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A One Health Approach to Reducing Livestock Disease Prevalence in Developing Countries: Advances, Challenges, and Prospects

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Abstract

Challenges in livestock production in developing countries are often linked to a high disease prevalence and may be related to poor husbandry, feeding, and nutrition practices, as well as to inadequate access to preventive veterinary care. Structural barriers including chronic poverty, gender roles, inadequate supply chains, and limitations in surveillance infrastructure further complicate progress. Despite many challenges, the livestock sector substantially contributes to agricultural GDP, and reducing livestock disease prevalence is a goal for many countries. One Health initiatives that work across disciplines and sectors to reduce livestock diseases are underway around the world and use integrated approaches that consider the connections between humans, animals, and their shared environments. The growing recognition of the role livestock play in sustainability and livelihoods, as well as their involvement in zoonotic disease transmission and global health security, has highlighted the need for disease reduction strategies as described in this review.

INTRODUCTION

There are nearly 40 billion livestock (including pigs, sheep, goats, cattle, and poultry) around the world; more than half live in developing countries (1). By 2050, livestock product demand is expected to increase dramatically in response to growing populations and increased incomes (2, 3). To meet this demand, livestock production practices continue toward intensification and commercialization, presenting added environmental and ethical concerns. Livestock serve many roles in developing countries, contributing to food security, livelihoods, savings, women's empowerment, and economic development (4). Livestock-derived products also provide high-quality, bioavailable, nutrient-dense animal-source foods, which vastly improve diet quality and positively impact cognitive development and growth, particularly during a child's first 1,000 days (from conception to 2 years old) (5).

Historically, livestock production in developing countries has been challenged by a high disease prevalence, often coupled with poor husbandry, feeding, and nutrition practices and inadequate access to preventive veterinary care including vaccines, appropriate pharmaceuticals, and animal health service providers. Zoonotic diseases are strongly correlated with poverty, with much of the global burden occurring in poor countries (6). Poor livestock keepers are particularly vulnerable to the effects of animal diseases, which can have a major impact on their incomes and livelihoods (7). Despite advancements in diagnostics, data sharing, and disease reporting, there is an incomplete picture of the burden of livestock disease globally. Recently, the World Organization for Animal Health (WOAH) launched the Global Burden of Animal Diseases initiative to better understand the economic burden of animal diseases (8).

Implicit in the success of a livestock sector is that livestock are healthy and reproductively sound. A thriving agricultural sector can fuel economic growth, create jobs, increase rural incomes, and reduce malnutrition (9). The estimated global market value of livestock production is similar to global crop production (~2.57 trillion USD) (10). Though it varies between countries, the livestock sector contributes substantially to agricultural GDP, with a global average of 40% (11). Furthermore, the livestock sector and its broad connections with the economic and social fabric of communities are directly and indirectly connected to more than half of the UN Sustainable Development Goals (12). For these reasons, livestock sector investment and decreasing livestock disease prevalence are a common thread across many developing countries' strategic plans. Achieving gains in this domain has also been a priority of bilateral donors, international organizations, and philanthropies in the last few decades. This has been driven by several factors, including international attention to livestock disease eradication efforts, such as the rinderpest eradication campaign, and outbreaks of highly pathogenic avian influenza (HPAI) in the early 2000s. The growing recognition of the role livestock play in emerging zoonotic diseases with pandemic potential, the increasing global demand for livestock products and animal-source food, population growth, the environmental footprint of livestock, and alarming increases in antimicrobial resistance have all refocused livestock disease reduction efforts.

Many of these disease reduction efforts have adopted a One Health approach, recognizing that the health of animals, humans, and the environment are interconnected. Although not a new concept, this term gained traction in the early 2000s, following visionary work decades earlier by Calvin Schwabe and early promotion by wildlife conservation and ecology professionals (13, 14). Response to the severe acute respiratory syndrome outbreak (SARS) in 2003 furthered its recognition as an approach to complex challenges (15). The UN Quadripartite One Health High-Level Expert Panel (16) defines One Health as

> an integrated, unifying approach that aims to sustainably balance and optimize the health of people, animals, and ecosystems. It recognizes the health of humans, domestic and wild animals, plants, and the wider environment (including ecosystems) are closely linked and interdependent. The approach mobilizes multiple sectors, disciplines, and communities at varying levels of society to work together to foster well-being and tackle threats to health and ecosystems, while addressing the collective need for healthy food, water, energy, and air, taking action on climate change and contributing to sustainable development.

The UN Quadripartite includes the WOAH, the Food and Agriculture Organization, the World Health Organization, and the UN Environmental Program.

The international community has taken steps in operationalizing One Health approaches, intentionally working across sectors to address complex health challenges including zoonotic diseases and antimicrobial resistance. First published in 2014, the US Centers for Disease Control and Prevention developed a One Health Zoonotic Disease Prioritization Tool, which has helped countries and regions collaboratively identify and prioritize zoonotic disease threats of national concern. Designed to integrate input across the human health, agriculture, environment, and wildlife sectors, such tools have been used in many countries (17, 18). Conducting activities related to zoonotic disease prioritization has also helped countries take steps related to public health risk preparedness and is aligned with global metrics related to International Health Regulations and the Joint External Evaluation process (19). This is a voluntary, collaborative, multi-sectoral process that countries can use to identify gaps in their human and animal health systems and to strengthen their ability to address global health issues including zoonotic diseases. The Quadripartite One Health Joint Plan of Action (2022–2026) presents a framework and policy recommendations related to six interdependent action tracks designed to address key health challenges at the human–animal–plant–environment interface (20). Livestock disease surveillance and/or reduction efforts are a common thread across all six action tracts (**Figure 1**). Furthermore, many countries around the world have developed National One Health Strategic Plans or similar policies. These efforts illustrate the importance of policy setting and zoonotic disease prioritization as tools to focus collective energy on specific diseases and of institutionalizing cross-sectoral collaboration.

Reducing livestock disease prevalence in under-resourced settings frequently presents challenges. Inadequate diagnostic and surveillance infrastructure, weak governance, conflict and security issues, absent or inadequate biosecurity practices, wildlife–livestock interactions, remote communities, lack of cold chain, insufficient trained veterinary and paraveterinary personnel,

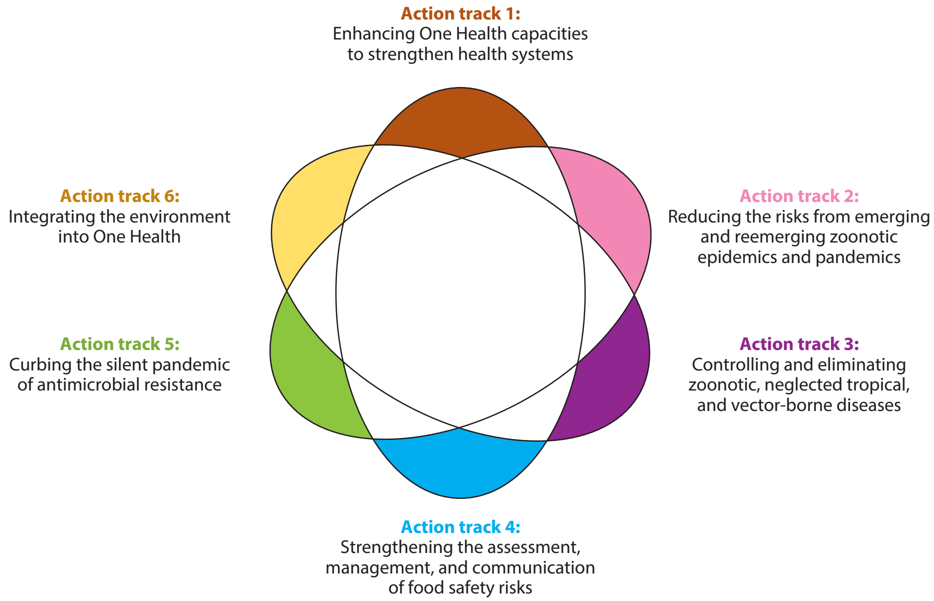

Figure 1

The Quadripartite One Health Joint Plan of Action (2022–2026) presents a framework and policy recommendations related to six interdependent action tracks designed to address key health challenges at the human–animal–plant–environment interface. Livestock disease surveillance and/or reduction efforts are a common thread across all six action tracts. Figure reproduced with permission from Reference 20.

transhumance, lack of access to vaccines and other pharmaceuticals, poverty, lack of empowerment, and more can all make addressing livestock diseases especially difficult. For these reasons, and recognizing that in many developing countries livestock husbandry practices are frequently integrated closely with the household and often are more exposed to environmental and ecological factors, the global animal health community is increasingly recognizing that adopting disease intervention approaches that reflect a One Health approach is important for successful outcomes (**Figure 2**).

The following sections summarize considerations and interventions that can improve livestock health rooted in a One Health approach. The examples highlight various diseases and interventions covering a range of geographies and livestock species. Interventions featuring vaccination approaches, the critical role of social science and community engagement, animal husbandry practices, and ecological countermeasures will help readers understand the breadth of different approaches to livestock health improvement. Specific case studies have been chosen to illustrate the interdependencies of highlighted concepts.

HOST-PATHOGEN-ENVIRONMENT CONSIDERATIONS

Over the past few decades, the wildlife–livestock interface has garnered increasing attention within the context of infectious disease dynamics and zoonotic disease risk. Interactions between livestock and wild animals have significant implications for the emergence, amplification, and transmission of pathogens that affect both animal and human populations. Wild animals are increasingly recognized for their role in livestock and human diseases as both spillover and maintenance hosts (21). Livestock frequently serve as amplifying hosts for zoonotic diseases that originate in wildlife and eventually spill over into people (22).

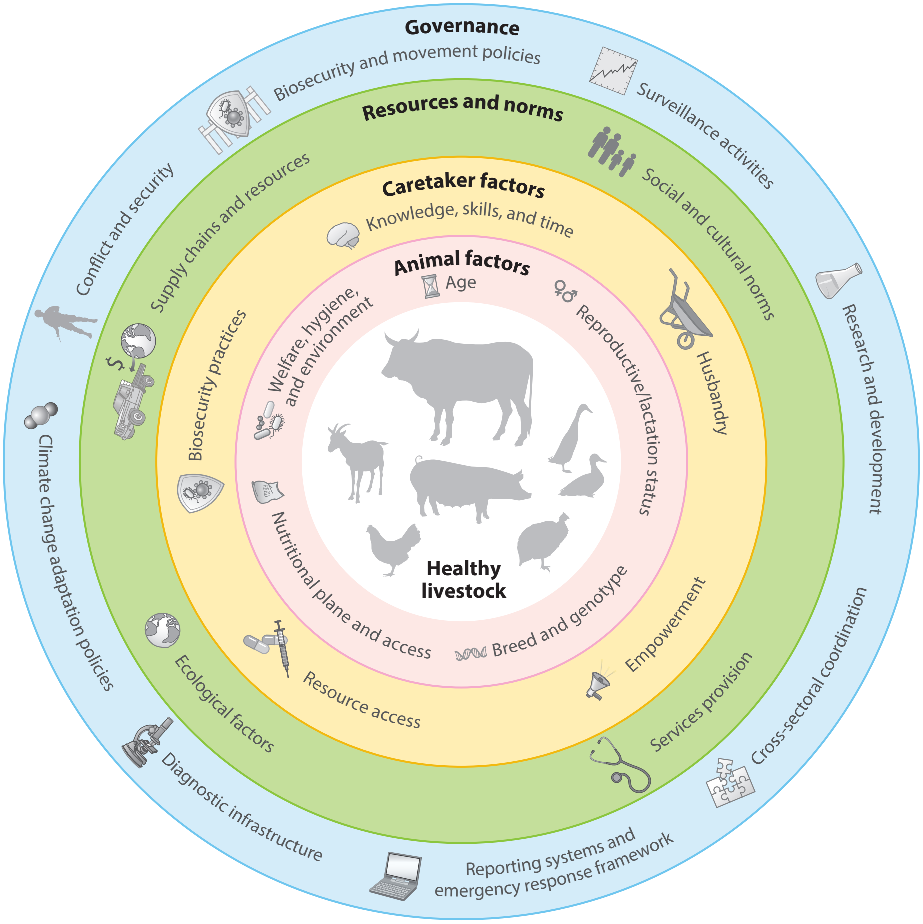

Figure 2

A One Health approach to livestock health recognizes that multiple layers of factors interact and influence animal health outcomes.

The factors driving emergence events are complex. Human-driven land-use change, which often includes encroachment into wildlife habitat, can influence the dynamics of infectious diseases in wildlife hosts, drive pathogen shedding in wildlife populations, and lead to novel contact opportunities between taxa, resulting in greater potential for cross-species transmission and pathogen spillover from wildlife to livestock and humans as well as spillback from these populations into wild animals (23–25).

Integrated disease surveillance and modeling play a pivotal role in enhancing our understanding of the underlying drivers of disease emergence and spread. By combining data collection across taxa groups with disease models, we can uncover patterns of zoonotic spillover and pathogen transmission that inform our understanding of disease dynamics. An integrated approach not only provides insights into the ecological and epidemiological factors driving spillover but also enables the identification of high-risk areas and vulnerable populations to target for surveillance and risk mitigation strategies. Using brucellosis and HPAI, we highlight how integrated surveillance and modeling have been used to elucidate the complexities of disease transmission pathways, identify hosts and their role in maintaining and spreading the pathogen, uncover risk factors for spillover and cross-species transmission, and inform interventions for disease prevention and control.

Brucellosis

Brucellosis remains a livestock and public health concern in many lower-income countries, with biovars of *Brucella abortus*, *Brucella melitensis*, *Brucella ovis*, *Brucella canis*, *and Brucella suis* recognized in livestock (26). Clinical signs of brucellosis infection in domestic animals include abortion, reduced fertility, and decline in milk production, with significant economic consequences (27). Human brucellosis presents with nonspecific clinical signs such as fever, malaise, fatigue, and arthritis (26).

Brucella species have been identified in a wide range of terrestrial and aquatic wildlife (28–32). When planning control measures for brucellosis, the presence of wildlife maintenance hosts must be considered (30). Spillback from wildlife to livestock is especially measurable in areas where brucellosis has been eradicated in domestic animals, such as the Greater Yellowstone area of the United States (21). Research has shown transmission events from cattle into wildlife in this area and that brucellosis spillovers into cattle now are predominantly from elk and not bison; spatial separation of bison and cattle has made transmission between cattle and bison uncommon (33, 34).

Disease transmission dynamics between wildlife and livestock are much harder to elucidate in areas where brucellosis is endemic in livestock. A meta-analysis of brucellosis in African wildlife showed that exposure to the disease has been documented in African buffalo, as well as various antelope, carnivore, and miscellaneous wildlife species on the continent, but so far, only the African buffalo has been proven to be a maintenance host for the disease (30). Livestock contact was found to be a predictor for brucellosis exposure in antelopes and carnivores (considered spillover species) but not in African buffalo, a reservoir species that maintains the disease without cattle contact (30).

Control methods for brucellosis in domestic livestock include vaccination, test and removal, and spatial separation from wildlife carriers (33). In high-income countries with well-funded veterinary services, eradication of brucellosis has been achieved through large-scale disease control campaigns. In contrast, in lower-income countries, targeted control measures may be more feasible and realistic to implement (27). Across much of the world, brucellosis remains a neglected, endemic zoonotic disease; more than 500,000 new cases are reported each year, but this is thought to be a vast underestimate of the true burden of the disease (35). Across sub-Saharan Africa and Asia, brucellosis has commonly been identified as a prioritized zoonotic pathogen, underscoring the continued importance of a multi-sectoral, multipronged approach to surveillance and disease reduction efforts (18, 19, 35).

H5N1 Highly Pathogenic Avian Influenza

Recent changes in the ecology of H5N1 HPAI highlight the importance of an integrated approach to disease surveillance for understanding and mitigating risk factors for emergence and spread of these complex zoonotic diseases circulating at the wildlife–livestock–human interface. Since detection of a new H5N1 HPAI virus lineage (goose/Guangdong lineage) in Asia in the 1990s, new genotypes and clades of these H5N1 viruses have emerged through multiple mutations and reassortments with other influenza A viruses during a series of spillover and spillback events between poultry and wild bird populations (36, 37). Ultimately, endemic circulation with repeated spillover from poultry to wild bird populations (38) led to widespread dissemination of the most predominant clade across Asia, Europe, Africa, and, more recently, North and South America and Antarctica (36, 39–43). Since 2021, this virus has caused unprecedented mortality events in wild birds and has also affected terrestrial and marine mammals (44–47). There have been human infections with this H5N1 HPAI virus; however, to date, these infections have been isolated and typically associated with domestic livestock contact (48).

Cross-species transmission of influenza A viruses is key in the evolution and ecological dynamics of these viruses. Wild aquatic birds are the primary reservoir hosts of influenza A viruses (49).

Low pathogenic avian influenza viruses of the subtypes H5 and H7 that circulate naturally in wild birds can acquire mutations in the H protein that lead to systemic infections with high mortality in poultry (HPAI). As a result, control efforts have focused primarily on prevention and eradication through strict biosecurity in poultry operations, isolation of exposed poultry, and culling of infected flocks (46, 50). However, recent integrated surveillance and molecular epidemiological studies have demonstrated a shift in the ecology of this virus (i.e., frequent infections and broad dissemination in wild avian hosts as well as recurrent spillover and spillback events between wild and domestic bird populations, and changes in the virus with cross-species transmission) (42, 44, 51). This has illuminated the complex interactions at the wild–domestic animal interface and the consequent challenges associated with control of this disease.

Epidemiological findings can inform recommendations for disease prevention and control measures (42, 44, 52). For example, many HPAI distribution models have illustrated how land cover, particularly the presence of wetlands, and environmental variables, which are often used as a proxy for the presence of wild birds, predict outbreak risk (53–55). In addition, Schreuder et al. (56) showed how spatial variation in HPAI outbreak risk in the Netherlands was predicted based on wild bird densities in addition to land cover variables. In addition, in 2023, Lambert and colleagues (52) conducted a systematic review of mechanistic models that have been applied to field outbreaks of avian influenza to better understand the characteristics of transmission and efficacy of control measures. According to the review, optimal control strategies varied by virus subtype, the local context, and the goal of the intervention. Overall, vaccination in poultry was optimal when the goal was to minimize the number of culled flocks. On the other hand, testing and culling was ideal for limiting the magnitude of the outbreak, and not surprisingly, early detection and response improved the efficacy of control measures, reinforcing the importance for surveillance and outbreak preparedness (52).

Given the changing dynamics of H5N1 HPAI clade 2.3.4.4b identified through models, uncertainties around host range and potential environmental persistence, and the complex multisectoral and multi-jurisdictional approach needed for disease control, Harvey et al. (57) have proposed decision analysis to aid in allocation of resources and prioritization of research to inform management and conservation actions. They offer structured decision-making as a means to provide a transparent and systematic framework for reducing uncertainty and informing the prioritization of resources and activities for H5N1 HPAI research and management actions.[1]

THE ROLE OF SOCIAL SCIENCE AND COMMUNITY ENGAGEMENT AND EDUCATION

The influence of societal factors on disease dynamics is increasingly recognized (58–61). Examples can be found in the COVID-19 pandemic, the 2014–2015 Ebola epidemic in West Africa, and the African swine fever (ASF) epidemic in Eastern Europe (62, 63). The understanding of how human behavior drove transmission of the Ebola virus, achieved through multidisciplinary, community-centered approaches drawing on social science, was critical to bringing that epidemic under control (64). Poor stakeholders face many specific challenges related to animal disease spread (65–67). In chronic poverty situations, which are the reality for many smallholder farmers across the world, low investments in farming lead to low levels of biosecurity, which in turn lead to high risk of spreading and attaining diseases, resulting in low and insecure income and livelihood

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[1] At the time of writing this manuscript (April 2024), H5N1 infection in dairy cows in multiple states across the United States and the first reported incident of dairy farm worker infected with H5N1 in Texas were actively being reported. The authors acknowledge that this field is rapidly changing, and new information is available daily (58).

shocks (68, 69). Poverty is thus both an important consequence of animal disease and a specific, unique factor influencing smallholders' possibilities to prevent and control diseases (70–72).

Understanding and representing different stakeholders' perspectives is central for limiting the spread, occurrence, and negative consequences of animal diseases (72, 73). Community education and outreach campaigns grounded in strong social sciences approaches are critical to reaching and maintaining positive relationships with communities often left out of mainstream policy decisions and social safety net programs. Methods such as participatory rural appraisal and other traditional anthropological research approaches have proven effective in reaching livestock producers and generating community-driven solutions that can reduce livestock disease, especially those that encourage interactive participation, local ownership, and self-mobilization (74, 75). Researchers in Rwanda demonstrated how a One Health framework that integrated education, research, and outreach facilitated a scalable approach through Extension Agents that improved hygienic milking practices and reduced mastitis indicators (76).

It is also crucial to recognize gender and the specific challenges women may face as livestock keepers or caretakers. A growing body of literature recognizes important gender differences related to livestock production and that women often face additional barriers to accessing services for the livestock they care for (77, 78). For example, Babo and colleagues (79) documented distinct knowledge differences about brucellosis between men and women in pastoralist communities in northwest Côte d'Ivoire. Other researchers have described how rigid gender norms can affect livestock value chains, vaccine administration, and vaccine distribution systems for Newcastle disease and peste des petits ruminants in Senegal (80).

African Swine Fever

ASF is a lethal hemorrhagic viral fever of pigs with no current cure or commercially available vaccine (81). Its introduction to the Caucasus region in 2007 started an unprecedented, global epidemic (82). Smallholder pig farming is part of the traditional way of life and an important component of agricultural livelihoods across the globe (83, 84). Globally and historically, it is in smallholder settings that ASF has proven most difficult to control, with activities such as trade in pigs and pork undertaken by poor people to earn their livelihood driving the infection (85, 86). At the same time, it has been known for more than 100 years that ASF spread can be prevented by applying basic biosecurity practices (87). Despite this, ASF continues to cause severe negative impacts for pig producers all over the world (88). The increasing global interest in ASF during the current epidemic has, however, created more understanding of the human dimensions of ASF epidemiology (89–91).

The response to this frequently has been to investigate smallholders' knowledge, attitudes, and practices (92–95). These studies generally report poor implementation of prevention and control measures but come to different conclusions about what is hindering implementation, and they are often based on the assumption that improved knowledge will lead to improved practice, a direct correlation that is seldom observed (96–98). As an example, a study from Uganda found that smallholder biosecurity knowledge changed after trainings, whereas their practices were not changed to the same degree (99). Societal and structural factors, such as peer pressure, poverty, and lack of access to animal health and veterinary services, have been reported to influence prevention and responses to disease outbreaks more than knowledge (59, 100).

Better understanding of the local social, economic, and cultural dimensions of pig keeping and disease transmission is thus essential for improving prevention and control of ASF (and hence for sustainably reducing disease and controlling impacts) (60). For this, local disease drivers need to be identified and understood, and livelihood contexts and stakeholder knowledge must be considered (69, 73, 101). Contemporary research further shows that to be effective, control measures need to be adapted so that they are scientifically relevant, possible to act on, and considered a priority among all other necessary tasks to perform in the complex day-to-day realities of subsistence pig farming (6, 102). Participatory and cocreational approaches engaging multiple stakeholders at the community level have proven effective in this regard (103, 104). Success factors mentioned are the cocreational process and broad community engagements as such, as well as the methods' ability to embed social, economic, and cultural factors of local ASF epidemiology into biosecurity advice adapted to the smallholder context.

Parasite Control

An example of an impactful, low-input, low-cost method of disease detection and treatment efficacy monitoring is the FAMACHA© system, which is a surveillance method for detecting livestock suffering the clinical effects of a gastrointestinal parasite, *Haemonchus contortus*. *H. contortus* is a parasite of small ruminants (sheep, goats) found worldwide, which causes anemia, weight loss, and ill-thrift, with loss of production if infections are severe. In addition to being a leading cause of production loss in small ruminants, in temperate and tropical regions, the resistance of *H. contortus* to all classes of anthelmintics is high and widespread across the globe (105–108). Sheep and goats are among the most important sources of animal protein globally and are critical for food security and livelihoods (109, 110).

The detection and quantification of *H. contortus* infections in livestock generally rely on individual or pooled fecal sampling and are unfeasible for most small producers. The FAMACHA© system was created by South African researchers to combat anthelmintic resistance in the detection and treatment of *H. contortus* (111, 112). The scoring system involves the evaluation of ocular mucous membrane color as an indicator of clinical anemia. Animals are examined using a reference chart on a laminated card and are assigned a score, and treatment decisions can be made based on their degree of clinical anemia indicated by their score. In this way, only animals unable to cope with the parasite burden are selectively treated with an anthelmintic, thus preserving a larger refugia of susceptible parasite genetics, decreasing treatment costs, and allowing culling decisions to be made without expensive diagnostics.

Since the FAMACHA© system's introduction in the mid-1990s, its use as an effective tool for selective deworming has been studied extensively in several different species (sheep, goats, camelids), production systems, and climates globally (111–117). With sufficient training, clinical evaluation of anemia was found to be reliable for practical use in most trainees, including trainees with low literacy rates (111, 112). Community outreach efforts to train nonveterinary livestock personnel have resulted in a widely adopted method of gastrointestinal parasite selective deworming in global communities and has even been used as part of community-based breeding programs as part of the African Goat Improvement Network to select and preserve phenotypic characteristics in goats that make them more resistant to disease (109, 118). The ability to easily train and get community buy-in with low-cost diagnostic decision-making tools has been highly impactful for the health and productivity of small ruminants, while simultaneously reducing the use of anthelmintics and slowing the rate of resistance development.

ANIMAL HUSBANDRY AND FARM BIOSECURITY PRACTICES

Successful livestock producers, regardless of region or species, will attest to the importance and value of good animal husbandry, including food, water, shelter, cleanliness, and low-stress handling. Additionally, following basic biosecurity practices appropriate to the species and production system, such as maintaining a closed herd; limiting visitor access to the herd; recording movements of people, vehicles, and animals on the farm; quarantining new animals; isolating sick animals;

maintaining records; separating pregnant and young stock from the rest of the herd; following cleaning and disinfection protocols; appropriately disposing of dead animals; and preventing interaction with wildlife or neighboring herds are all important to reducing livestock disease. However, in many low-resource settings, structural factors and barriers, including poverty, gender norms, competing time demands, inadequate feed and water resources, lack of effective and reliable supply chains, inadequate physical infrastructure, and weak institutions and policies, result in less than ideal husbandry and biosecurity practices (69). Often in these settings, disease and poor nutrition disproportionately affect the young and pregnant stock. The following example provides insights from Ethiopia.

Young Livestock Mortality

Ethiopia's livestock population, the largest in Africa, contributes 45% of its agricultural production (123). Cattle, the most economically significant subsector, were estimated at 70 million head in 2020 (124). Livestock development is fundamental to Ethiopia's sustainable growth, and a shift toward improved productivity, rather than increasing animal numbers, is necessary for sustainable growth (125). However, livestock development is constrained by high morbidity and mortality rates among young stock (123, 125, 126). Diarrhea and respiratory diseases are commonly found in sick young animals, and zoonotic pathogens such as *Cryptosporidium parvum* and *Escherichia coli K99* are also frequently identified (126). These pathogens are associated with environmental enteropathy, malnutrition, and stunting in young children in settings with poor water, sanitation, and hygiene (127, 128). Similarly, in young livestock, these are associated with poor colostrum consumption, nutrition, hygiene management, and husbandry practices (129–132).

Several initiatives to reduce young stock morbidity and mortality have been implemented in Ethiopia. Among those, the Young Stock Mortality Reduction Consortium (YSMRC) was formed in 2016 to (*a*) identify the main causes of morbidity and mortality among young stock and (*b*) pilot a group of interventions for applicability and affordability (133). The YSMRC found one of the most striking issues in young calves was suboptimal feeding. Appropriate feeding is crucial for calf growth and health (129, 130) and includes intake of high-quality colostrum within the first 24 h of life, consumption of 2 L of milk or quality milk replacer twice a day, appropriate supplemental feeding, and provision of unlimited clean water. However, the YSMRC found that 21–29% of calves had inadequate colostrum intake, and 44% of calves received less than the recommended amount of milk per feeding (0.5 L). The situation was particularly severe in pastoral herds, where 15% of calves were fed less than 0.5 L of milk and received virtually no supplemental feed, and only 18% of pastoral herders reported providing water to their calves. Suboptimal levels of nutrition in cattle are supported by other papers that also found poor animal feeding practices, indicating a need for enormous improvement (134).

The YSMRC's interventions aimed at improving farmer knowledge and behaviors related to fundamental feeding and neonatal care practices significantly reduced the risk for calf diarrhea and mortality (133). These findings are supported by published literature on livestock development interventions, which have shown increased knowledge, improved animal health outcomes, and increased income from animal products following the implementation of packaged interventions among rural users of working equids and other livestock species in Ethiopia (135, 136). Similar findings have been reported among cattle farmers in Tanzania and Mali, fish farmers in Vietnam, and chicken farmers in Myanmar (137–140).

A complex web of factors influences the success of livestock-based interventions in low-income countries. The availability of resources, farmer education and training, access to information and support, cultural and social norms, and the economic and political environment all play a role. But these factors do not affect all production systems equally, and understanding these differences

INTERNATIONAL DEVELOPMENT INITIATIVES

The international development and humanitarian sectors provide various examples of food security, human nutrition, and water/sanitation/hygiene (frequently referred to as nutrition-sensitive agriculture) interventions that have included livestock husbandry and/or health type interventions in multiple geographies (142). Popularized by international nonprofit organizations, livestock transfer activities, often complemented by animal husbandry or Community-Based Animal Health Worker training programs, have also been conducted with varying degrees and types of impact (143). In Tanzania, the Health Animals and Livelihoods Improvement Program (HALI, from the Swahili word for state of health) was initiated in 2006 as a One Health program working with pastoralist communities living within the Ruaha ecosystem (144). A transdisciplinary, grassroots effort focused initially on zoonotic diseases and water quality, the HALI project has demonstrated the importance of community engagement throughout a project's life cycle (145).

is key to avoiding a one-size-fits-all approach to scaling up interventions (125, 141). Adopting new behaviors and/or technologies requires a holistic understanding of the many factors that affect adoption and highlights the need to incorporate social scientists (141). See the sidebar titled International Development Initiatives for more examples.

VACCINATION

Vaccination of susceptible populations historically has been a relatively safe and effective way of preventing disease (146). The origins of modern-day vaccination have One Health roots going back to the late 1700s. Different from the ancient practice of variolation, a method of inoculation against smallpox using ground-up lesions from infected patients or recently variolated individuals, the first smallpox vaccines used infective material from the less virulent cowpox virus. In 1796, Edward Jenner conducted the first successful vaccination of a child with cowpox virus, followed two months later by challenging the boy with smallpox exposure; he documented the procedure in 1798. Reports across the literature credit several other contemporaries of Jenner, including Benjamin Jesty and John Fewster, who were practicing vaccination with cowpox virus material several decades earlier than Jenner (147). The procedure was later termed vaccination, derived from *vacca*, a Latin word for cow. It was not until almost 100 years later that the first veterinary vaccines for fowl cholera and anthrax came into existence (146). Veterinary vaccine science has often helped accelerate human vaccinology, due to faster development and approval processes (148). The availability of thermotolerant rinderpest vaccine, paired with deep community engagement and epidemiologically informed vaccination strategies, was essential for the eradication of rinderpest (see the sidebar titled Rinderpest Case Example). In the twenty-first century, the veterinary profession has a diverse array of livestock vaccines available; modern technologies, including next-generation sequencing, mRNA vaccines, and machine learning (ML), will inevitably only accelerate the development of vaccines in the future. Effective vaccination programs also have tremendous potential to contribute to the global efforts to combat antibiotic resistance, as veterinary vaccines help prevent and control infectious diseases, reducing the need for antibiotics to treat susceptible infections (148).

In developing countries, livestock vaccines are essential tools for improving productivity and managing endemic diseases, such as Newcastle disease in poultry; peste des petits ruminants in sheep and goats; and brucellosis, anthrax, clostridial diseases, foot-and-mouth disease, and lumpy skin disease in cattle. However, vaccination strategies must be paired with solid epidemiological knowledge of the specific disease and effective community engagement approaches. Furthermore,

RINDERPEST CASE EXAMPLE

Perhaps no other livestock disease better exemplifies how a One Health approach can be used to eradicate a disease than rinderpest. In 2011, the Food and Agriculture Organization (FAO) declared rinderpest, a highly contagious *Morbillivirus* (*Paramyxoviridiae*, includes measles, distemper, and peste des petits ruminants virus, among others), eradicated following a decades-long effort that incorporated many of the examples featured throughout this article. With up to a 100% mortality rate, and responsible for the deaths of hundreds of millions of livestock and wildlife, such as buffalos, zebus, antelopes, and giraffes, rinderpest caused the fall of empires, triggered famines, catalyzed the founding of formal veterinary schools, and inspired the establishment of the Office International des Epizooties, now known as WOAH (119). Dedicated community engagement efforts; nuanced awareness of the local social, political, and economic contexts; thermostable vaccines; strong epidemiological understanding of the disease; effective surveillance and diagnostic capacity; transparent reporting; and international commitment were paramount to eradicating rinderpest (120, 121). Youde's (120) article, "Cattle Scourge No More: The Eradication of Rinderpest and Its Lessons for Global Health Campaigns," chronicles a 3,000-year history of rinderpest through a One Health lens. After decades of rinderpest eradication efforts across much of Africa and Asia, the jointly led FAO and WOAH Global Rinderpest Eradication Program leveraged the trust and detailed knowledge of local customs and herding practices of Community-Based Animal Health Workers (CAHWS) to gain access to and vaccinate cattle in hard-to-reach communities, in tandem with a massive epidemiological survey (122). Ultimately, only through participatory disease surveillance and deep community engagement with Sudanese CAHWS, accompanied by best practices in outreach materials including songs, poems, picture books, and cloth flip charts, was rinderpest successfully eradicated in Africa (119).

commercial availability, vaccine quality and safety, licensing for use in the country, cold-chain maintenance, and cost–benefit analyses are all relevant considerations prior to recommended use.

Combined child and livestock vaccine campaigns have been piloted in some rural pastoral communities. In the early 2000s, researchers in Chad worked with the Ministries of Health and of Livestock Production to vaccinate more than 149,255 livestock against anthrax, pasteurellosis, blackleg, and contagious bovine pleuropneumonia; 4,653 children <5 years of age against diphtheria, whooping cough (pertussis), tetanus, and polio; and 7,703 women against tetanus. Challenges with follow-up most commonly were due to nomadic movement rather than vaccine hesitancy (149). Similar joint programs have successfully delivered services to nomadic Fulani communities in Nigeria (150). However, much potential remains in scaling up integrated service delivery options, and researchers in Kenya have developed a community-informed One Health framework that could be applied to similar contexts (151).

Rift Valley Fever Vaccine Development

Rift Valley fever (RVF) is a classic example of a One Health pathogen that severely impacts both human and animal health. *Rift Valley fever phlebovirus* (RVFV; family *Phenuivirdae*, genus *Phlebovirus*) is a mosquito-borne human and veterinary pathogen associated with large outbreaks of severe disease across continental Africa, Madagascar, and occasionally the Arabian Peninsula (152, 153). RVF disease outbreaks are driven by complex ecological and climatic dynamics that influence the emergence of transovarially infected *Aedes* spp. floodwater mosquito vectors that then precipitate widespread amplification of the virus among livestock and other mosquito vectors, leading to widespread fetal loss and lethality among livestock animals. Human cases can result from contact with virus-contaminated livestock tissues, fluids, aborted fetal materials, or milk and directly from infected mosquito bites (154–156). A reportable disease, recent notable

RVF events include a 2018 outbreak in Kenya, with 24 confirmed human cases, 6 deaths, and a large number of livestock affected, and a widespread 2010–2011 outbreak in South Africa, with more than 8,000 animal deaths, at least 11,000 animal cases, and more than 250 human cases with 25 confirmed deaths (157, 158). The 2006–2007 RVF outbreak in Kenya resulted in more than 1,000 human cases reported across Kenya, Somalia, and Tanzania, with millions of livestock affected (159).

The health impacts of RVF can be dramatic, with a rapid and sudden development of thousands to tens of thousands of acutely ill human cases and widespread and devastating agricultural impact on potentially millions of livestock. RVFV is also the only significant known hemorrhagic fever virus of humans that also causes high-level mortality and morbidity in livestock animals; this adds an enhanced layer of complexity to control strategies to ensure the biosafety and biosecurity of the food supply. RVF control programs must balance the needs of multiple stakeholders ranging from individually affected human patients, local livestock herdsmen, and medical and veterinary practitioners to national-level authorities working in public health, agriculture, food safety, and, importantly, animal welfare issues (160, 161).

RVFV is uniquely suited for a One Health approach to prevent both livestock and human disease through integrated vaccination programs (160, 162) (**Figure 3**). Vaccination strategies using rapid-acting one-dose vaccines for animals could prevent the RVFV amplification among livestock and could provide a window of opportunity to interrupt emergent RVFV outbreaks by both reducing further infection of anthropophilic mosquito vectors and eliminating the threat posed by infected livestock tissues. Widespread use of animal vaccines could have major health and economic impacts by simultaneously reducing human morbidity and mortality and providing major positive monetary benefits to farmers and herdsmen, especially in resource-poor areas, where the death of even small numbers of livestock can result in significant declines in overall family health and wealth. Similarly, vaccines approved for use in the human population could target high-risk occupational and special risk groups, such as veterinarians, farm workers, pastoralists and their families, and other animal health personnel. Multiple research groups are currently pursuing vaccine candidate designs that could be used in both animals and humans if regulatory approvals are granted for true One Health utilization in endemic areas (160, 162). If successful, these approaches may revolutionize the tools available to reduce the impacts of this and other high-consequence, but neglected, diseases of livestock and people around the world.

Newcastle Disease Virus

Often found in rural, resource-poor areas, village poultry production remains an important economic activity and contributes to food security, livelihoods, and women's empowerment in many developing countries (163). Newcastle disease (ND) virus (NDV) is one of the biggest constraints to village poultry development, and although it can infect up to 236 different avian species, the primary reservoirs of the highly pathogenic (velogenic) version of the virus are poultry populations (164). Velogenic NDV endemicity in Central America, Asia, and Africa makes it a priority issue to overcome (165–167). ND can cause mortality rates as high as 90% among village chicken flocks (168). Several factors must be considered to make village poultry vaccination approaches fully effective. One of the biggest challenges is the existence of a cold chain from vaccine production to vaccine application. Although thermotolerant or inactivated vaccines (such as I-2 vaccine and some oil-adjuvanted products) are available in certain regions, most available products are the conventional live attenuated la Sota strain vaccines, which require refrigeration.

Deep community engagement that empowers community vaccinators with the knowledge and tools to independently carry out vaccination is crucial. Community members and other stakeholders must understand the benefits and basic science behind regular vaccine campaigns,

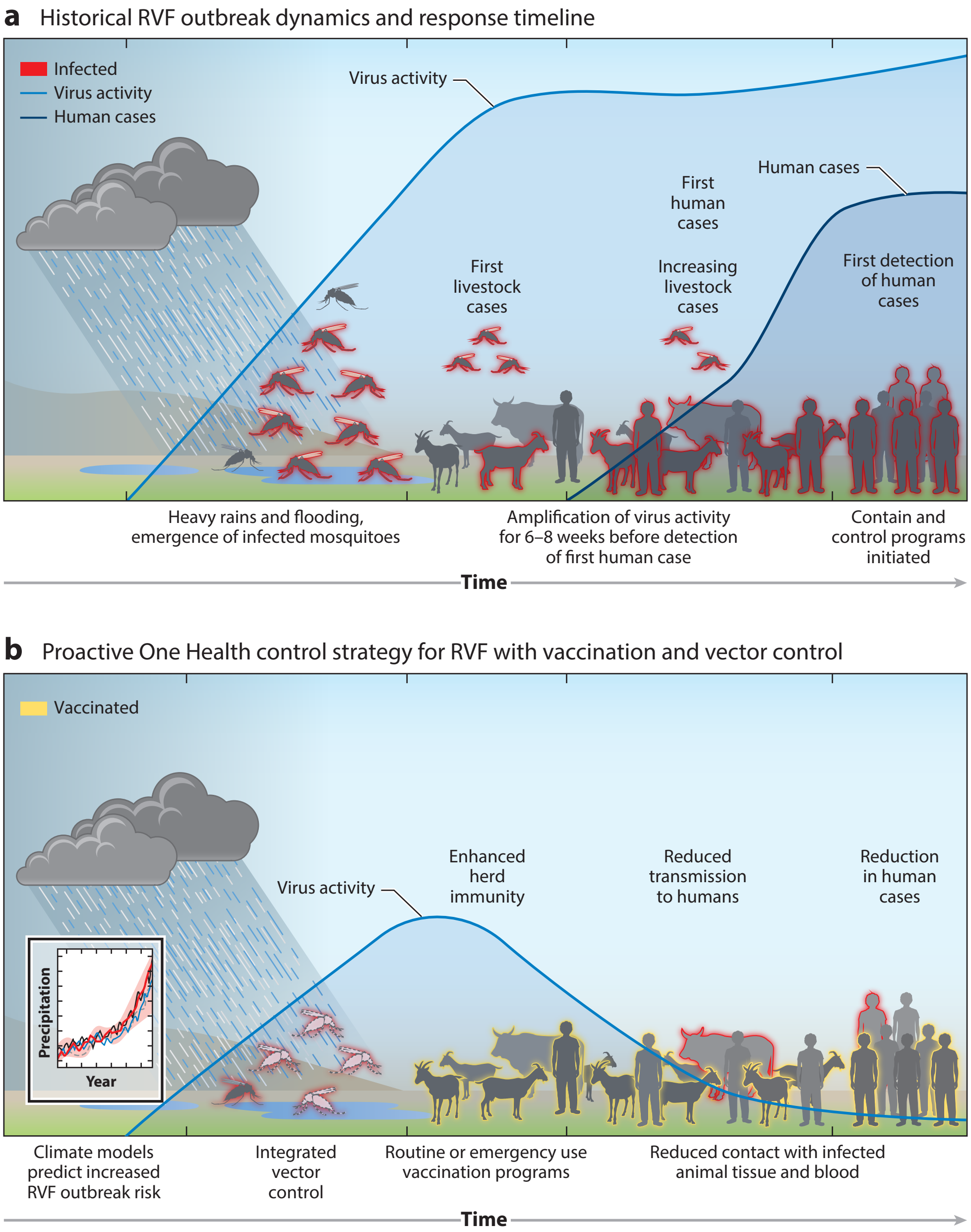

Figure 3

Rift Valley fever (RVF) virus outbreak dynamics. (*a*) A typical detection and response scenario with no effective disease surveillance and control strategies. (*b*) A One Health approach to enhanced outbreak prediction, vector control, and routine or emergency response vaccination of animals and humans to mitigate health impacts. Figure adapted from Reference 160.

because vaccine delivery should be targeted 3 weeks to a month before historical outbreak times and repeated throughout the year for the entire village. Furthermore, as discussed earlier, adhering to basic biosecurity principles and good animal husbandry practices including nutrition, management, and hygiene is essential for birds to generate a proper immune response. The concept of biosecurity units is also important and generally represents the unit that can be protected, impeding the introduction of birds and/or pathogens. In a rural village setting, this unit is usually the entire village, which may be 20–50 households. The goal of the program is to vaccinate the village effectively and uniformly at a given time. Social aspects such as gender, cultural beliefs, and personal motivation also play a role in how and why farmers elect to vaccinate their birds. If the community is not motivated and willing to contribute, developing rapport and community uptake can be impossible (169).

Successful NDV vaccination programs can have a huge impact on poultry production, human nutrition, and family economic well-being. Birds that do not die of NDV can grow and produce meat and eggs, sometimes in excess, allowing the household to consume good quality protein and sell some of the products in local markets. These revenues usually are used to cover food, hygiene, clothing, medical, or education costs (170). Examples of livestock and human nutrition development programs that combined various poultry value chain activities (including NDV vaccine campaigns) with food security and nutritional interventions are in the literature, with various outcomes (142, 171). A randomized control trial studying the effect of NDV adoption on the livelihoods of Tanzanian poultry farmers is also being conducted currently, with funding from the Global Alliance for Livestock Veterinary Medicines (172).

Because biosecurity and sustainable ND vaccination programs can be difficult to implement in rural poultry production system settings, researchers are also working on other approaches to addressing ND. With the advancement of genomic technologies, genetic improvement has provided a promising complementary approach in enhancing disease resilience to NDV infection by selective breeding (173). The Feed the Future Innovation Lab for Genomics to Improve Poultry (**https://gip.ucdavis.edu**) led such an effort. In summary, local Ghanaian and Tanzanian chicken ecotypes were challenged with low- and high-pathogenic NDV strains to evaluate disease resistance parameters including viral load, anti-NDV antibody response, and survival time (173, 174). The moderately high heritabilities of these parameters suggest that genetic improvement on these traits is feasible (173, 175). Genome-wide association analysis was conducted to identify genomic regions affecting these disease resilience parameters in African local ecotype chickens, then an economically affordable low-density single-nucleotide polymorphism panel was developed to genotype breeding individuals by selecting more resilient birds, focusing primarily on survival time (173). Although the first generation of genomic selection has been conducted, it is expected that multiple generations of selection are needed to breed marketable ND-resilient local ecotypes (176).

ECOLOGICAL INTERVENTIONS

Ecological interventions for pathogen spillover prevention (also called ecological countermeasures) are a subject of growing interest (177–180). According to Sokolow et al. (177), interventions directed at the ecological processes involved in spillover are potentially underused approaches for developing sustainable solutions to minimize spillover. These approaches typically have little to no adverse effects on the environment and can complement traditional disease prevention and control strategies, such as vaccination and treatment (177, 181). Ecological countermeasures are defined as highly targeted, landscape-based interventions aimed at mitigating one or more components of spillover triggered by land use change, a primary driver of pathogen spillover from wildlife to humans (25). The focus is on addressing perturbations that lead to increased infections in wildlife populations; greater pathogen shedding in wild animal hosts and spillover into other hosts, including humans; and subsequent spread in human populations (25, 180). These countermeasures, which consider the interactions among hosts or between hosts and their shared environments that may be driving spillover, can lead to innovative nature-based solutions (e.g., habitat restoration) for mitigating cross-species transmission.

Several case studies highlight the benefits of using ecological interventions/countermeasures as an approach to zoonotic disease prevention. For example, policies requiring fruit trees to be planted at a minimum distance from pig sties, to reduce spillover of Nipah virus from bats to pigs, have prevented Nipah virus outbreaks in Malaysia since 1998 (182). This intervention provided a more sustainable solution as compared to initial culling of pigs, which resulted in devastating economic losses for farmers. Similarly, a current intervention involving winter foraging habitat restoration for *Pteropus* spp. bats in Australia could allow bats to return to their native habitats and winter foraging behaviors away from the human-dominated agricultural landscapes, where bats have taken up roost near horse pastures due to winter food shortages that have occurred due to forest loss and climatic events (183). In Senegal, reintroduction of native river prawns, a natural enemy for snail intermediate hosts, to a river system where dam construction had restricted their movements has been implemented as a successful complementary approach to schistosomiasis control (184). When used in combination with ongoing conventional medical treatments in the communities, the prawns controlled the snail population and decreased or locally eliminated the parasite in the system. Protection or restoration of wetland habitats can mitigate the risk of zoonotic pathogen spillover. Wu et al. (185) assessed how waterfowl habitat protection was related to HPAI H5NI outbreaks in China. They found that proximity between unprotected waterfowl habitats and rice paddy fields, which are used by free-ranging domestic fowl, generally increased HPAI outbreak risk, whereas proximity to the most highly protected wetland habitats had the opposite effect, illustrating the potential for wetlands to serve as a buffer between wild and domestic birds and mitigate risk of spillover.

THE ROAD AHEAD

Public health and veterinary medicine have come far in recent decades. Advances in computational power paired with improved algorithms for ML and other artificial intelligence modalities will revolutionize disease surveillance and management strategies. Already, automated commercially available diagnostic technologies using ML models are being used to identify and diagnose gastrointestinal parasitic infections and interpret cytologies (186). In Tanzania, researchers have developed a ML model that diagnoses three common poultry diseases (coccidiosis, *Salmonella*, and ND) by fecal image analysis (187). Researchers in China have used a similar image analysis ML model to detect and predict sick broiler chickens through noninvasive motion image analysis (188). Other technologies will continue to accelerate the development of affordable and rapid point-of-care diagnostics that will improve surveillance and rapid response capabilities that have plagued under-resourced areas. Remote disease surveillance capacities will likely be paired with ecological countermeasure efforts. Furthermore, joint infrastructure that provides integrated diagnostic, research, and surveillance activities, such as the Canadian Science Centre for Human and Animal Health, demonstrates that joint surveillance is possible and cost effective (189).

ML technologies also offer enormous promise for future applications in exploring host–pathogen interactions and discovering drug and vaccine candidates (190). Solutions to antimicrobial resistance may well be identified through AI technologies. Many of these platforms are agnostic to species, and once established they can be applied to a variety of pathogens. As the NDV example illustrates, continued advances in genomics and genetic engineering will likely continue to offer solutions for identifying genetic variations related to specific disease or stressor tolerances and may also help position the livestock industry to be more resilient toward future climate change (191).

Precision livestock farming, driven largely by sensor technology and big data, will also continue to grow in its use, accessibility, and adoption across farming systems. Already, sensors are used to detect a range of biological, chemical, or physical properties including motion, temperature, weight, sounds, facial recognition, water usage, feed consumption, and more across many types of production systems and livestock species (192). Similar to how cell phone technology leapfrogged much of the developing world past landline phones, the accessibility and innovation of some sensor technologies have vast potential to revolutionize livestock production in developing countries.

CONCLUSION

As the world reckons with the convergent challenges of climate change, land use changes, biodiversity loss, and the continued threat of endemic and emerging infectious diseases, coupled with feeding a growing population, livestock production and medicine must adapt and evolve to meet those challenges. Ecological countermeasures will need to be scalable and used to complement the more traditional epidemiological and husbandry-based approaches to improving livestock health. Often, these more affordable strategies can be used in low-resource settings while simultaneously contributing to food security and climate adaptation goals.

Throughout this article, recurrent themes emerge related to the importance of social science to inform risk assessments and epidemiological research, design appropriate interventions, and cocreate community engagement strategies. Furthermore, there is no substitute for following basic biosecurity and good animal husbandry practices. No vaccination strategy will compensate for inadequate nutrition, insufficient colostrum, lack of water, poor hygiene, or loose biosecurity. It is also apparent that whereas tremendous global progress has been made in the development of One Health National Action Plans, One Health Frameworks, and similar high-level policies in the last decade, adoption and reporting of actual One Health interventions that holistically address livestock disease challenges and systematically evaluate their impact have been slower.

Livestock development initiatives focused on animal health improvement, along with routine veterinary services provision and surveillance efforts, could increase inclusion of impact evaluation within their programs. In a 2020 scoping review of livestock interventions in low-income countries, only 15 of 78 eligible publications used a randomized control design, which is considered the gold standard for impact evaluation (193). Furthermore, most of these papers were from studies conducted in Africa, followed by those in Asia and only one from Latin America. Livestock systems face disease challenges worldwide; sharing best-practice, low-cost, scalable, and accessible solutions to reducing livestock disease prevalence should be a priority of researchers and producers.

As the world accelerates into new solutions based on fast-paced and rapidly evolving platforms that rely on AI technologies, researchers and the private sector in high-income countries should remain cognizant of the importance and need to democratize these technologies. Skyrocketing youth populations in developing countries often mirror growing livestock populations in the same geographies; as those youth seek educational and career opportunities, the precision livestock sector and advanced diagnostic technologies may be particularly lucrative for qualified, highly trained individuals. As commercialized livestock production continues to increase in developing countries, so should opportunities for employment and improved practices adoption, as humanity reckons with simultaneously meeting demands for livestock products while balancing environmental concerns and adapting to a changing climate along with emerging disease threats.

DISCLOSURE STATEMENT

B.B. is an inventor of patents describing the DDvax^{TM} Rift Valley fever vaccine technology (USPTO: 8,673,629, 9,439,935, 10,064,993). The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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