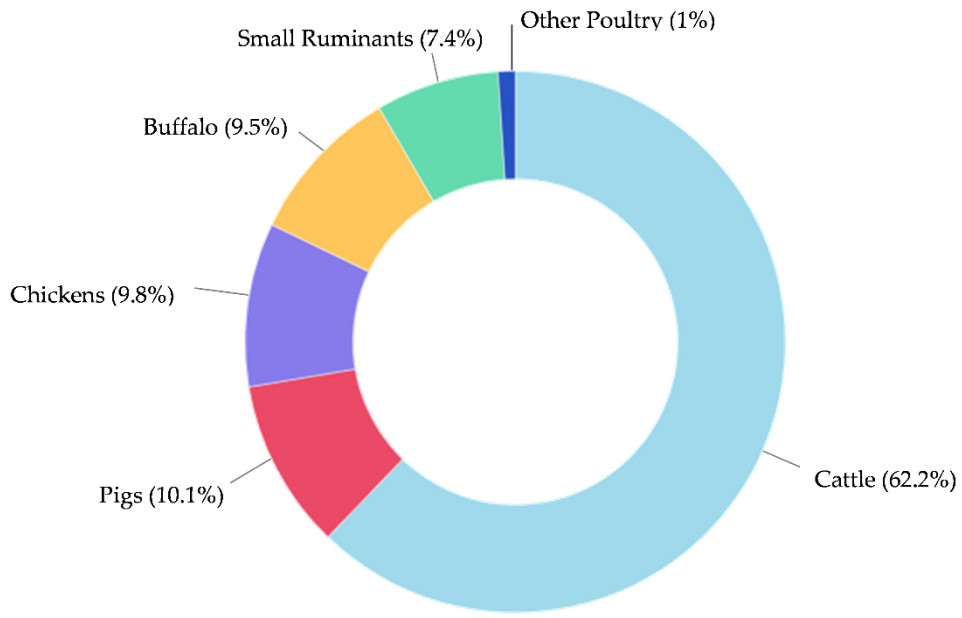

Figure 2. Emissions from livestock (by species). Figure drawn by authors with data source from [102].

Livestock GHG emissions arise directly through raising animals, including enteric fermentation, manure, and associated energy consumption. Indirect emissions mainly come from feed production and related land use change. Some studies indicate that indirect emissions exceed direct emissions, while others show the opposite [103,104].

3.1. Direct Effects: Enteric Fermentation and Manure Management

Enteric fermentation occurs mainly within ruminant animals' digestive systems, where microbes break down coarse plant materials and, in the process, produce methane, which is emitted by exhaling, belching, and other means. This is the largest ruminant emission source [105]. Non-ruminants also produce methane during digestion but in much smaller amounts. A variety of factors affect ruminant emission quantity, such as feed characteristics, use of feed additives, and animal health condition. The most influential ones are feed quality and feed intake. Higher feed digestibility leads to lower enteric methane emission and higher animal production. Increased feed intake leads to more methane being produced. The rate of conversion from feed energy intake to methane depends on species, production systems, and regional characteristics [7].

Manure also contributes to emissions in the form of methane and nitrous oxide (N_2O) emissions. The anaerobic decomposition of organic material releases methane, and nitrous oxide is released mainly from ammonia decomposition. Organic matter and nitrogen content in manure are the two chemical components that can lead to N_2O emissions during storage and processing [104]. Hogs and dairy cows are the largest source of manure-related methane emissions [106]. The largest manure-related N_2O emissions come from soil emissions associated with manure application [103]. The manure storage and handling process greatly affects resultant emissions, particularly when manure is handled in ponds or lagoons [106]. Other factors that affect manure emissions include air temperature, moisture, duration of waste management, and animal diet. If manure is handled through solid systems (e.g., deposited on pastures), N_2O emissions will be higher than methane since the generation of N_2O requires both aerobic and anaerobic conditions. Methane emissions are higher when manure is treated in liquid systems using lagoons or ponds.

3.2. Indirect Effects: Feed Production and Land Use Change

3.2.1. Feed Production

Emissions related to feed production, processing, and transport constitute about 45% of livestock-related emissions. Of all these feed-related emissions, N_2O from fertilization of feed crops and CH_4 from manure application to pasture generate about 50%, while related land use change generates about 25% [7]. Emissions from feed production consists of CO_2, N_2O, and CH_4. CO_2 emission arises from the production of fertilizers and pesticides for feed crops, feed transportation and processing, fuel used in production, and associated land use change. N_2O emissions are mainly from fertilizer use and manure application, with a small portion coming from the cultivation of leguminous feed crops (e.g., rice, soybeans, peas, alfalfa, and clover). The amount of feed-related CH_4 emissions is much smaller than that of feed-related CO_2 and N_2O emissions.

3.2.2. Land Use Change

Land use change is another indirect source of livestock-related GHG emissions. Gerber et al. [7] calculated that land use change contributes 9.2% of total livestock GHG emissions. This occurs through land use change to produce pasture (6%) and feed crops (3.2%). Agricultural land occupies 38% of the global land surface, with about two-thirds of this for livestock [107]. Driven by population growth, urbanization, and growing incomes, the demand for livestock and livestock products is expected to increase, inducing more livestock production. By 2050 compared to 2005/2007, world meat production is projected to increase by 76% and milk by 63% [108]. Associated with this, grazing intensities are projected to increase by about 70%, with feed demand almost doubled [109].

Historically, increased production of livestock and livestock feed has significantly impacted land use, which affects the natural carbon cycle [3]. Plants take CO_2 from the atmosphere and nitrogen (N) from the soil and store them in above- and below-ground biomass. Forest lands sequester more carbon in soil and vegetation than croplands and pastures, and thus when forest land is converted to cropland and pasture, much of the sequestered carbon is released into the atmosphere.

There is debate on appropriate procedures for accounting for emissions from land-use change, and there is no current shared consensus. Different scale and land-use change factors result in significantly different results. [110]. Steinfeld et al. [103] estimated that deforestation due to the expansion of pasture and feed crops is responsible for 8% of total anthropogenic CO_2 emissions. Hong et al. [111] estimated that land-use emissions accounted for 27% of global total anthropogenic GHG emissions during the 1970—2017 period.

3.2.3. Energy Consumption

Energy consumption is another source of CO_2 emissions, mainly related to fossil fuel use. For livestock, energy-related emissions occur across the supply chain spanning from production of fertilizers, use of machinery, and transport of feed and livestock. On-the farm animal-related energy includes that used for heating/cooling, ventilation, illumination, and milking. Upstream feed production uses energy in production, drying, and commodity transport. Downstream energy is used in processing livestock commodities and packing and transporting final products to retailers. The total energy consumption along the livestock supply chain contributes about 25% of total emissions in the livestock sector [7].

4. Adaptation

Climate change adaptation refers to adjustment in ecological, social, or economic systems to reduce the negative or enhance the positive impacts of climate change. In an agricultural setting, adaptation can occur through ecological change or human action. For livestock, natural adaptation results from different mechanisms through which animals adapt to climatic conditions. Human adaptation involves actions and practices that could help animals adapt to climate change and enhance the livestock performance. In a livestock context, adaptation actions can be divided into three broad classifications: animal responses, management actions, and resource [112].

4.1. Animal Responses

Animals can adapt through physiological, biochemical, immunological, anatomical, and behavioral responses [113]. Herein, we focus on behavioral responses. For details on other animal adaption mechanisms, see Gaughan et al. [112].

Commonly observed responses to heat stress include reduced feed intake, shade seeking, increased sweating and panting, increased water intake and drinking frequency, increased standing time and decreased lying time, and reduced defecation and urination frequency.

It is noteworthy that domestic animals are rarely exposed to a single stress. Besides heat stress, under feeding, lack of water, and poor nutrition may occur together. The cumulative effects of multiple stressors may be multiplicative rather than additive [112]. Animals may not be able to fully adapt to climate stressors by themselves, and thus producers may need to help in order to sustain livestock production and profitability. However, one should note that climate change can be so large that it may not be possible overcome an effect and in such cases, more extreme actions, such as changes in land use, species, or abandonment, may be in order [114].

4.2. Human Adaptation Strategies

Human adaptation strategies involve breeding, production/management system modifications, and institutional and policy changes. Table3presents a brief summary of livestock management adaptation strategies, and a detailed discussion follows.

Table 3. Summary of human adaptation strategies.

Animal Genetics
•Choose species that are more heat-tolerant •Genetic selection to changed conditions
Physical modification
•Provide shade and sprinklers for outdoor animals •Improve/supply cooling systems indoors
Feed and pest management
•Modify diet composition and feeding time •Supplemental feeding •Adoption of integrated pest management
Livestock system
•Diversify livestock species •Adjust stocking rate •Integrate livestock system with forestry or crops

4.2.1. Animal Genetics

Breed selection has traditionally been used to improve livestock production efficiency and has facilitated a massive increase in livestock production. However, current species selected for higher production in some cases have higher metabolic heat production and hence can be more susceptible to heat stress [115]. As future climate is predicted to be hotter, with more frequent heat extremes, breeding techniques and breed type selection can also be an adaptation action. Genetic variation in heat stress response in livestock species has been observed and measured [116,117]. Some breeds are less affected by heat stress, such as smaller, lighter-colored animals [118], or breeds can show great physical and physiological adaptation to heat stress. If such trait is heritable, selective breeding for heat tolerance could be used to improve animal adaptation to climatic stress [119,120]. Producers can switch breeds, for example, using more Bos indicus cattle [121,122].

4.2.2. Physical Modification

Physical modification of the environment can also be undertaken and can be broadly divided into two groups: outdoor and indoor.

For animals kept outdoors on grasslands or pasture, one cost-effective adaptation method is shade provision. This lowers exposure to solar radiation and reduces heat stress [39,123]. Sprinklers and misters could also help to decrease body temperatures [124], and they are more effective in drier weather. Huynh [125] suggested the use of a combination of different methods as there exist interaction effects. For example, the combination of sprinkling and a covered pen without an outdoor yard leads to higher daily gain for hogs than the provision of sprinkling alone.

For livestock kept indoors, in buildings, physical modification options can involve use or addition of (1) ventilation systems, (2) heat reducing building materials (e.g., insulation and orientation), and (3) forced air velocity, fogging, misting, sprinkling, and pad cooling [126]. Air conditioning and pad cooling have been found to have the best performance

in terms of lowering heat stress [126], but the high initial investment and operating expense might make them impractical [127].

4.2.3. Feed and Pest Management

Feeding practices can be used to improve animal performance under heat stress. These involve modification of diet composition, changes in feeding time and/or frequency, and water management [120]. These practices help alleviate heat stress through increasing energy content, increasing nutrient and electrolytes or certain minerals intake, and maintaining water balance. Feeding modifications in cattle [128,129], hogs [130–132], and poultry [66,133,134] have all been investigated, and the general effect is positive.

Pest management has not been fully discussed as livestock adaptation, although researchers have noticed that future changes in precipitation patterns may affect the spread and quantity of some vector-borne pests [52]. There are several concerns related to livestock pest management. First, some pests will develop resistance to insecticides and drugs in a short time, which would limit the effectiveness of insecticides or drugs. Thus, in practice, it is suggested to use the rotation of insecticides with different modes of action [135]. Second, high-density or confined systems can encourage pests and disease outbreak, with poultry in particular suffering a lot from pest problems [136]. Third, drug residues in animal products due to inappropriate use of pesticides may be a potential threat to public health [137]. As a result of these considerations, integrated pest management is needed [138], as well as improved techniques in pesticides.

4.2.4. Livestock Management System

Livestock management adaptations can involve one or more of the following strategies:

(1) Diversification of livestock species: Multi-species farming enhances the producer's ability to cope with a changing climate and the associated change in rangeland conditions and can also improve the sustainability of livestock farms [139,140].
(2) Adjustment in stocking rates: Díaz-Solís et al. [141] found that adjusting stocking rate can be used to reduce the effect of drought on cow-calf in Mexican state of Coahuila. Mu et al. [142] found that in the U.S., the stocking rate of cattle decreases as THI increases and precipitation increases in summer.
(3) Integration of livestock system with forestry or crops: Because of their positive synergistic effects on soil properties and nutrient cycling, mixed crop–livestock or forestry–livestock can help with soil degradation, reduce chemical use, and generate economies of scale at the farm level [143,144].

5. Mitigation

There are mitigation measures that reduce livestock GHG emissions. Gerber et al. [7] indicated that livestock emission intensities vary greatly between production systems and regions and the mitigation potential lies in the gap between the management techniques that result in the lowest and highest emission intensities. They estimated that the emissions from the livestock sector can be reduced by 18% if producers in a given system, region, and climate adopt the practices currently applied by the top 25% of producers with the lowest emission intensity and 30% if using techniques employed by the top 10%. We summarize many potential mitigation options in Table4and discuss them below.

5.1. Land Resource Management

Substantial livestock mitigation lies in livestock management and land use. Thornton et al. [145] estimated that the maximum mitigation potential from livestock and pasture management is approximately 7% of the global agriculture mitigation potential to 2030. Possible strategies involve adoption of improved pastures, intensification of ruminant diets, changes in ruminant breeds, reductions in stocking rate, and lowering grazing intensity. Havlík et al. [146] indicated that significant emission reduction could be achieved through transitions to more efficient and less land-demanding livestock systems. They also found

that mitigation policies targeting land-use-change-related emissions are 5–10 times more efficient than policies targeting emissions from livestock only.

Table 4. Summary of mitigation strategies.

Land resource management
•Improve grazing management •Alter grazing intensity and or manure use to enhance Carbon sequestration
Enteric fermentation management
•Modify diet and nutrition for livestock • Genetic selection
Manure management
•Alter storage practices •Modify diet and nutrition for livestock
Fertilizer management
•Increase nitrogen efficiency •Offest commerial nitrogen use by using manure

Another land-use-related mitigation category deals with carbon sequestration, which mainly relates to feed crop production. Carbon sequestering actions include using conservation tillage, selecting to produce higher yielding crops, reducing deforestation, converting cropland to grassland, and improving grass species [3,103].

5.2. Enteric Fermentation Management

As discussed above, enteric fermentation is the main source of ruminant methane emissions. This emission source can be reduced through dietary management and genetics. Knapp et al. [147] found that nutrition and feeding strategies such as improving forage digestibility can reduce enteric methane emission by 2.5–15% per unit of milk produced and that more significant reductions can be achieved if combined with genetic and management approaches. Feed additives and supplements, such as antibiotics, lipids, grain, and ionophores, have also been shown to decrease enteric methane emissions [105,148].

5.3. Manure Management

Livestock manure generates both N_2O and CH_4 emissions, and most of these are related to storage and handling methods [3]. Altered manure storage practices can reduce manure GHG emissions. These include shortened storage duration, lowered storage temperature, solid–liquid separation, and less use of water [149,150]. Anaerobic digestion processes, in which microorganisms break down manure in the absence of oxygen, produce a mixture of biogas (mainly CH_4 and CO_2) and digestate that can be captured and used as bioenergy to generate heat or electricity. This also indirectly reduces GHG emissions by replacing emission-intensive fossil energy and by changing the composition of emissions from the traditional combination of N_2O and CH_4 into a combination of CO_2 and CH_4 [151]. Anaerobic digestion can lead to an over 30% reduction in GHG emissions compared to traditional manure treatment [152]. Dietary adjustment for animals can also be used to reduce manure emission as it could change the volume and composition of the manure.

5.4. Fertilizer Management

Fertilizer application in feed crop production contributes N_2O emissions attributable to the livestock sector. Associated mitigation strategies aim at increasing nitrogen application efficiency. Possible measures include the use of time-released nitrogen, precision application, organic fertilizers, plant breeding, genetic modifications, and changes in plant species [153,154]. However, it is complex to calculate the mitigation potential of increasing fertilizer efficiency on animal feed production, and this leaves a gap for future studies to discover.

Another possible practice related to reducing emission from feed production involves shifts in types of livestock feed. Pikaar et al. [155] analyzed the potential of using microbial proteins (MP) as a feed replacement, finding that it can replace 10–19% of conventional crop-based animal feed protein demand, which leads to a reduction by 7% in agricultural greenhouse gas emission.

6. Discussion

On the one hand, climate change can affect livestock production directly through increased heat stress and indirectly through impacts on the quantity and quality of forage and crop-based feeds, as well as land and water availability. Associated adaptation strategies could target direct animal responses, by adjusting their living environment and feed, or focus on the modification of production and management systems.

On the other hand, livestock production influences climate change by contributing to 14.5% of the global anthropogenic GHG emissions. Mitigation strategies from the livestock side could help address enteric emissions and improve manure management, along with more emission efficient feed production through reduced use of N-fertilizer and land carbon sequestration. Figure3provides an overview of the major impacts, emission types, and actions covered in this review.

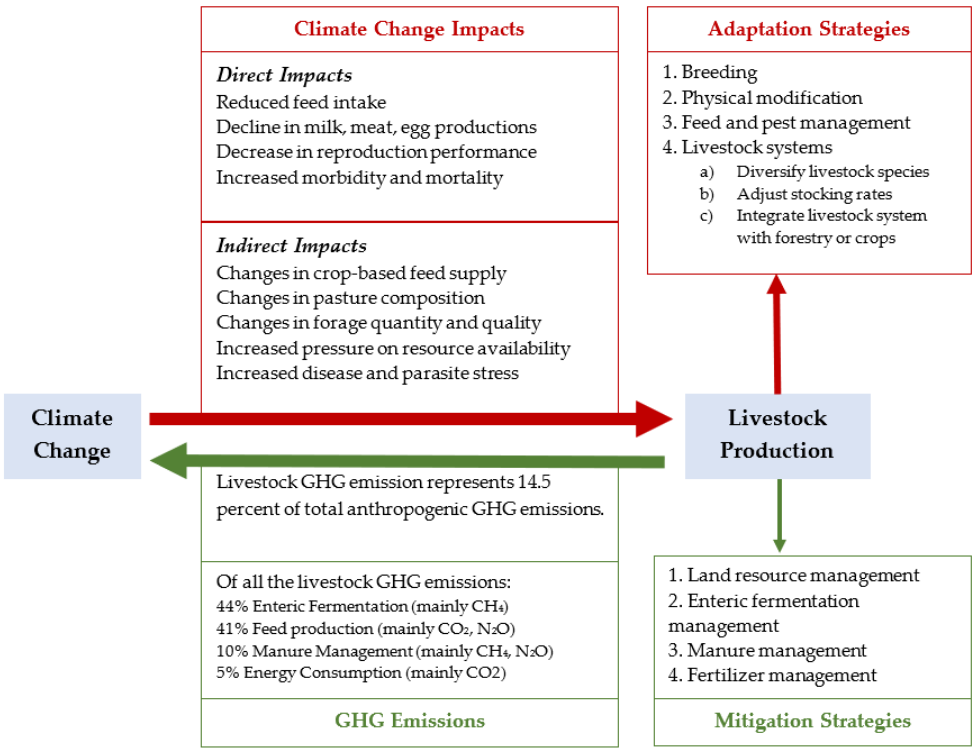

Figure 3. An overview of the relationship between climate change and livestock production.

Despite the numerous studies carried out in this field, there remain a number of research gaps. First, the literature mainly focuses on ruminants, with less coverage of other

species, such as hogs and poultry. These animals are also affected, and their productivity may even be more affected than that of ruminants [13]. Considering emissions on the basis of the per-unit protein produced, chicken meat, eggs, and pork have lower emission intensities compared to beef meat, and this could be exploited as a mitigation strategy [102]. Thus, research on non-ruminants is needed. Second, current publications have a strong focus on grassland-based livestock systems, while a mixed crop–livestock system produces half of the world's food and supports a large number of households in developing regions [156]. This additional research is needed on livestock in such production systems. Third, adaptation and mitigation strategies are not universally applicable, being place, species, and context specific. In addition, some options are too costly or resource intensive to be applied in a number of settings and the strategy potential is limited by the dietary needs for milk, meat, and eggs and by local conditions in terms of income, awareness of climate change impacts, experience, loan terms, and many other factors [157]. Research is needed to identify locally appropriate mitigation and adaptation strategies, especially in the context of developing countries, as well as policy approach for encouraging and implementing adoption. For doing this, better data, methods, and coverage are needed.

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