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Climate Change and Animal Health: A Review of Emerging Threats and Adaptation/Mitigation Strategies

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ABSTRACT: Climate change stands as one of the most pressing global challenges of the 21st century, profoundly reshaping ecosystems and threatening the balance of life on earth. Its effects are wide-ranging, influencing human societies, wildlife, and the natural environment in interconnected ways. Among the many sectors vulnerable to these shifts, livestock production faces particularly severe risks, as dairy farming depends heavily on stable climatic conditions for sustainability and productivity. Rising temperatures, erratic rainfall patterns, prolonged droughts, intense floods, and fluctuating humidity directly impair animal health and welfare. Heat stress emerges as a primary concern, reducing feed intake, lowering milk yield in dairy animals, decreasing growth rates in animals, and compromising overall immunity. Reproductive performance also suffers significantly, with issues such as reduced fertility, irregular estrous cycles, lower conception rates, and higher incidences of embryonic loss or stillbirths becoming more common under thermal stress. Indirectly, climate change exacerbates disease pressure by altering pathogen dynamics and wide range of vectors. Warmer conditions and changing precipitation favour the spread of vector-borne disease while increased humidity and flooding create ideal breeding grounds for parasites and waterborne pathogens. These shifts heighten the frequency and severity of infectious outbreaks, posing serious threats to herd health and food security. To build resilience in livestock systems, comprehensive mitigation and adaptation strategies are essential. These include developing climate-resilient breeds through selective breeding for heat tolerance and disease resistance, implementing improved shelter designs and shading, adopting precision nutrition and water management, strengthening early warning systems for disease surveillance, and preserving natural habitats that support biodiversity and buffer environmental extremes. Equally important are sustained efforts in public education, community engagement, and policy support to raise awareness and promote sustainable practices across farming communities. Only through integrated, proactive approaches can livestock systems adapt to a changing climate and remain viable for future generations.

Keywords: Climate change, Animal health, Livestock production, Strategies.

INTRODUCTION

Climate change has emerged as the defining global challenge of the 21st century. The steady rise in earth's average surface temperature stands out as one of its most alarming consequences. This ongoing climate disruption is profoundly affecting ecosystems, economies, and human societies in numerous ways. Climate change is a crucial global issue that has far-reaching consequences, including its impact on animal health. As temperatures rise and weather patterns become more erratic, animals are faced with new challenges and risks to their well-being (IPCC, 2022).

Among the most visible impacts are shifting weather patterns, rapid melting of polar glaciers, rising sea levels, and altered rainfall distribution. These changes are occurring at an unprecedented pace, largely driven by human activities i.e. primarily the burning of fossil fuels, widespread deforestation, industrial expansion, and accelerated urbanization and all of which release massive quantities of greenhouse gases into the atmosphere.

Carbon dioxide (CO_2), released mainly from the combustion of coal, oil, and natural gas, remains the dominant contributor to long-term climate change. While methane (CH_4) and nitrous oxide (N_2O) are far more potent greenhouse gases per molecule, their shorter atmospheric lifetimes mean they play a comparatively smaller role over longer timescales. Major sources of methane include landfills, rice cultivation, livestock digestion and natural gas leaks, while nitrous oxide mainly comes from nitrogen fertilizers used in agriculture.

Climate change represents one of the defining challenges of our time, with far-reaching consequences for the planet including the health of animals. Rising global temperatures, shifting rainfall patterns, and the increasing frequency and intensity of extreme weather events are rapidly altering ecosystems and posing serious threats to animal welfare. Understanding these impacts and implementing effective adaptation and mitigation strategies is essential for safeguarding biodiversity, ensuring food security, and maintaining healthy, resilient ecosystems. Together with other human-driven pressures, climate change disrupts both natural and agricultural systems, affecting animal health. Changes in host distribution, population density, and exposure to existing pathogens are driving the emergence and spread of diseases in animals and animal-human interface.

GLOBAL AND NATIONAL CLIMATE CHANGE SCENARIOS

Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming (IPCC, 2021). According to the IPCC Sixth Assessment Report (AR6) Working Group I, global surface temperature increased by 1.09°C (likely range: 0.95–1.20°C) in 2011–2020 compared to the pre-industrial baseline (1850–1900), with larger warming over land at 1.59°C (1.34–1.83°C) than over the ocean at 0.88°C (0.68–1.01°C) (IPCC, 2021). Global net anthropogenic greenhouse gas (GHG) emissions reached an estimated 59 ± 6.6 $GtCO_2$-eq in 2019, representing a 12% increase (6.5 $GtCO_2$-eq) from 2010 and a 54% increase (21 $GtCO_2$-eq) from 1990. The largest share and absolute growth in gross emissions came from CO_2 from fossil fuel combustion and industrial processes (CO_2-FFI), followed by methane (CH_4), while fluorinated gases (F-gases) exhibited the highest relative growth from low baseline levels in 1990. Average annual GHG emissions during 2010–2019 were higher than in any previous decade on record (IPCC, 2023).

In developing nations such as India, rapid population growth, economic development, urbanization, industrial expansion, and environmental degradation compound the challenges of managing global warming and climate change. India's average annual temperature has risen by approximately 0.7°C between 1901 and 2018, aligning closely with the global average during this period (Krishnan *et al.*, 2020). Projections under high-emission scenarios indicate that India's average temperature could increase by about 4.4°C by 2100 relative to the 1976–2005 baseline (Krishnan *et al.*, 2020). The impacts of climate change are far-reaching and affect all aspects of the Earth's natural systems, including. **Rising sea levels:** Melting glaciers and thermal expansion of oceans contribute to rising sea levels, threatening coastal communities, and ecosystems. **Ocean acidification:** Increased CO_2 absorption by oceans makes them more acidic, harming marine life that relies on calcium carbon ate to build their shells and skeletons. **Disrupted weather patterns:** Climate change disrupts weather patterns, leading to more frequent and severe droughts, floods, heat waves, and wildfires (Hoegh and Bruno, 2010; Trenberth *et al.*, 2014; IPCC, 2022).

Significant regional changes in precipitation patterns have also occurred. Summer monsoon rainfall (June–September) declined by around 6% between 1951 and 2015, with notable reductions over the Indo-Gangetic Plains and the Western Ghats. In contrast, the frequency of extreme daily precipitation events (exceeding 150 mm/day) increased by about 75% over central India during the same period (Krishnan *et al.*, 2020). The frequency and spatial extent of droughts have risen significantly from 1951 to 2016, particularly affecting central India, the southwest coast, the southern peninsula, and north eastern regions (Krishnan *et al.*, 2020).

IMPACTS OF CLIMATE CHANGE

The impacts of **climate change** are multifaceted, profoundly affecting ecosystems, human societies, animals, and the broader environment, as comprehensively assessed by the Intergovernmental Panel on Climate Change (IPCC, 2021) in its Sixth Assessment Report (AR6).

Climate change is a looming threat to animal health across the globe. Rising temperatures and erratic weather patterns disrupt the delicate balance of ecosystems, leading to a cascade of negative effects on animal populations. Delving deeper into the specific ways climate change is impacting animal health shows some devastating consequences (Eissa, 2024).

IMPACTS OF CLIMATE CHANGE ON ANIMALS

Climatic factors including rising ambient temperature, relative humidity, solar radiation, and altered precipitation patterns **-** directly and indirectly influence feed and water availability, fodder quality, heat stress, production performance, animal growth, reproduction, and disease occurrence.

Temperature rise is the dominant driver affecting most critical aspects of livestock production. It reduces feed intake, impairs growth rates, lowers milk and meat yields, and reproductive efficiency. For instance, heat stress leads to metabolic disruptions, oxidative stress, and immune suppression, increasing vulnerability to infections and potentially causing mortality in severe cases (Thornton *et al.*, 2022).

Forage quantity and quality are adversely affected by the combined influences of higher temperatures, elevated CO_2 and shifting precipitation patterns, leading to reduced pasture productivity and greater reliance on supplemental feeds in many regions (IPCC, 2022).

Disease occurrence is primarily driven by temperature increases and variations in rainfall patterns. Higher temperatures and humidity shifts expand the geographic range and seasonality of vector-borne and parasitic diseases, while heat stress weakens immune responses, facilitating pathogen proliferation and outbreaks (Caminade *et al.*, 2019; IPCC, 2022).

THE EFFECTS OF CLIMATE CHANGE ON ANIMAL HEALTH ARE CATEGORIZED INTO DIRECT AND INDIRECT IMPACTS:

DIRECT EFFECTS: Direct effects of climate change on animal health primarily arise from alterations in environmental conditions, including elevated air temperature, relative humidity, precipitation patterns, droughts, and floods. These factors contribute to temperature-related morbidity and mortality in livestock, with heat stress being the predominant direct impact (IPCC, 2022; Thornton *et al.*, 2022).

a) Heat stress: Animals maintain physiological processes within an optimal range known as the thermal neutral zone or thermal comfort zone. When ambient temperatures exceed the upper critical limit of this zone, heat stress occurs, influenced by temperature, humidity, species, breed, age, and physiological status (e.g., lactation, growth stage). Heat stress disrupts metabolism, physiology, endocrine function, and immune responses, leading to reduced performance and welfare. Long-term environmental changes on animal health can be physiologically monitored through indicators such as rectal temperature, pulse and respiration rates, metabolic rate, endocrine profiles, and oxidative status. (Bernabucci *et al.*, 2002; Thornton *et al.*, 2022). Projections indicate substantial risks, temperature increases exacerbate extreme heat stress globally, particularly in tropics and some temperate zones. For cattle, a 1–5°C rise can lead to significant productivity losses and, in extreme scenarios (e.g., heatwaves), elevated mortality in grazing systems. Recent modeling using CMIP6 data estimates that without adaptation, heat stress could expose over 1 billion cattle to extreme conditions by century's end under high-emission pathways, with pronounced effects on dry matter intake, liveweight gain, milk yield, and fertility (Thornton *et al.*, 2022; North *et al.*, 2023).

b) Effect on Productivity and animal welfare: Among climatic variables, ambient temperature fluctuations have the most drastic impact on livestock production. Heat stress reduces feed intake (typically 3–5% per additional degree above the thermoneutral zone), impairs feed conversion ratio **(**FCR**)**, and decreases nutrient utilization efficiency, resulting in lower growth rates, milk yields, and overall output (Thornton *et al.*, 2022; IPCC, 2022). In India, heat stress has been estimated to cause significant monetary losses, equivalent to approximately 2% of total national milk production annually (around 1.8 million tonnes in earlier assessments), with projections indicating escalating losses in key regions like the northern plains (e.g. 361–377 thousand tonnes annually projected for 2010–2039 under moderate scenarios, and up to 3.4 lakh tonnes by 2030 in high-density areas) (Choudhary and Sirohi 2022).

The poultry industry is similarly compromised, with production declining sharply at temperatures above 30°C**.** Heat stress in birds reduces body weight gain**,** feed intake**,** carcass weight**,** and meat quality parameters such as protein and muscle calorie content, alongside increased FCR and mortality risks (Esminger *et al.*, 1990; Tankson *et al.*, 2001; recent reviews: Nawaz *et al.*, 2021; Goo *et al.*, 2019; Wasti *et al.*, 2020). Chronic exposure further impairs growth performance, with studies showing reductions in body weight gain by up to 32.6% and feed intake by 16.4% in affected broilers.

c) Effect on Reproductive efficiency: In males**,** elevated environmental temperatures impair semen quality and libido**.** Sertoli cells, crucial for spermatogenesis, are primary targets of heat stress, leading to disrupted sperm maturation and increased oxidative damage (Ahmad *et al.*, 2022). Heat stress is associated with reduced sperm concentration, motility, and overall quality in bulls, pigs, and poultry, with effects persisting for weeks post-exposure due to the ~60-day spermatogenesis cycle in bulls (Karaca *et al.*, 2002; Kunavongkrit *et al.*, 2005; Morrell, 2020; Brito *et al.*, 2023). Livestock farming is facing growing challenges due to climate change. Both animal welfare and male fertility are parameters easily affected by thermal stress. Spermatogenesis is a highly thermosensitive process, and therefore heat stress leads to a marked decrease in the fertilizing capacity of spermatozoa (Capela *et al.*, 2022). Semen quality from the same bulls had a 90% pass rate for cryopreservation purposes in winter, dropping to less than 50% in summer (Netherton *et al.*, 2022).

In females, rising temperatures and humidity disrupt follicular dynamics**,** oocyte competence**,** and estrus expression**,** often resulting in a higher incidence of silent heat or anestrus (Barati *et al.*, 2008). Heat stress alters oocyte growth and quality in cows and pigs, impairing embryo development, fertilization rates, and pregnancy establishment through mechanisms like reduced estradiol production and granulosa cell viability (De Rensis and Scaramuzzi, 2003; King *et al.*, 2006; Roth *et al.*, 2022). Poor fertility is further linked to energy deficits, hormonal imbalances (e.g., lower LH and progesterone), and carry-over effects lasting 2–3 estrous cycles, with conception rates dropping 20–30% in summer (Roth *et al.*, 2022; IPCC, 2022). Semen quality and libido get affected by heat stress. The primary target cells for heat stress are Sertoli cells (Ahmad *et al.*, 2022). Existing climatic conditions and the rise of temperatures affects the testes and impose detrimental effects on the seminal parameters.

INDIRECT EFFECTS: Indirect effects of climate change on animal health and production primarily stem from alterations in microbial density**,** shifts in the distribution and abundance of vector-borne diseases**,** food and water shortages, and increased risks of foodborne or waterborne diseases. These pathways disrupt the complex interactions among hosts, pathogens, and the environment, often exacerbating disease emergence and transmission (Lacetera, 2019; IPCC, 2022). Rising temperatures can alter precipitation patterns and extreme weather events due to a negative impact on livestock productivity and exacerbate zoonotic disease transmission. Climate change affects the spread of zoonotic diseases by altering the distribution of vectors, pathogens, and hosts.

a) Disease occurrence and epidemiology are influenced by any climate-related factor that modifies the host-pathogen-environment triangle. Under changing climate scenarios, there is an increased probability of emergence or re-emergence of many zoonotic and parasitic diseases in livestock. Climate change can alter pathogen transmission routes, expand outbreak potential for serious illnesses, and introduce new diseases to previously unexposed populations, with vector-borne, waterborne, and foodborne pathogens being particularly sensitive (Caminade *et al.,* 2019; IPCC, 2022; Thornton *et al.,* 2022).

b) Vector-borne diseases are especially vulnerable, as climatic variables directly affect vector survival, replication, distribution, density, biting rates, and pathogen incubation periods within the vector. Arthropod vectors (e.g., mosquitoes, ticks) are highly sensitive to temperature, precipitation, humidity, and other environmental conditions that influence their reproduction, development, behavior, and population dynamics (Caminade *et al.*, 2019; IPCC, 2022). Hot and humid weather conditions typically lead to a significant rise in the population of arthropod vectors, resulting in greater harm to animals during these favourable periods (Sridhar *et al.,* 2020).

c) Climate change affects pathogens: Climate change significantly influences pathogen dynamics in livestock systems, altering transmission patterns, seasonal cycles, and outbreak risks through changes in temperature, precipitation, and extreme weather events (Caminade *et al.,* 2019; IPCC, 2022; Thornton *et al.,* 2022). The number of infectious cycles for seasonally sensitive diseases can increase or decrease depending on the duration and intensity of the warm season. Warmer conditions often lengthen transmission seasons by shortening pathogen generation times, accelerating vector development, and enabling more generations per year for warm-associated pathogens, while potentially reducing cycles for cold-sensitive ones. This leads to higher pathogen loads and extended periods of risk in many regions (IPCC, 2022; Baylis and Risley, 2023).

Extreme weather events**,** particularly flooding**,** exacerbate pathogen spread by causing agricultural runoff from livestock farms and contaminated lands to pollute water supplies. This runoff introduces zoonotic pathogens such as entero-haemorrhagic Escherichia coli (EHEC, e.g., O157:H7) and Cryptosporidium parasites into farm water systems, threatening livestock health through waterborne transmission and increasing risks of outbreaks. Flooding also facilitates broader contamination of surface waters, heightening zoonotic spillover potential to humans via shared water resources (Ten Veldhuis *et al.* 2010; IPCC, 2022).

d) Feed and water availability

Feed and water availability for livestock are profoundly influenced by geographical, seasonal, and climatic conditions, with climate change altering fodder quantity and quality through rising temperatures, shifting precipitation patterns, elevated atmospheric CO_2, and increased frequency of extreme events like heatwaves and droughts (IPCC, 2022; Thornton *et al.,* 2022).

In arid and semi-arid regions**,** temperature increases are particularly harmful to pasture and livestock production, as they exacerbate evapotranspiration, reduce soil moisture, and shorten growing seasons in many cases. The continuous rise in biospheric temperatures has modified the quantity, distribution, and reliability of average annual precipitation, while primary drivers such as elevated CO_2 concentrations can stimulate plant growth (CO_2 fertilization effect) but often reduce nutritional quality in forages e.g., lower protein, minerals, and digestibility in C3 grasses (Godde *et al.*, 2021; IPCC, 2022). Climate change is simultaneously increasing carbon dioxide concentrations (CO_2) and temperature. These factors could interact to influence plant physiology and performance. (Denney *et al.*, 2024)

Water scarcity is a growing global constraint, with its magnitude determined by supply relative to demand. Climate change contributes to reduced water availability and altered usage in animal production systems**.** Rising temperatures are projected to increase per-animal and per-land-area water consumption (due to higher evapotranspiration and physiological needs), as well as irrigation demands for feed crops. Additional concerns include increased water salinity from sea-level rise in coastal areas and intensified competition for water among livestock, crops, and non-agricultural uses in coming decades (Konapala *et al.*, 2020; IPCC, 2022).

CLIMATE CHANGE AND ZOONOSIS

Climate change and zoonoses represent interconnected global health threats, as environmental shifts facilitate the emergence, re-emergence, and altered transmission of zoonotic pathogens diseases transmitted between animals and humans. Current consensus from authoritative sources, including the World Health Organization (WHO), Centers for Disease Control and Prevention (CDC), and United Nations Environment Programme (UNEP), indicates that approximately 60% of known infectious diseases in humans are zoonotic in origin, while up to 75% of emerging or re-emerging infectious diseases originate from animals (WHO, 2023–2025 updates; CDC, 2024; UNEP-ILRI, 2020). Zoonotic pathogens thus tend to be associated with emerging processes more frequently than non-zoonotic ones, driven by factors like land-use change, biodiversity loss, and climate variability.

STRATEGIES TO MITIGATE RISKS

Adaptation and mitigation strategies are crucial for bolstering livestock resilience to climate change while curbing the sector's contribution to greenhouse gas (GHG) emissions. Adaptation enhances animal tolerance to stressors such as heat, drought, and disease, whereas mitigation can substantially lower livestock-related emissions through improved efficiency and management (FAO, 2020; IPCC, 2022; Bashiru and Oseni 2025).

Climate-resilient animal breeding is central to developing breeds that endure rising temperatures, emerging pathogens, and resource limitations. Selective breeding programs prioritize heritable traits like heat tolerance (e.g., enhanced sweating, lower respiration rates, lighter coat color, and smaller body size), disease resistance, and efficient feed conversion, fostering genetic diversity and long-term sustainability. Genomic advancements and molecular biology facilitate the identification of key genes (e.g., those involved in heat shock response, skin/hair thermoregulation, oxidative stress) and enable genomic selection for accelerated progress (Renaudeau *et al.*, 2012; Cheng *et al.,* 2022). Producers can transition to or crossbreed with inherently heat-tolerant breeds, such as Bos indicus (zebu) cattle and derivatives, which demonstrate superior thermotolerance, parasite resistance, and adaptation to tropical/subtropical environments compared to Bos taurus (Barendse, 2017). Selective breeding programs play a pivotal role in developing animal breeds that can withstand the challenges posed by a changing climate. Through careful selection of traits such as heat tolerance, disease resistance, and efficient resource utilization, scientists and farmers can create livestock varieties that are better adapted to rising temperatures and emerging diseases. These climate-resilient breeds not only ensure sustainable livestock production but also promote genetic diversity within animal populations, enhancing their overall resilience to environmental stressors (Saldana *et al.,* 2023).

Management modifications strengthen system resilience through diversification and integration. These include diversifying livestock species and crop varieties to boost tolerance to drought, heatwaves, and precipitation variability; integrating livestock with forestry and crop production for enhanced resource use, soil health, biodiversity, shade provision (reducing surface temperatures by 2–5°C), carbon sequestration, and diversified income, and adjusting farm operations (e.g., grazing timing, location, water management) (IFAD, 2010). Diversification mitigates climate-related disease risks and extreme events, while silvopasture systems offer microclimate regulation, improved forage quality, and economic buffers via multiple revenue streams. Agroforestry practices play a crucial role in enhancing climate resilience, particularly in regions vulnerable to climate variability. Quantitative studies reveal that agroforestry systems improve soil fertility, water retention, and crop productivity, reducing vulnerability to droughts and other climate-induced stresses (Abebaw *et al.,* 2025).

ROBUST SURVEILLANCE

Robust surveillance systems in veterinary services are vital for monitoring climate-sensitive diseases in livestock, enabling early detection of shifts in pathogen distribution, vector activity, and outbreak patterns driven by warming temperatures, altered precipitation, and extreme events (FAO, 2020; IPCC, 2022). Investments in advanced diagnostic tools, data analytics, and integrated surveillance platforms allow veterinarians and researchers to identify emerging or re-emerging diseases more rapidly and reliably. Early detection facilitates prompt interventions such as targeted vaccination campaigns, treatment protocols, movement restrictions, and quarantines preventing escalation into large-scale epidemics that threaten animal populations, livelihoods, and food security (FAO EMPRES-AH, ongoing since 1994; WOAH/FAO GF-TADs, 2004–present).

EFFECTIVE PREVENTIVE MEASURES

An effective strategy for adapting livestock production to climate change requires a multidisciplinary perspective. It must integrate expertise from fields such as agricultural sciences, financial analysis, social studies, governance frameworks, and ecology. National authorities and scientific organizations need to promote cross-disciplinary partnerships to create targeted policies, innovative tools, and assistance initiatives for producers that balance societal, financial, and ecological priorities. By adopting an interdisciplinary approach, LMICs can enhance their adaptive capacity, ensure food security, and promote sustainable livestock production systems in the face of climate change challenges (Sargison, 2020). Insights from the social sciences are vital in adaptation planning, as they help ensure interventions respect community expertise, cultural practices, and specific requirements. Effective adaptation requires participatory approaches where livestock farmers, extension officers, and policymakers collaborate to design context-specific solutions (Andrieu *et al.,* 2019). Such involvement can significantly boost participation in efforts like locally driven breeding schemes. In addition, farmer cooperatives and knowledge-sharing networks can enhance resource pooling and dissemination of best practices for adaptation (Eise *et al.*, 2021). Incorporating social insights is also critical for overcoming reluctance toward novel tools via targeted awareness and behavior-modification efforts.

Financial considerations are equally important to render adaptation options affordable and appealing for livestock keepers in LMICs. Authorities, banks, and global bodies should fund supportive structures across various levels. For example, climate insurance and credit access that provide livestock farmers with insurance schemes against climate-induced losses can enhance resilience and encourage investment in climate-smart technologies (Kramer, 2023). Additionally, economic rewards such as labeling schemes and higher prices for eco-friendly meat, milk, and eggs can motivate shifts toward resilient practices. Joint ventures involving state agencies, research bodies, and private enterprises can channel resources into advanced monitoring systems, clean energy adoption, and predictive alerts for livestock operations.

Truly sustainable approaches must reduce the ecological impact of livestock farming while building greater tolerance to climatic stresses. This can involve nature-based methods, such as combining trees, bushes, and grasslands in silvopastoral setups (trees, shrubs, and pasture). These systems boost carbon storage, elevate feed nutrition, and offer natural cooling to lessen heat-related strain on animals. Improved handling of water and feed resources via techniques like collecting rainfall, optimized watering, and drought-tolerant forage varieties helps maintain reliable supplies. Furthermore, converting animal manure into biogas not only cuts methane release but also supplies clean power to countryside communities.

ONE HEALTH APPROACH

The One Health approach is an integrated, unifying strategy that aims to sustainably balance and optimize the health of people, animals, plants, and ecosystems. Climate-sensitive changes in animal disease patterns can increase zoonotic risk through higher pathogen circulation in livestock, expanded vector habitats, and increased human exposure during outbreaks and disasters. Veterinary and public health services may face higher workload and surveillance demands, while farm workers experience direct heat-related occupational risks.

WOAH's recent communications and technical materials emphasize strengthening surveillance and intersectoral collaboration to address endemic and zoonotic vector-borne diseases under changing climates. From a food safety perspective, climate change can increase contamination risks (water quality deterioration, cold chain disruptions, higher bacterial growth rates) and influence mycotoxin patterns in feed, with downstream animal health and residue implications.

RELEVANCE TO CLIMATE CHANGE, ANIMAL HEALTH AND LIVESTOCK

Climate change amplifies One Health risks by altering pathogen dynamics, vector ranges (e.g., ticks, mosquitoes), wildlife-human interfaces, and livestock vulnerability (e.g., heat stress, forage scarcity, disease outbreaks). A One Health lens supports adaptation through integrated surveillance, resilient agrifood systems, and ecosystem restoration to mitigate spillover risks and sustain animal production (Lacetera, 2019; IPCC, 2022). In this context, it addresses production-limiting issues like zoonoses (e.g., brucellosis), AMR from overuse of antibiotics, and food chain safety, while promoting climate-resilient practices (FAO, 2020).

CONSERVATION OF NATURAL HABITATS

Conservation of natural habitats and ecosystem restoration are two essential, synergistic strategies for mitigating the adverse effects of climate change on animals, including wildlife and livestock. These nature-based approaches enhance biodiversity resilience, provide refuges and migration pathways, and support essential ecosystem services such as food availability and habitat stability (FAO, 2020; IPCC, 2022; IUCN, 2023).

Protected areas, ecological corridors and forestry programs are key conservation measures. Protected areas act as refuges for species during climate extremes, conserve gene pools, and facilitate adaptation by offering high-quality, less-vulnerable habitats. Ecological corridors enable species movement in response to shifting climate conditions, reduce fragmentation impacts, maintain genetic diversity, and boost overall ecosystem resilience - critical as climate change drives range shifts and habitat loss (Tekola *et al.*, 2012; IUCN, 2023). Restoring degraded ecosystems, such as wetlands, forests, mangroves, peatlands, and grasslands, not only sequesters significant carbon dioxide from the atmosphere but also recreates vital habitats for diverse animal species, supports breeding/nesting grounds, and improves resilience to extremes like droughts and floods (IPCC, 2022; Mitsch and Gosselink, 2015). Restoration efforts, including coastal and inland wetland rehabilitation, provide thermal buffers, reduce erosion, and offer nurseries for marine/livestock-related species while mitigating climate impacts. Collaboration among governments, local communities, Indigenous peoples, and conservation organizations is fundamental for establishing, managing, and effectively governing these protected and restored areas, ensuring equitable benefits, respect for rights, and long-term protection of vulnerable species and ecosystems (IPCC, 2022; IUCN, 2023).

PUBLIC AWARENESS AND EDUCATION

Public awareness and education are indispensable for building support and driving action on the intricate links between climate change, animal health, livestock sustainability, and broader environmental health. Targeted campaigns for farmers, policymakers, the general public, and animal caregivers highlight the importance of sustainable practices, reduced emissions, resilient systems, and ethical animal welfare in the context of climate challenges. Education fosters behavioural shifts toward lower-impact diets, improved management, and policy support, addressing awareness gaps that contribute to under-emphasis on livestock's climate role (Happer and Wellesley 2019). Initiatives under One Health frameworks integrate veterinary, public health, and environmental education to promote holistic solutions.

CONCLUSION

The mechanisms through which climate change affects animal health, disease transmission, and human health are frequently oversimplified in public discourse and some analyses. While climate variables like temperature, precipitation, and extreme events clearly influence pathogen ecology, vector dynamics, host susceptibility, and transmission pathways, only a limited number of studies provide rigorous, field-validated evidence of direct causal effects attributable solely to climate change, often due to confounding factors such as land-use changes, biodiversity loss, and anthropogenic drivers (Lacetera, 2019; IPCC, 2022; Caminade *et al.*, 2019). The flare-up of insect vectors, livestock-origin diseases and surges in food safety hazards are projected to persist and intensify for decades under ongoing warming scenarios. These trends arise from expanded vector ranges, prolonged transmission seasons, altered pathogen survival, and increased extreme weather facilitating contamination (FAO, 2020; IPCC, 2022; Thornton *et al.*, 2022).

Comprehensive risk analysis must consider the broader context of transmission ecology for insects, pests, and diseases. Transmission involving prominent free-living parasite stages is particularly modulated by environmental factors, with wetter/warmer conditions favouring parasite proliferation and snail intermediate hosts (Caminade *et al.*, 2019).

Effective risk management for emerging disease complexes - where climate change acts as a key driver alongside other factors is best addressed through a "One Health" framework. This integrated approach unites human, animal, plant, and environmental health sectors for holistic surveillance, early warning, prevention, and response, emphasizing transdisciplinary, equity, and multisectoral collaboration to mitigate interconnected threats like zoonoses, AMR, and foodborne risks (FAO 2020; IPCC, 2022).

Climate change is reshaping animal health risks through direct heat stress, altered disease ecologies, and system disruptions from extreme events. Evidence consistently indicates negative impacts on productivity, reproduction, welfare, and disease risk across livestock systems, with particularly strong data supporting heat stress impacts in dairy cattle. Strengthening resilience requires integrated strategies: climate-smart housing and cooling, improved feed–water security, vector and parasite management, risk-based vaccination, and climate-informed surveillance under a One Health framework. Global guidance underscores surveillance and adaptive management as essential to address escalating climate-sensitive disease threats. Coordinated investments in prevention, early warning, and resilient veterinary systems will be critical to protect animal health, livelihoods, and food security in the coming decades.

FUTURE SCOPE

The future scope of addressing climate change impacts on animal health lies in advancing rigorous, multidisciplinary research to disentangle direct climatic effects from confounding drivers like land-use change and biodiversity loss, thereby generating robust, field-validated evidence for causal attribution. Projections indicate persistent intensification of vector-borne diseases, livestock pathogens, and food safety risks under continued warming, necessitating enhanced predictive modeling of shifting transmission ecologies, expanded vector ranges, and prolonged seasons. A key priority is scaling the One Health framework globally through strengthened transdisciplinary collaboration, integrated surveillance systems, early warning mechanisms, and equity-focused interventions that unite human, animal, plant, and environmental sectors to mitigate zoonoses, antimicrobial resistance, and interconnected threats. Investments in climate-resilient veterinary infrastructure—such as adaptive housing, vector/parasite controls, risk-based vaccination, and climate-informed monitoring—will be essential to bolster livestock resilience, safeguard productivity, reproduction, and welfare, while protecting livelihoods and food security. As emerging disease complexes evolve amid accelerating environmental changes, coordinated global action, innovative technologies, and policy alignment offer promising pathways to build adaptive capacity and reduce vulnerabilities in the coming decades.

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