Effectiveness of Veterinary Service Interventions in Improving the Wellbeing of Livestock-Dependent Populations in Ghana

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List of Abbreviations

AAS	African Academy of Sciences
AESA	Alliance for Accelerating Excellence in Science in Africa
Afrique One-ASPIRE	Afrique One-African Science Partnership for Intervention Research Excellence
AJOL	African Journal Online
aOR	Adjusted Odds Ratio
ASF	African Swine Fever
BCR	Benefit-Cost Ratios
bTB	Bovine Tuberculosis
CAHWs	Community Animal Health Workers
CBPP	Contagious Bovine Pleuropneumonia
CCPP	Contagious Caprine Pleuropneumonia
CHPS	Community-based Health Planning and Services
CI	Confidence Interval
CLHWs	Community or Lay Health Workers
cOR	Crude Odds Ratio
COVID-19	Coronavirus Disease 2019
DALYs	Disability-Adjusted Life Years
DDT	Dichlorodiphenyltrichloroethane
DELTAS	Developing Excellence in Leadership, Training, and Science
ECOWAS	Economic Community of West African States
FAO	Food and Agriculture Organization of the United Nations
FGDs	Focus Group Discussions
FMD	Foot-and-Mouth Disease
GALVmed	Global Alliance for Livestock Veterinary Medicines
GBADs	Global Burden of Animal Diseases
GDP	Gross Domestic Product
GHC	Ghanaian Cedis

GHG	Greenhouse Gas
GIPC	Ghana Investment Promotion Center
GSS	Ghana Statistical Service
ILO	International Labour Organization
IQR	Interquartile Range
IRR	Internal Rate of Return
KAPS	Kwahu Afram Plains South
LMICs	Low- and Middle-Income Countries
LSD	Lumpy Skin Disease
MD	Mean Difference
MeSH	Medical Subject Headings
MESTI	Ministry of Environment, Science, Technology and Innovation
MFAD	Ministry of Fisheries and Aquaculture Development
MoFA	Ministry of Food and Agriculture
MOH	Ministry of Health
MRR	Marginal Rate of Return
ND	Newcastle Disease
NEPAD	New Partnership for Africa's Development Planning and Coordinating
ODK	Open Data Kit
OECD	Organisation for Economic Co-operation and Development
OIE	Office International des Epizooties
PANVAC	Pan-African Veterinary Vaccine Center
PFJ	Planting for Food and Jobs
PHC	Primary Healthcare
PhD	Doctor of Philosophy
PPR	Peste-des-Petits Ruminants

PRISMA-ScR	Preferred Reporting Items for Systematic Reviews and Meta-Analyses–Extension for Scoping Reviews
PVS	Performance of Veterinary Services
QQ-plot	Quantile-Quantile Plot
RII	Relative Importance Index
SD	Standard Deviation
SDGs	Sustainable Development Goals
SSA	Sub-Saharan Africa
TADs	Transboundary Animal Diseases
TLUs	Tropical Livestock Units
UK	United Kingdom
UNEP	United Nations Environment Programme
USD	United States dollar
VLUs	Veterinary Livestock Units
VOs	Professional Veterinary Officers
VSD	Veterinary Services Directorate
WHO	World Health Organization
WHOQOL-BREF	The World Health Organization Quality of Life Brief Version
WOAH	The World Organization for Animal Health
WTP	Willingness to Pay

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Summary

Livestock represent valuable assets for many people globally, especially in low- and – middle income countries (LMICs). In LMICs, livestock production serves multiple purposes, including generating income for households, serving as a store of wealth against uncertainties, and providing companionship to farmers. In addition, livestock products serve as the primary source of protein in the diets of the majority of the population in LMICs. However, in many LMICs, animal diseases are highly prevalent among herds due to inadequate disease control measures, leading to significant livestock mortalities. These mortalities not only result in livelihood losses for farming households, but also have a negative impact on productivity in the livestock sector, thereby contributing to heightened public food insecurity. Although disease prevention measures are available and can effectively control livestock diseases in principle, many farmers in LMICs do not regularly utilize these measures. Thus, the goal of this research was to provide evidence on effective and cost-effective preventive veterinary interventions, identify the barriers to their utilization in Ghana, and assess the willingness of livestock farmers to pay for these interventions to protect their livestock assets, and improve overall wellbeing.

The first part of the research provides a synthesis of existing evidence on the effectiveness and cost-effectiveness of preventive veterinary interventions for the control of infectious livestock diseases. The findings from this scoping review indicate that, vaccination is the most widely implemented preventive intervention against infectious livestock diseases in sub-Saharan Africa (SSA). Furthermore, vaccination is also the most effective and cost-effective strategy compared to the other approaches employed throughout the region. However, the findings showed that the effectiveness of vaccination is highest when implemented under controlled conditions, and tend to reduce due to various field challenges including adverse weather events, cold chain failures, and mismatch between vaccine and circulating pathogen strains. The evidence therefore suggests that integrating pathogen surveillance into vaccination interventions, and optimizing vaccine delivery tools in the field would enable countries to effectively control the majority of livestock diseases.

In the subsequent chapters, this research examined the existing strategies used by livestock farmers and veterinary service providers to address the infectious diseases affecting livestock, the performance of veterinary services in meeting the health needs of animals, the barriers to vaccination utilization by farmers, farmers’ willingness to pay for vaccination to protect their herds against the diseases, and the effect of poor animal health on farmers’ wellbeing in Ghana. The results reveal that transboundary animal diseases i.e. contagious bovine pleuropneumonia (CBPP), foot– and –mouth disease (FMD), and peste– des –petits ruminants (PPR) are highly prevalent among livestock herds, causing significant animal mortalities. The veterinary system weaknesses identified from both farmers’ and veterinary officers’ perspective relate to shortfalls in the veterinary workforce, and the material resources to deliver effective animal health services. As a result, majority of the farmers utilize the services of informal providers - who are not regulated by the veterinary system - or manage the livestock diseases on their own. In most of the cases, the medicines applied by the farmers were not useful for the conditions being treated. Thus, a reduction in the occurrence of the diseases, especially through disease prevention strategies, have a potential to reduce the disease burden, and the workload on the veterinary system, while safeguarding the valuable livestock assets of livestock dependent populations.

The results showed that the utilization of vaccination services by livestock farmers in Ghana is significantly low. The main factors hindering access to vaccination were identified as a combination of demand and supply barriers. On the demand side, barriers primarily stem from farmers’ limited awareness and sometimes misconceptions about the benefits of vaccines, as well as the financial burden associated with vaccine affordability. Particularly, the requirement for farmers to bear the full cost of vaccine vials, even if they do not own a sufficient number of animals to utilize an entire vial. Competing expenditure needs also exert an influence on farmers' decision-making process to use vaccination services. The supply-side barriers are mainly due to the limited number of professional veterinary officers accessible to farmers, and inadequate veterinary health infrastructure, which restricts the availability and accessibility of veterinary services when required. To overcome these barriers to vaccination uptake, the farmers suggested several measures, including the formation of localized community networks of farmers. This proposed strategy involves harnessing the strength of a collective group of farmers to coordinate vaccination visits with veterinary officers, thereby improving access to veterinary services and enhancing vaccination rates.

Furthermore, the results from the contingent valuation component of this research showed that, when sensitized on the benefits of vaccines for enhancing livestock productivity, many farmers demonstrate a willingness to pay for vaccination against CBPP and PPR, even exceeding the prevailing prices. Thus, by leveraging community sensitization and engagement, it is feasible to achieve the national vaccination target of 50% at the existing vaccination costs. However, our estimates also revealed that to attain the desirable target of 70% coverage for CBPP and PPR control, it would be necessary to introduce subsidies to ensure broader inclusivity and participation in vaccination programs, especially for female farmers and farmers residing in the poorest districts.

Adopting a One Health perspective to examine the relationship between poor animal health and farmers' wellbeing, our research results showed a significant and negative effect of increasing levels of disease-induced animal mortalities on the overall wellbeing of livestock farmers. Specifically, we observed significant negative impacts of poor animal health on the psychological and physical domains of farmers' wellbeing.

The overall findings of this research emphasize that the inadequate utilization of effective preventive strategies like vaccination, and shortfalls in the provision of veterinary services in Ghana contribute to the persistence of livestock diseases in herds. This in turn results in substantial losses in livestock productivity and livelihood for households. Furthermore, the current disease management strategies employed by farmers pose considerable risks to public health and food safety. Beyond the implications of livestock diseases for livelihoods, public health and food security, the wellbeing of livestock farmers is also negatively affected. Therefore, policy interventions addressing the existing challenges in the veterinary service delivery and promoting the adoption of vaccination services are necessary to mitigate the impacts of livestock diseases in Ghana.

Additionally, the research conducted in this doctoral project lays the foundation for future research work to evaluate various intervention strategies to enhance the effectiveness of veterinary services in Ghana. Furthermore, there is the need for empirical research studies evaluating various approaches that promote community participation and utilization of preventive veterinary services, especially vaccination, in order to mitigate the occurrence and impacts of livestock diseases on the population.

Chapter 1 Introduction

1.1 Agriculture’s role in economic development

Agriculture plays a pivotal role in fostering the economic development of many countries, particularly for low- and middle-income countries (LMICs). It provides employment for people, products from agricultural activities contribute to food security, energy fuel and clothing, and the productivity in the agriculture sector contributes to the overall economic output of countries (FAO et al., 2022). According to the Food and Agriculture Organization of the United Nations (FAO), approximately 870 million persons globally were employed in 2021 within the agriculture sector, representing about 27% of the global share of employment. In the least developed regions like Africa, agriculture accounted for approximately 50% of total employment, compared to 5% in Europe, 10% in the Americas and 30% in Asia (FAO, 2022b). Despite its significant contribution to the employment of people and livelihoods, agriculture's overall share of the global economic output in 2021 was relatively small, amounting to approximately 5% of the total economic productivity. However, in LMICs, agriculture's contribution is considerably higher. On average, it accounted for around 25% of the gross domestic product (GDP) in low-income countries and 10% of the GDP in middle-income countries (Alston and Pardey, 2014; The World Bank, 2023).

Agricultural production encompasses crop, livestock and fish farming, and forestry. The farming systems and agricultural products vary systematically in countries and/or regions based on area specific characteristics including soils, climate, technologies, and the costs of agricultural inputs (Dixon et al., 2001; Liang and Plakias, 2022). Furthermore, the degree of farming system intensification is also influenced by population growth and the increasing demand for food (Jayne et al., 2014; Snapp and Pound, 2017). Globally, the crop sector significantly dominates agricultural production, contributing on average about 60% of the overall productivity across regions in 2021 (OECD and FAO, 2022). Cereals remain the predominant crop produced worldwide, accounting for one-third of the total crop production (FAO, 2022a). Within the sub-Saharan Africa (SSA) region, the crop sector’s contribution to agricultural production varies, ranging from approximately 90% in West Africa to 50% in Southern Africa (OECD/FAO, 2016). Although the crop sector dominates agriculture production at the aggregate level, livestock production remain key to the livelihoods of many people.

1.1 Livestock contributions to livelihoods, food security and wellbeing

Livestock products including meat, milk, eggs, wool, and leather contribute to the livelihoods of many people. They not only offer income-generating opportunities for poverty alleviation, but also serve as a crucial protein source in human diets, ensuring nutritional wellbeing, and contributing to overall food security. Additionally, livestock plays a role as draft power in land cultivation and transportation of goods, and supports asset securitization as a means of mitigating uncertainties, and in certain cases, livestock serve as companion animals within households providing other non-economic benefits (Otte and Knips, 2005; Brown, 2006; Kamuanga et al., 2008; Pound, 2017; Yurco, 2018; FAO et al., 2021). Livestock production is done using either intensive or extensive methods, with high income countries predominantly adopting intensive systems, while LMICs primarily rely on extensive systems (Thornton, 2010).

The past two decades have seen significant growth in the livestock production across all regions; with the growth driven largely by LMICs (FAO, 2017; Pandey and Upadhyay, 2022). For example, when comparing livestock data for 2000 and 2020, there was an average growth of approximately 12% in the number of live animals reared across species. Poultry birds exhibited the highest growth rate of 21%, while pig production declined slightly by 2%. Overall, global meat production increased by 45% to reach approximately 340 million tons, milk production increased by 53% to 887 million tons, and egg production increased by 69% to 87 million tons (FAO, 2022a). In spite of this growth, the increased per capita demand for livestock products, which has more than doubled since the late 20th century poses a significant challenge to ensuring food security for the population (FAO, 2017). The anticipated persistence of this increased demand due to population growth in the coming three decades, further exacerbates the situation. There is a need for strategies that sustainably improve livestock productivity to meet the demand (OECD and FAO, 2021). Thus, the utilization of advanced technologies and innovative climate-friendly strategies to meet the breeding, nutrition, and healthcare needs of animals holds the potential to efficiently improve livestock productivity (El-Hage Scialabba, 2022; Pandey and Upadhyay, 2022). By adopting these approaches, it becomes possible to meet the projected demand in a sustainable manner.

Although there is significant agricultural land endowment in many LMICs particularly in SSA, there is an underutilization of this potential in terms of overall agricultural productivity and specifically within the livestock sector, resulting in lower productivity per square kilometer of cultivated agricultural land compared to other regions (Deininger et al., 2011; Jayne et al., 2014). Studies have reported significant inefficiencies in the livestock production in many LMICs (Krasachat, 2008; Conradie, 2017; Acosta and De los Santos-Montero, 2019; Nin Pratt et al., 2019). In most LMICs, the livestock sector is dominated by smallholder farmers who engage in subsistence-based animal rearing, whereas large-scale farmers are relatively few. The livestock are reared in either pastoral, mixed crop-livestock, or in intensive systems (Steinfeld et al., 2006; Herrero et al., 2013). The majority of livestock farming households in LMICs rear the animals using the mixed-crop livestock system, and predominantly in rural areas where access to essential extension services are limited (FAO, 2003; Rosegrant et al., 2009). Moreover, challenges such as climate change, inadequate investments and technology deficiencies further impede the efficiency of livestock production in the LMICs. Indeed, the low productivity of the livestock sector not only contributes to the general food insecurity among the population but also exacerbates food insecurity within farming households (Dixon et al., 2001; Rufino et al., 2013; Fraval et al., 2019; Alpízar et al., 2020; Nuvey et al., 2022b).

1.2 Key challenges to livestock productivity in LMICs

The majority of farmers in LMICs engage in extensive livestock production. As a result, the increasing frequency and severity of adverse events such as droughts, land use conflicts, and infectious animal diseases, leads to considerable animal losses that greatly affects farming households (Valbuena et al., 2015; De Haan et al., 2016; FAO, 2017; Grace et al., 2017; Marzin et al., 2017). Most of these adverse events are either linked to the negative effect of climate change, high population growth and/ or underperformance of veterinary services (Dean et al., 2013; Godber and Wall, 2014; FAO et al., 2018; Cheng et al., 2022). Climate change-induced rising ambient temperatures have been reported to have detrimental effects on the nourishment, growth, and productivity of livestock, as well as on the incidence of infectious diseases (Nardone et al., 2010; Cheng et al., 2022).

On the other hand, livestock production contributes to climate change through greenhouse gas (GHG) emissions (United Nations Environment Programme, 2022). The FAO Global Livestock Environmental Assessment Model estimates that livestock production-related GHG emissions account for approximately 50% of methane, 24% of nitrous oxide, and 26% of carbon dioxide emissions globally (FAO, 2021). These impacts are however less pronounced in extensive livestock systems (Thornton and Herrero, 2010; Rust, 2019). Thus, it is essential to develop strategies that enhance livestock productivity per animal head to mitigate the impacts on climate change, while maximizing the benefits to the population (Llonch et al., 2017). Nevertheless, studies have reported that the high prevalence of infectious diseases among livestock exacerbates GHG emissions associated with livestock production, while also reducing livestock productivity (Altizer et al., 2013; Fox et al., 2018; Ezenwa et al., 2020).

In many LMICs, infectious livestock diseases are highly prevalent causing significant morbidity and mortality among herds. This significantly hampers livestock productivity and results in considerable expenses in disease control measures (Fadiga et al., 2013a; Grace et al., 2015). Animal diseases account on average for about 7% of adult cattle deaths, 21% of calf deaths, 15% of adult sheep and goat deaths, and 23% of lamb and kid deaths in LMICs. Consequently, farmers lose to diseases on average, one animal for every head of cattle sold, and one animal for every two sheep or goats sold (Pradère, 2014). Additionally, livestock diseases contribute to decreasing market value for livestock products, losses in trade through restrictions, and overall food insecurity from increased hunger and malnutrition, particularly among vulnerable populations (Dehove et al., 2012; FAO et al., 2021). As a result, there have been efforts over the years to provide reliable estimates of both the direct and indirect costs of livestock diseases to inform policy actions for effective disease control. The World Organization for Animal Health (WOAH, founded as OIE) in 2021 initiated the Global Burden of Animal Diseases (GBADs) programme for this purpose. The GBADs estimates show that approximately USD 300 billion is lost to livestock diseases annually worldwide (WOAH, 2023). Effective and cost-effective disease control strategies are therefore needed to tackle the impact of infectious animal diseases on the population.

1.3 Strategies for tackling infectious livestock diseases

Given the substantial direct and indirect costs on the population associated with animal diseases, various disease control programs and strategies at local, national, regional, and international levels have been proposed and implemented over the years to mitigate the impacts of animal diseases. In principle the implementation of quality veterinary services, both preventive and curative, within established disease control programmes enables countries to effectively detect and control animal diseases (OIE, 2014b, a). However, in most LMICs, many animal diseases still lack adequate control tools, while some of the existing disease control strategies require continuous innovation to be able to overcome the emerging challenges (Karesh et al., 2012).

Moreover, the provision of veterinary services has been ineffective in many LMICs, primarily due to limited involvement from public and private veterinary personnel, as well as livestock producers. This is partly due to lack of adequate public and private investments in animal health services leading to significant shortfalls in human and material resources (Cheneau et al., 2004). For instance, the estimated human resource capacity of the veterinary workforce in SSA stands at an average of only seven animal health professionals (comprising two veterinarians and five para-veterinarians) for every 100,000 inhabitants. In contrast, countries such as the United States and the United Kingdom maintain an average of 50 animal health professionals per 100,000 individuals (Jaime et al., 2021). The lack of investments leading to shortages in human and material veterinary resources is often attributed to the implementation of drastic structural adjustment policies during the 1980s aimed at addressing high indebtedness levels of LMICs (Smith, 2001; Sen and Chander, 2003).

In addition to the deficiencies in human and material veterinary resources required for the effective control of animal diseases in LMICs, are challenges with the supply and use of medicines for animal health. A recent review showed that 80% of countries in Africa lack the capacity to control the registration, import and production, distribution and usage of veterinary medicines and biologicals. They also report a lack of residue testing programmes in more than two-thirds of the countries (OIE, 2019a). As a result, the overwhelming majority of farms in SSA use antimicrobials regularly, often without professional veterinary advice (OIE, 2019a; Kimera et al., 2020). Several studies have reported a strong link between antimicrobial use in animal production and the persistence of medicine residues in livestock products, and the development of related antimicrobial resistant pathogens (Van Boeckel et al., 2015; Van Boeckel et al., 2017; Van Hao et al., 2020; Mshana et al., 2021; Omwenga et al., 2021; Azabo et al., 2022). Thus, the misuse of medicines in animals poses a significant threat to public health.

Considering the apparent inadequacies in veterinary service resources, a decrease in disease occurrence, particularly through the implementation of disease prevention strategies, would greatly reduce the disease burden, and the workload on veterinary service providers as well as the associated negative impacts. Substantial investments in veterinary services from both the public and private sectors would be crucial for achieving effective delivery of veterinary services, and ultimately enhancing livestock productivity. These investments need to be targeted to effective and cost-effective disease control strategies to be able to achieve the optimal impact (Hasler et al., 2017; OIE, 2019b). There is therefore a need for studies that describe the relative effectiveness and cost-effectiveness especially of preventive veterinary interventions for animal disease control, to inform policy actions.

However, few studies have attempted to synthesize existing evidence on veterinary interventions to provide an overview of their relative effectiveness and cost-effectiveness. A scoping review evaluated livestock interventions implemented in developing countries for their effectiveness in achieving development outcomes, and found that livestock-transfer programs have potential to enable farmers manage diseases effectively, with potential added benefits for improving farmer wellbeing (Lindahl et al., 2020). The authors did not consider the profitability of the interventions. Studies synthesizing evidence on the effectiveness and profitability of preventive veterinary interventions are lacking in the literature. Some studies which previously addressed the cost-effectiveness of preventive veterinary interventions were limited in scope, focusing on specific diseases and/or interventions (Molla et al., 2017a; Singh et al., 2018). In addition, there is the need for research to evaluate other issues related to existing strategies adopted by farmers for controlling livestock diseases within their herds. Participatory epidemiological approaches present an excellent means through which researchers could understand the management of animal health issues by livestock owners (Turkson, 2009; Alders et al., 2020). Thus, in addition to synthesizing evidence on the effectiveness and profitability of preventive veterinary interventions for controlling livestock diseases, we employed participatory epidemiology tools to evaluate disease control strategies employed by livestock farmers in Ghana.

1.4 Linkages between animal, and human health and wellbeing

Recent scientific advancements have highlighted significant interconnections between human, animal, and environmental health, with the associated heightened risks for disease transmission and spread between animals and humans, known as zoonoses (Chitnis et al., 2015). This can be attributed, in part, to the rising populations of both humans and domestic animals, as well as the consequent intensification of agricultural practices, which lead to increased proximity between these species and other wildlife species (Morse, 1995; Jones et al., 2013; Reperant et al., 2013; Cunningham et al., 2017). Zoonotic diseases can be transmitted directly through contact with infected animals, or indirectly via consumed food or other fomites. Throughout history, more than 800 zoonotic diseases have been identified, representing over 60% of all infectious diseases affecting humans (Taylor et al., 2001; Jones et al., 2008; Hubálek and Rudolf, 2010). In the past two decades, several zoonotic disease outbreaks have been reported worldwide, resulting in millions of human deaths. These include viral diseases such as Ebola virus disease, highly pathogenic avian influenza, Rift Valley fever, severe acute respiratory syndrome, marburg virus disease, rabies, lassa fever disease and more recently COVID-19 disease. There have also been bacterial zoonotic diseases including anthrax, brucellosis, tuberculosis, and salmonellosis, and parasitic diseases like trypanosomosis, cysticercosis, and toxoplasmosis (Gebreyes et al., 2014; GALVmed, 2023; WHO, 2023). It is estimated that in LMICs, emerging zoonoses constitute approximately 26% of the disability-adjusted life years (DALYs) lost to infectious diseases, and 10% of total DALYs lost (Grace et al., 2012). A recent review found that zoonoses driven by agricultural activities account for more than 25% of all the infectious diseases, and more than 50% of zoonotic diseases in humans (Rohr et al., 2019). Therefore, the inadequate control of infectious livestock diseases not only endangers animal health, but also poses a substantial threat to human health.

Thus, the importance of tackling infectious disease risks among livestock cannot be overemphasized, and remains crucial for the prevention and control of zoonoses. Various strategies have been devised to mitigate the transmission risks by reducing the underlying drivers of disease emergence. This is essential considering the significant economic burden posed by the global spread of zoonotic diseases (McKibbin and Sidorenko, 2006; Pike et al., 2014; Cunningham et al., 2017). Nevertheless, in order to justify interventions for controlling animal diseases especially in LMICs, it is imperative that the costs of disease control remain lower than the losses incurred from the diseases themselves. The cost-effectiveness evaluations accounting for the cross-sector economic impacts of zoonotic diseases, provides a holistic overview of the feasibility of any disease control strategy (Narrod et al., 2012). However, the existing frameworks for reliably estimating the full societal costs of zoonoses and the benefits of disease control strategies in animal health, which are crucial for informing policy decisions, are not well-developed, primarily due to the lack of up-to-date data on the actual impact of diseases on herd composition, and productivity parameters (Daszak et al., 2000; Zinsstag et al., 2016).

In principle, cost-effectiveness evaluations of infectious animal disease intervention strategies require in-depth understanding of the specific pathogen characteristics, host range, and the risks of emergence (Cleaveland et al., 2001; Zinsstag et al., 2009). In some cases, the costs of the intervention strategies may appear higher than the associated benefits when considering the benefits to only a singular sector (public or animal health). However, conducting a cross-sector cost-benefit analysis allows for a comprehensive assessment of the societal costs and benefits of the strategies. For instance, the control of certain zoonoses like brucellosis through livestock vaccination may not be profitable solely for public health, but if the benefits to livestock are included, it becomes highly profitable (Roth et al., 2003). Efforts have also been made to identify approaches for maximizing the benefits per unit cost expended in control strategies for infectious diseases. The provision of joint animal and human vaccination services, particularly in pastoral settings, has shown potential for effective infectious disease control in both humans and animals (Schelling et al., 2005; Schelling et al., 2007).

Unfortunately, a significant portion of the existing literature examining the connections between animal and human health has predominantly focused on the potential transmission of infections between the species, the influence of antimicrobial usage on emergence of pathogen resistance, and the impact of animal diseases on food security, as well as the associated costs and benefits of implementing effective control measures. However, it is important to recognize that the impact of animal diseases on human populations could extend beyond livelihood loss, zoonotic infections, and food insecurity. Previous studies have reported strong bonds between humans and animals, with livestock fulfilling additional social roles, including serving as companion animals for farmers (Swanepoel et al., 2010; Wilkie, 2010; Petitt, 2013). In recent years, there has been a growing adoption of animal-assisted therapeutic approaches aimed at aiding individuals in overcoming various health and social challenges. These therapies harness the positive influence of animals to support improvements in the overall wellbeing of people (Beck, 2000; Morrison, 2007; Bert et al., 2016; Hediger et al., 2019). The health of animals is therefore integral to the psychosocial wellbeing of people, especially livestock dependent populations. Infections among animals could affect livestock farming households who share strong emotional bonds with their animals, beyond the risks of infection spread. Previous studies have identified associations between infectious disease outbreaks in livestock, and poor psychosocial wellbeing of farmers (Peck et al., 2002; Mort et al., 2005; Brown, 2006; Taylor et al., 2008). It is noteworthy that most of the previous studies examining the linkages between poor animal health and the wellbeing of farmers were conducted in developed countries. However, there is a dearth of such studies in LMICs contexts, which has influenced the focus of my master's project and subsequently, this doctoral thesis. This doctoral project was conducted as a follow-up to a prior study done during my master’s studies in Ghana. My master’s project sought to identify the main sources of livestock losses, and how these affect the psychosocial wellbeing of livestock farmers (Nuvey, 2019). In the next section, I provide an overview of the agriculture sector in Ghana, along with prior study results that informed the doctoral research project goals.

1.5 Overview of the agriculture sector in Ghana

Ghana is a country in West Africa with a population of approximately 31 million people in 2021, and a per annum population growth rate of 2.1% (GSS, 2022). About 60% of the country’s population are economically active, with a higher share of males (64%) compared to females (53%) engaged in economic activity (GSS, 2021a). The Ghana Statistical Service (GSS) and Ministry of Food and Agriculture (MoFA), work collaboratively to provide statistical information pertaining to agricultural output. So far, a total of four comprehensive agricultural censuses have been conducted; in 1950, 1970, 1984/85, and 2017/18. Additionally, data on agriculture is obtained from the national population censuses conducted in 1960, 1970, 1984, 2000, 2010, and 2021, as well as projections based on previous census data (GSS, 2020a, 2021b).

According to the GSS data, agriculture is the second largest source of employment after the services sector in 2021, employing about 32% of the population. Approximately 11% of the population engaged in agricultural activity in Ghana rear livestock, with the majority of the livestock rearing (53%) being for income generation, while the rest is directly consumed by the households, or used for other socio-cultural purposes (GSS, 2020a, 2022). The agricultural system in Ghana is predominantly traditional and rain-fed, with smallholder farmers accounting for more than 80% of persons engaged in agriculture (FAO, 2005; GIPC, 2021). Data from the GSS show that agriculture contributed about 19% of the national GDP in 2019, with the livestock sector accounting for 14% of the total agriculture production (GSS, 2020b).

There are six distinct agro-ecological zones in Ghana, corresponding to specific climatic conditions within the areas. These zones are the Sudan Savanna, Guinea Savanna, Transition, Deciduous Forest, Evergreen, and Coastal Savanna agro-ecological zones. Livestock rearing predominantly takes place in the Savanna zones located in the northern part of the country, as well as in the plains along the Volta river basin in the Transition and Deciduous Forest zones that are found in the central and southern parts of Ghana (GSS, 2013; Asare-Nuamah and Botchway, 2019).

Livestock production in Ghana

According to the 2017/18 agricultural census in Ghana, approximately 18 million animals were reared by 446,000 households. About 80% of the livestock farmers are rural dwellers, keeping about 60% of all the livestock reared in the country. The main livestock species reared include poultry (74%), ruminants (21%), with other non-ruminant species including pigs, donkeys and rabbits among others, accounting for 5% of the livestock population. Like in other LMICs, the production system for livestock in Ghana is mainly extensive, and dominated by smallholder farmers. About 80% of the livestock holders are aged 30 years or older, and 82% are male (GSS, 2020a).

Table 1 below illustrates the changes in livestock production statistics and the human population census in Ghana over the past two decades. The data demonstrates an overall growth in the human population by approximately 63% since 2000, while livestock production experienced an average increase of 142% across various species. Poultry production saw a remarkable surge of 275%, followed by pigs (161%) and goats (139%), which more than doubled their production levels over the period. Sheep production increased by approximately 86%, whereas cattle production increased by less than 50%. Although there was a marginal decline in poultry production in 2010, the sub-sector quickly recovered, as evidenced by the strong rebound recorded in 2018. Cattle production on the other hand increased by about 86% in 2010 but declined by 20% in 2018. The production of sheep steadily rose throughout the period. However, by 2018, there was a relative slowdown in the growth of goat and pig production, following the initial substantial increases reported in 2010. Based on the available data, the country currently does not possess the self-sufficiency to meet the demand for livestock products of the population. As a result, there is a heavy reliance on the importation of livestock and livestock products to supplement the local supply (MoFA, 2019).

Table 1: Ghana livestock and human census statistics – 2000 to 2021 (in 1'000)

Livestock census	2000	2010	†2018	% Growth
Cattle	1302	2423	1943	49%
Sheep	2743	3199	5102	86%
Goats	3077	5502	7366	139%
Pigs	324	817	845	161%
Poultry	20472	19229	76870	275%
Human census	**2000**	**2010**	**2021**	**% Growth**
People	18913	24659	30833	63%

Source: Ghana Statistical service (GSS) and Ministry of Food and Agriculture (MoFA) (MoFA, 2011; GSS, 2013; MoFA, 2019; GSS, 2020a). † Most recent census data available; livestock data from the 2021 Population and Housing Census are yet to be published. The population data are round off to the next thousand. "% Growth" shows the percentage growth in the populations from 2000 to 2018 for livestock, and from 2000 to 2021 for the human population.

Veterinary services structure in Ghana

The Veterinary Services Directorate (VSD) of the Ministry of Food and Agriculture is responsible for overseeing the provision of veterinary services for animal health in Ghana. The license to practice veterinary medicine is administered by the Veterinary Council of Ghana (Turkson, 2003). Clinical veterinary services including curative, preventive, and animal health promotion activities are primarily provided by individuals with specialized training in veterinary medicine (veterinarians), and veterinary para-professionals: veterinary technical officers, animal health officers, and veterinary nurses, who possess bachelor, diploma, or certificate in animal health education from accredited training institutions (Diop et al., 2011; Adeapena et al., 2021). In addition, some veterinary professionals are engaged in academic institutions as lecturers and/or researchers, in laboratories as laboratory scientists, and in administrative roles, with or without involvement in clinical practice (Turkson, 2003). Efforts have been made to enhance the veterinary workforce by employing community livestock workers, commonly referred to as Community Animal Health Workers (CAHWs), who receive limited training to serve as support staff in rural communities, thereby complementing the work of professional veterinary service providers (Turkson, 2008; Mockshell et al., 2014). The majority of veterinary service providers are employed by the government and deployed across the country by the VSD, while a limited number of private providers typically operate exclusively in urban areas (Turkson, 2003).

Based on the most recent report assessing the performance of veterinary services (The PVS Gap Analysis) conducted in collaboration with the WOAH in 2011, Ghana had an estimated 39609 veterinary livestock units (VLUs). The VLUs serve as a measure of the workload per veterinary officer, calculated by dividing the standardized total number of animal heads in tropical livestock units (TLUs) by the number of veterinary personnel. The findings in the report indicate substantial deficiencies in veterinary human resources, in addition to shortfalls in material resources as well as funding gaps, thus hindering effective veterinary service delivery (Diop et al., 2011). To further illustrate, Zinsstag J. (personal communication, October, 2021) observed between two visits to the Pong Tamale Veterinary Laboratory in the Northern Region of Ghana; first visit was in 1991 and the other visit in 2021, a massive decline in the veterinary service workforce stationed in the laboratory from more than 20 personnel to just about 5 veterinary personnel over the 30 year period.

Prior research findings underpinning the doctoral project goals

As shown in previous studies, the provision of adequate veterinary services is critical to achieving better animal health and livestock productivity (Cheneau et al., 2004; Khan et al., 2013; Pradère, 2014; Baker et al., 2021; Campbell et al., 2021). However, as a result of the prevailing constraints in resources for veterinary service provision in Ghana, animal diseases represent the main impediment to livestock productivity, despite the occurrence of other adverse events among herds. The research conducted during my masters studies, revealed that nine out of ten farmers experience the loss of their animals annually to infectious diseases (Nuvey et al., 2020).

In response to the high prevalence of diseases, farmers employ various strategies to mitigate their impact. These strategies include self-treatment of animal diseases usually without professional veterinary advice, and the sale of diseased or dead animals to recover their losses (Nuvey et al., 2020; Nuvey et al., 2021). Furthermore, our findings indicated an association between the severity of losses experienced by farmers and the occurrence of mental health issues such as depression, stress, and anxiety in affected farmers. In addition, farmers facing significant losses were more likely to report physical conditions, including cardiovascular illnesses (Nuvey et al., 2020). Thus, the previous study has shown that not only do animal diseases hinder livestock productivity, but also adversely affect the wellbeing of livestock farmers, in addition to potential food safety issues arising from the introduction of high-risk livestock products into the food chain. Building upon these findings, the primary objective of this doctoral project was to review evidence on effective and cost-effective veterinary interventions for mitigating the impact of animal diseases on the population. And based on the findings of the effective and cost-effective interventions, we also aimed to identify the existing challenges with access to the interventions, and estimate on average how much farming households are willing to invest in the interventions in order to inform policies that will promote enhanced animal health, improved livestock productivity, food security, and the wellbeing of livestock farmers.

Chapter 2 Aim and objectives

2.1 Aim

Building on the previous evidence in the literature of the impact of livestock diseases on the livestock sector in Ghana, the aim of this PhD thesis is to provide a synthesis of existing evidence on effective and cost-effective preventive veterinary interventions, assess the barriers to their utilization, and determine the willingness of livestock farmers to pay for the interventions to protect their livestock assets, and wellbeing.

2.2 Objectives

Given the above aim, the specific objectives are to:

1. Systematically review the literature on the effectiveness and cost-effectiveness of preventive veterinary interventions for controlling infectious diseases of ruminants in sub-Saharan Africa (Chapter 3)
2. Identify priority diseases affecting livestock and evaluate the strategies used by farmers and veterinary officers in managing infectious livestock diseases in herds, as well as the performance of veterinary services in meeting animal health needs of farmers (Chapter 4)
3. Determine the level of vaccination uptake by households, and the main barriers to the supply and utilization of vaccination services (Chapter 5)
4. Assess the livestock farmers' valuation and willingness to pay for vaccines to protect livestock resources against priority infectious diseases (Chapter 6)
5. Assess the relationship between the severity of animal disease mortality in herds and the wellbeing of livestock farmers (Chapter 7)

Each of the specific objectives above are covered in separate chapters of this thesis (Chapters 3 to 7). In Chapter 8, I present the discussion and conclusions from the main findings reported in these preceding chapters, and provide recommendations to inform policy actions and future research. In Chapter 9, I present a policy brief for the use of the relevant policy makers in Ghana. The policy brief summarized the key findings and challenges identified, and presented concise recommendations to address them.

Chapter 3 Effectiveness and profitability of preventive veterinary interventions in controlling infectious diseases of ruminant livestock in sub-Saharan Africa: a scoping review

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3.1 Abstract

Agriculture in general, and livestock production in particular, serve as a livelihood source for many people in sub-Saharan Africa (SSA). In many settings, lack of control of infectious diseases hampers livestock productivity, undermining the livelihood of rural populations. This scoping review sought to identify veterinary interventions previously evaluated as well as their relative effectiveness in controlling infectious livestock diseases. To be included, papers had to be written in English, German or French, and had to describe the effectiveness and/or profitability of preventive veterinary intervention(s) against anthrax, blackleg, bovine tuberculosis, brucellosis, contagious bovine pleuropneumonia, contagious caprine pleuropneumonia, foot-and-mouth disease, goat pox, lumpy skin disease, pasteurellosis, peste-des-petits ruminants, and/or sheep pox in any SSA country. Of the 2748 publications initially screened, 84 met our inclusion criteria and were analyzed. Most of the studies (n = 73, 87%) evaluated the effectiveness and/or profitability of vaccination, applied exclusively, applied jointly with, or compared to strategies like deworming, antimicrobial treatment, surveillance, feed supplementation, culling and dipping in reducing morbidity and/or mortality to livestock diseases. The effectiveness and/or profitability of antimicrobial treatment (n = 5), test and slaughter (n = 5), and use of lay animal health workers (n = 1) applied exclusively, were evaluated in the other studies. Vaccination was largely found to be both effective and with positive return on investment. Ineffective vaccination was mainly due to loss of vaccine potency under unfavorable field conditions like adverse weather events, cold chain failure, and mismatch of circulating pathogen strain and the vaccines in use.

In summary, vaccination is the most effective and profitable means of controlling infectious livestock diseases in SSA. However, to achieve effective control of these diseases, its implementation must integrate pathogen surveillance, and optimal vaccine delivery tools, to overcome the reported field challenges.

Keywords: Effectiveness, Profitability, Preventive interventions, Ruminant livestock, Infectious disease, Vaccination, One Health.

3.2 Introduction

Agriculture accounted for 28% and 16% of the gross domestic product of low income and lower middle-income countries in 2020 respectively (Alston and Pardey, 2014; World Bank, 2022). In sub-Saharan Africa (SSA), agriculture serves as pivot of employment, providing jobs to more than half of the workforce; a majority of jobs in rural areas and up to 25% of the jobs in urban areas (OECD/FAO, 2016). Even though SSA accounted for the highest proportion of people employed in agriculture globally, more than 50% of its population (ILO, 2021), the region's productivity in agriculture remain the lowest globally (Alston and Pardey, 2014). This coupled with having the highest population growth rate, 2.5% per annum, predisposes the region to food insecurity (OECD and FAO, 2021). Therefore, more needs to be done to increase efficiency in production in order to improve the prospects of growth in the agricultural sector.

Agricultural production in SSA is dominated by the crop sector, which accounts for more than two-thirds of the production, measured in constant US dollars, although the share varies across the region with the highest (90%) and lowest shares (53%) in West and Southern Africa respectively (OECD/FAO, 2016). In spite of being dominated by crops at the aggregate level, livestock production remain key to the livelihoods of many people; serving as the main protein source in the diet, source of income, store of wealth against uncertainties and as companion animals (Otte and Knips, 2005; Brown, 2006; Yurco, 2018; OIE, 2019b). The majority of farmers in SSA engage in extensive livestock production. Thus, seasonality, availability of grazing resources, livestock diseases, security and conflict issues, and veterinary services availability affect their productivity greatly (Pica-Ciamarra et al., 2007; Valbuena et al., 2015).

Animal diseases are a major constraint to the development of the livestock sector, costing nearly 9 billion USD per year; about 6% of the value of the livestock sub-sector in Africa (Grace et al., 2015). The high incidence and persistence of diseases in livestock in the region have been driven by a combination of factors including climate change, poor regulation of livestock movements, low utilization of preventive measures against diseases, and under-performance of veterinary services (Bett et al., 2009; Dean et al., 2013; FAO, 2017). Animal diseases cause high mortality rates among livestock, especially in developing countries; diseases account for 7% of deaths in adult cattle, 21% of deaths in calves, 15% of deaths in adult sheep and goats and 23% of deaths in lambs and kids. Consequently, farmers lose on average one animal, for every animal sold in the case of large ruminants like cattle, and one animal for every two animals sold for small ruminants like sheep and goats to diseases (Pradère, 2014). Recent advances in science have shown a strong interface between human, animal and the environmental ecosystems, in terms of interdependence between the ecosystems and its associated heightened risks of disease transmission (Chitnis et al., 2015; Molina-Flores et al., 2020). Therefore, the lack of effective control of infectious livestock diseases do not only threaten animal health, but also poses significant threat to food security and public health.

For the most part, the provision of quality veterinary services enables countries to detect and control animal diseases effectively, thereby contributing to increased productivity of the livestock sector. The veterinary system delivers both curative and preventive services. With high utilization of particularly preventive veterinary strategies, the disease burden would be greatly reduced (OIE, 2019b). However, the delivery of veterinary services have been ineffective in many SSA countries, due to a limited participation of public and private veterinary personnel as well as livestock producers (Cheneau et al., 2004). The poor performance of veterinary services in many African countries is mainly due to inadequate investment in veterinary services since the drastic changes in veterinary service policies in the 1980s, with only a handful of countries benefiting from these shifts in policy (Smith, 2001). The shift in veterinary service policy is attributed largely to pressure from global financial institutions for developing countries to implement structural adjustment programs that promoted economic recovery to address high indebtedness levels, leading to the privatization of some veterinary services and reduction in the human, financial and material resources (Sen and Chander, 2003; Cheneau et al., 2004; Amankwah et al., 2014). In addition, veterinary drug supply is poorly regulated in the region and the sector is dominated by private non-professional actors with commercial interest (Jaime et al., 2021). Strong investments in the veterinary services from both public and private sectors would therefore be key to achieving effective veterinary service delivery to improve farmer productivity. However, veterinary services have been chronically under-resourced, with a relatively low share of agricultural and health security investments, especially in developing countries leading to uncontrollable epidemics and high losses (OIE, 2019b).

The World Organization for Animal Health (WOAH, founded as OIE) instituted the Performance of Veterinary Services (PVS) Pathway to assist countries comprehensively assess the strengths and weaknesses of their veterinary services, and provide opportunities for resolution. A recent review of PVS appraisal reports of the veterinary services in Africa conducted in 2019 identified limited human, financial and material resources that affect particularly the delivery of field veterinary services as major barriers to effective control of diseases in Africa (OIE, 2019a). In addition, the low utilization of preventive veterinary services by livestock farmers remain a major bottleneck to the effective control of diseases (Nuvey et al., 2020). Consequently, livestock diseases are ineffectively managed leading to a high burden of preventable infectious diseases and loss of livestock assets with large health, economic and psychosocial implications for farmers and the public at large (Mockshell et al., 2014; Nuvey, 2019). This scoping review was conducted to identify existing evidence in the SSA region regarding preventive veterinary interventions' effectiveness and profitability in the control of selected infectious diseases in ruminants.

3.3 Materials and methods

The study adopted the five-stage scoping review process proposed by Arksey et al. (Arksey and O'Malley, 2005), namely identification of research question, identification of studies, selection of the relevant studies, data extraction and presentation of results. We also took recent recommendations by Peters et al. (Peters et al., 2020) into account for each stage of the scoping review process.

Research questions related to the aims of the review:

Our research question was "what evidence exists regarding the effectiveness and profitability of preventive veterinary interventions for controlling infectious diseases in ruminants in sub-Saharan Africa?" Specifically, we sought to answer the following three questions:

i. What interventions are or have been deployed to prevent infectious diseases in ruminants?

ii. How effective are these interventions in reducing the burden of infectious diseases in ruminants?
iii. How economically beneficial are these interventions?

The PICO elements were as described as follows:

i. Population: ruminant livestock that are reared in sub-Saharan Africa
ii. Intervention: any strategy that is implemented with the aim of preventing or reducing the occurrence of infectious diseases in livestock
iii. Comparison: the comparison for the intervention, it could be a control group, a before-and-after comparison, or a comparison of use and non-use of the intervention in livestock
iv. Outcome: any documented outcome that describes the efficacy, effectiveness and/or profitability of the intervention on ruminant health

Any study published before May 11, 2021, was considered for inclusion in the review. The articles had to be in English, German, or French, and describe the effectiveness and/or profitability of preventive veterinary intervention(s) to be included in the review. The articles were screened for eligibility at the title, abstract and full paper review stages.

Eligibility criteria and definitions

We defined a "preventive veterinary intervention" as any implemented strategy aimed at preventing or reducing the occurrence (prevalence or incidence) of infectious diseases in ruminants. Ruminant was defined as livestock domesticated for milk and meat production and comprises cattle, sheep, goat, camel and buffalo. The infectious diseases of interest were anthrax, bovine tuberculosis (bTB), blackleg, brucellosis, foot-and-mouth disease (FMD), contagious bovine pleuropneumonia (CBPP), contagious caprine pleuropneumonia (CCPP), lumpy skin disease (LSD), pasteurellosis, sheep pox, goat pox, and peste– des –petits ruminants (PPR). These diseases were selected based on a report outlining them as key infectious diseases affecting ruminant livestock in the West African region (Molina-Flores et al., 2020), priority diseases targeted for control in Ghana (Diop et al., 2011) as well as results from a previous study in Ghana (Nuvey et al., 2020).

Study identification

We developed the search term for the review based on our research questions. With the assistance of professional librarians (library service of the University of Basel), we conducted an initial limited search and after evaluation refined the search terms. We applied the MeSH terms for each of the keywords and included the synonyms to improve the sensitivity of the search. We also used truncation to capture all possible uses of the keywords. The search term for sub-Saharan Africa, was adapted from the ISSG search filter resource, where we identified and refined the filter for use in PubMed (The InterTASC Information Specialists' Sub-Group, 2006; Ziegler, 2018). After the search strategy was optimized for PubMed, we then translated it using the SR-accelerator tool (Clark et al., 2020) developed by Bond University to generate the equivalent search term for Scopus. The search for the African Journals Online database was refined thereafter as it was less optimized for title/abstract and MeSH searches (see **Additional file 1** for the search terms used). The searches were conducted on PubMed, Scopus and African Journals Online in May and June 2021, and included all studies published before then. We also manually searched the reference lists from authors of the included studies.

Study selection

Two reviewers, FSN and JA, independently screened titles, abstracts and full texts and selected studies based on a priori inclusion/exclusion criteria. Studies were included if: i) they were published in English, French or German, ii) they employed observational (cross-sectional, case-control, cohort), secondary data analysis, and/or experimental designs, and iii) the title or abstract referred to or described the effectiveness and/or profitability of an intervention or strategy that aim to prevent or reduce the occurrence of any of the selected infectious diseases in ruminants.

Before the screening, FSN created an endnote library for all the articles retrieved from each search. The distinct endnote libraries were then merged and de-duplication automatically done using the “import into duplicates library” feature. Then, a manual de-duplication was done by screening the merged database to identify duplicates that were missed during the automatic process. The screening was done systematically according to the author names. Groups were created in the Merged EndNote library namely: relevant, irrelevant, duplicates, and no abstract or full-text unavailable for article classification. Relevant articles are those that meet the inclusion criteria. Irrelevant articles were articles that did not meet the inclusion criteria. Duplicates comprise all articles with multiple records. Articles without abstracts and/or full texts may be either relevant or irrelevant, after a retrieval of the articles by the library for screening.

Following this, the merged endnote library file was shared for independent screening of the article title and abstracts. The two reviewers met for the first time to review the a priori inclusion and exclusion criteria. After one week of independent screening, the two reviewers met again to compare notes on difficulties and identified strategies to overcome them. Where there were disagreements in classification of articles, the two reviewers met to resolve them by referring together to the a priori inclusion and exclusion criteria.

After the initial screening and classification, we also searched the cited references in the relevant articles for titles that could be relevant, screened and included the articles that met the inclusion criteria for the data extraction and analysis.

Data extraction

Data were extracted by FSN and was reviewed by JH. The information extracted for each included study were author(s) of study, year of publication, year of study, country of study, objective of the study, livestock species studied, study design employed, data collection methods, and the intervention(s) evaluated. Other information extracted were details of the outcome(s) of interest, measure of effect or profitability of the intervention(s) and study limitations and conclusions. The data were entered into Microsoft Access and exported to Microsoft Excel for analysis.

Synthesis of results

Given the broad range of eligible study types and research questions, outcomes and effect measures varied among studies. Therefore, it was not possible to generate a single summary measure of effectiveness or profitability. For studies that did not provide protective rates of intervention, but presented raw data on prevalence or incidence stratified by intervention and control groups, these analyses were done using the formula below.

Protective rate =

$$\frac{disease\ prevalence\ or\ incidence\ in\ control\ group - disease\ prevalence\ or\ incidence\ in\ intervention\ group}{disease\ prevalence\ or\ incidence\ in\ control\ group}$$

In addition, we used data on benefits of intervention and intervention costs provided by studies that assessed profitability without reporting benefit-cost ratios (BCR), to estimate the BCR of implementing the intervention using the formula below.

$$BCR = \frac{Benefits\ of\ the\ intervention = (Costs\ saved + New\ revenue)}{Cost\ of\ the\ intervention = New\ intervention\ cost}$$

The results were presented as average protective rates of each intervention and for specific infectious diseases with their respective ranges. We also present average benefit-cost ratios for interventions applied for specific infectious diseases where applicable.

3.4 Results

Articles retrieved in the review

The literature search yielded 2927 hits; PubMed = 1842 hits, Scopus = 906 hits and African Journal Online (AJOL) = 179 hits. After removing duplicates in the merged database, 2212 articles were identified for title and abstract screening. Only four articles could not be retrieved for screening and were excluded. Many of the articles (85%, n = 1873) were excluded at the title and abstract screening stage because they either did not describe interventions against the infectious diseases of interest, were not implemented in sub-Saharan Africa, or employed study designs excluded in the protocol. After the full text review for eligibility (n = 335), 67 articles met the inclusion criteria. A further 17 articles were found from the reference lists of included articles. Thus, 84 articles were included for data extraction and analysis. **Figure 1** shows the review process, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses–Extension for Scoping Reviews (PRISMA-ScR).

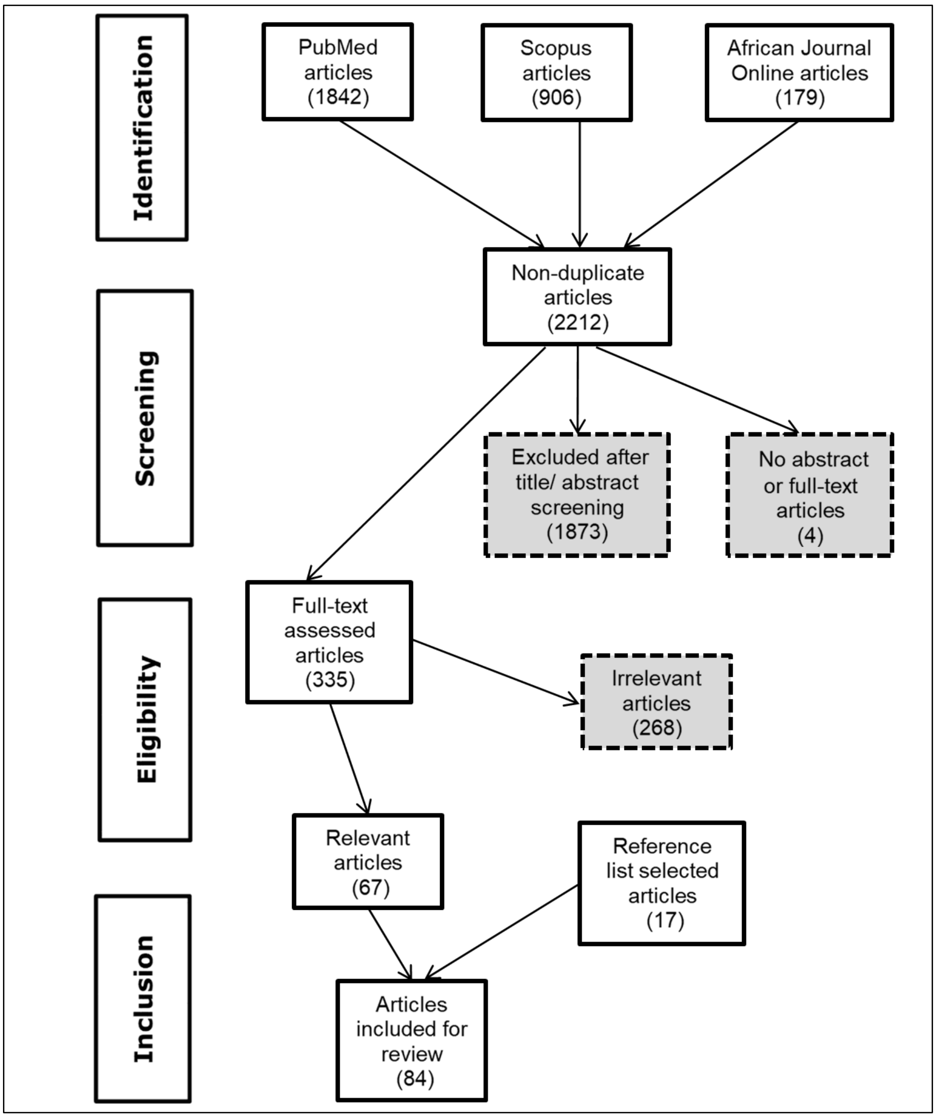

Figure 1: Steps followed during selection of studies for inclusion in the review

Characteristics of the reviewed studies

Out of the 84 publications reviewed, 40 (48%) were conducted in East Africa, 20 (24%) in West Africa, 14 (17%) in Southern Africa, 6 (7%) in Central Africa and 4 (5%) studies were done in multiple regions. The countries that dominated the published research on the effectiveness and profitability of preventive veterinary interventions were Kenya (n = 24), Ethiopia (n = 17), Nigeria (n = 9), Cameroon (n = 8) and South Africa (n = 7) (**Figure 2**). About half of the reviewed studies (n = 41) did not state the period during which they were conducted. For the studies (n = 43) that reported on the year of study, the earliest was done in 1954 and the latest in 2019. The studies were almost equally done in 20th and 21st centuries (before 2000, n = 20; after 2000, n = 23). In contrast, most of the studies (n = 60) were published after the year 2000.

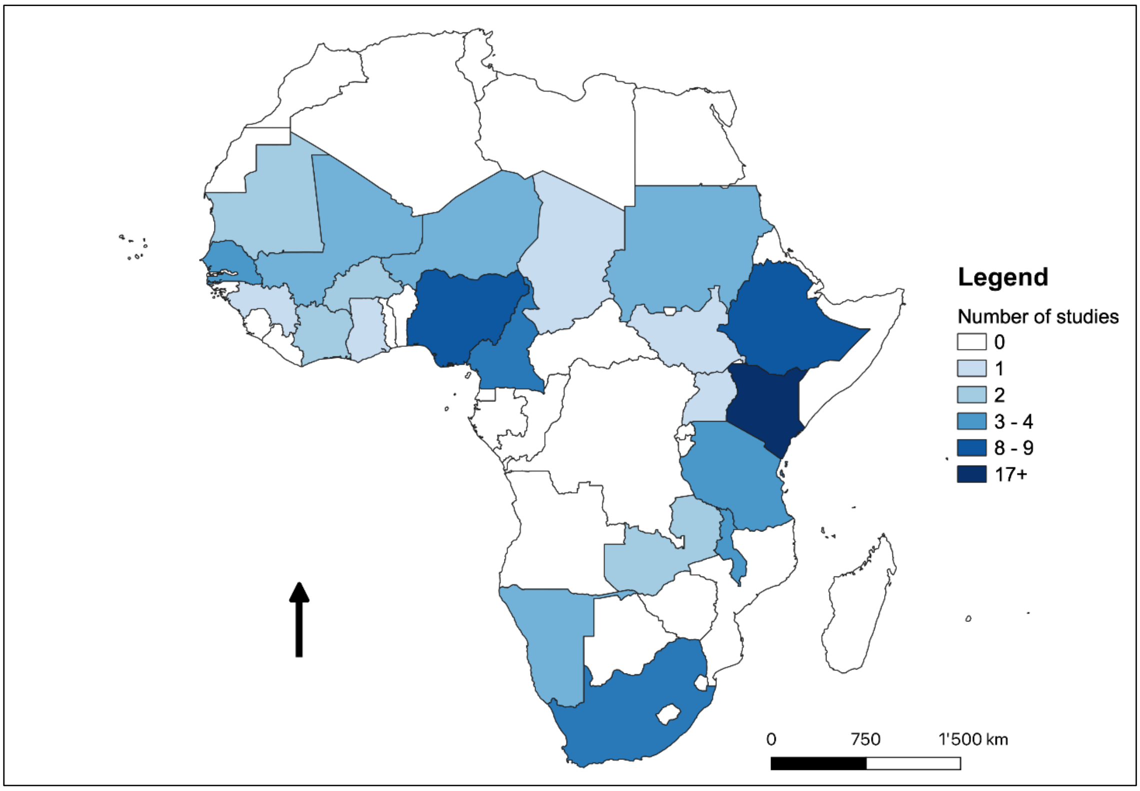

Figure 2: Geographical distribution of studies in the review

The studies described interventions aimed at reducing morbidity and mortality in cattle (73%, n = 61), goats (14%, n = 12), mixed animal species (10%, n = 8), sheep (2%, n = 2) and buffalos (1%, n = 1). About 92% (n = 77) of studies evaluated interventions against only one infectious disease: CBPP (n = 28), FMD (n = 15), Bovine TB (n = 10), PPR (n = 9), LSD (n = 7), Blackleg (n = 2), Brucellosis (n = 2), CCPP (n = 2), and Pasteurellosis (n = 2). The other studies were on at least two of the above-mentioned infectious diseases in addition to anthrax and/or goat pox. Vaccination was the most frequently evaluated intervention; vaccination only (n = 63), vaccination applied in addition to or compared with other measures (n = 10), antimicrobial treatment (n = 5), test and slaughter (n = 5), and use of community animal health workers (n = 1).

Most of the studies (61%, n = 51) were experimental [under controlled conditions (n = 33), field trials (n = 17) and both under controlled conditions and field trial (n = 1)], 19% were cross-sectional studies (n = 16), and 10% were retrospective studies (n = 8). Some studies combined two or more designs; cross-sectional and retrospective data analysis (n = 5), cross-sectional and experiments (n= 1), cross-sectional, retrospective data analysis and longitudinal designs (n = 1). Two of the studies adopted a cohort design. Detailed characteristics of the studies are shown in **Table S1** and **Table 2**.

Table 2: Summarized characteristics of studies reviewed

Variables	Description	Number of studies (references*)
Year study conducted	Before year 2000	20 (34, 36 – 40, 43 – 45, 48, 68, 69, 80, 92 – 94, 97 – 99, 101)
	Year 2000-2019	23 (41, 46, 52, 56, 57, 74, 79, 81, 83, 84, 89 – 91, 103, 105 – 108, 110 – 112, 115, 116)
Region of study	West Africa	20 (34, 37, 51, 56 – 58, 67 – 69, 92, 94, 96, 97, 101, 105, 107, 111, 114, 117, 118)
	Central Africa	6 (74, 83, 86, 98 – 100)
	East Africa	40 (35, 36, 39, 41, 42, 46, 47, 55, 59, 60, 62 – 66, 70 – 73, 79 – 82, 84, 85, 87 – 91, 95, 103, 106, 108 – 110, 112, 113, 115, 116)
	Southern Africa	14 (38, 40, 43 – 45, 48, 50, 54, 75 – 78, 93, 102)
	Two or more regions	4 (52, 53, 61, 104)
Objective of study	Effectiveness of intervention	63 (34 - 48, 50 – 79, 81 – 92, 95 – 98, 100, 101)
	Cost-benefits of intervention	17 (102 – 118)
	Effectiveness and cost-benefits	4 (80, 93, 94, 99)
Study design	Experimental study	51 (34, 37 – 44, 46, 48, 50 – 54, 59 – 69, 72 – 80, 83, 85 – 88, 92 – 101)
	Cross-sectional study	16 (36, 45, 55, 56, 57, 82, 84, 90, 103, 107, 108, 111, 112, 115, 116, 118)
	Secondary data analysis	8 (47, 58, 70, 102, 104, 113, 114, 117)
	Cohort study	2 (81, 110)
	Mixed (Two or more study designs)	7 (35, 71, 89, 91, 105, 106, 109)
Animal species involved	Cattle	61 (37, 40 – 47, 50 – 72, 74 – 77, 79 – 84, 87 – 91, 93, 102 – 104, 106 – 109, 111 – 116)
	Sheep	2 (94, 100)
	Goats	12 (34, 73, 78, 85, 86, 92, 95 – 97, 101, 110, 117)
	Buffalo	1 (48)
	Mixed (large and small ruminants)	4 (38, 98, 99, 118)
	Mixed (only small ruminants)	4 (35, 36, 39, 105)
Disease studied	Contagious bovine pleuropneumonia	28 (50 – 72, 104, 106 – 109)
	Foot and mouth disease	15 (74 – 84, 111 – 114)
	Bovine tuberculosis	10 (40 – 48, 102)
	Peste des petits ruminants	9 (95 – 101, 117, 118)

	Lumpy skin disease	7 (87 – 91, 115, 116)
	Blackleg	2 (39, 103)
	Brucellosis	2 (37, 38)
	Contagious caprine pleuropneumonia	2 (73, 110)
	Pasteurellosis	2 (93, 94)
	Two or more infectious diseases	7 (34 – 36, 85, 86, 92, 105)

***** Numbered references for the included studies are provided in the Supplemental section at the end of this Chapter.

Preventive veterinary interventions

The review revealed that the main preventive veterinary intervention was vaccination (n = 73, 87%) against the specified disease(s). The effectiveness and/or profitability of vaccination applied exclusively was evaluated in 63 of these studies. Nine studies evaluated effectiveness and/or profitability of vaccination plus: deworming (n = 4), antimicrobial treatment (n = 2), dipping (n = 1), and antimicrobial treatment and surveillance (n = 1). One study compared the effectiveness of feed supplementation versus vaccination applied jointly with deworming, while another study compared the profitability of vaccination, antimicrobial treatment and culling. The effectiveness and/or profitability of antimicrobial treatment (n = 5), test and slaughter (n = 5), and use of lay animal health workers (n = 1) applied exclusively, were also evaluated. **Table 3** provides a summary of the interventions evaluated in the reviewed studies.

Table 3: Distribution of the interventions applied against the infectious diseases of interest

Intervention	Disease	Frequency	Study reference*
Vaccination only	Anthrax	1	(35)
	Blackleg	3	(35, 39, 103)
	Bovine tuberculosis	6	(40, 41, 42, 43, 44, 45)
	Brucellosis	1	(37)
	Contagious bovine pleuropneumonia	23	(35, 54 – 72, 106 – 108)
	Contagious caprine pleuropneumonia	3	(35, 73, 110)
	Foot and mouth disease	13	(75 – 84, 112 – 114)
	Goat pox	2	(85, 86)
	Lumpy skin disease	7	(87 – 91, 115, 116)
	Pasteurellosis	2	(35, 93)
	Peste des petits ruminants	9	(35, 85, 86, 95 – 98, 117, 118)
Vaccination applied jointly with other interventions	Contagious bovine pleuropneumonia	3	(53, 104, 105)
	Anthrax	1	(34)
	Pasteurellosis	3	(34, 92, 94)
	Peste des petits ruminants	6	(34, 92, 99, 100, 101, 105)
Vaccination compared with other interventions	Contagious bovine pleuropneumonia	1	(109)
Antimicrobial treatment	Contagious bovine pleuropneumonia	3	(50 – 52)
	Foot and mouth disease	2	(74, 111)
Test and slaughter	Bovine tuberculosis	4	(46, 47, 48, 102)
	Brucellosis	1	(38)
Use of community animal health workers	Anthrax	1	(36)
	Blackleg	1	
	Contagious caprine pleuropneumonia	1	

*Numbered references for the included studies are provided in the Supplemental section at the end of this Chapter.

Effectiveness of the interventions

The effectiveness of the preventive interventions was evaluated in 75% (n = 63) of the reviewed studies while 5% (n = 4) evaluated both effectiveness and profitability. The effectiveness assessment was either for single interventions (n = 60), or a combination package of interventions (n = 7). To evaluate effectiveness, 43% (n = 36) of the studies computed morbidity or mortality rate differences or ratios between intervention and control groups. One-third of the studies (n = 31) reported protective rates of the implemented intervention(s) against morbidity and/or mortality in intervention and control groups. **Figure 3** shows the effectiveness of interventions evaluated for each disease. We provide a summary of the effectiveness of the interventions implemented across the studies by each infectious disease below.

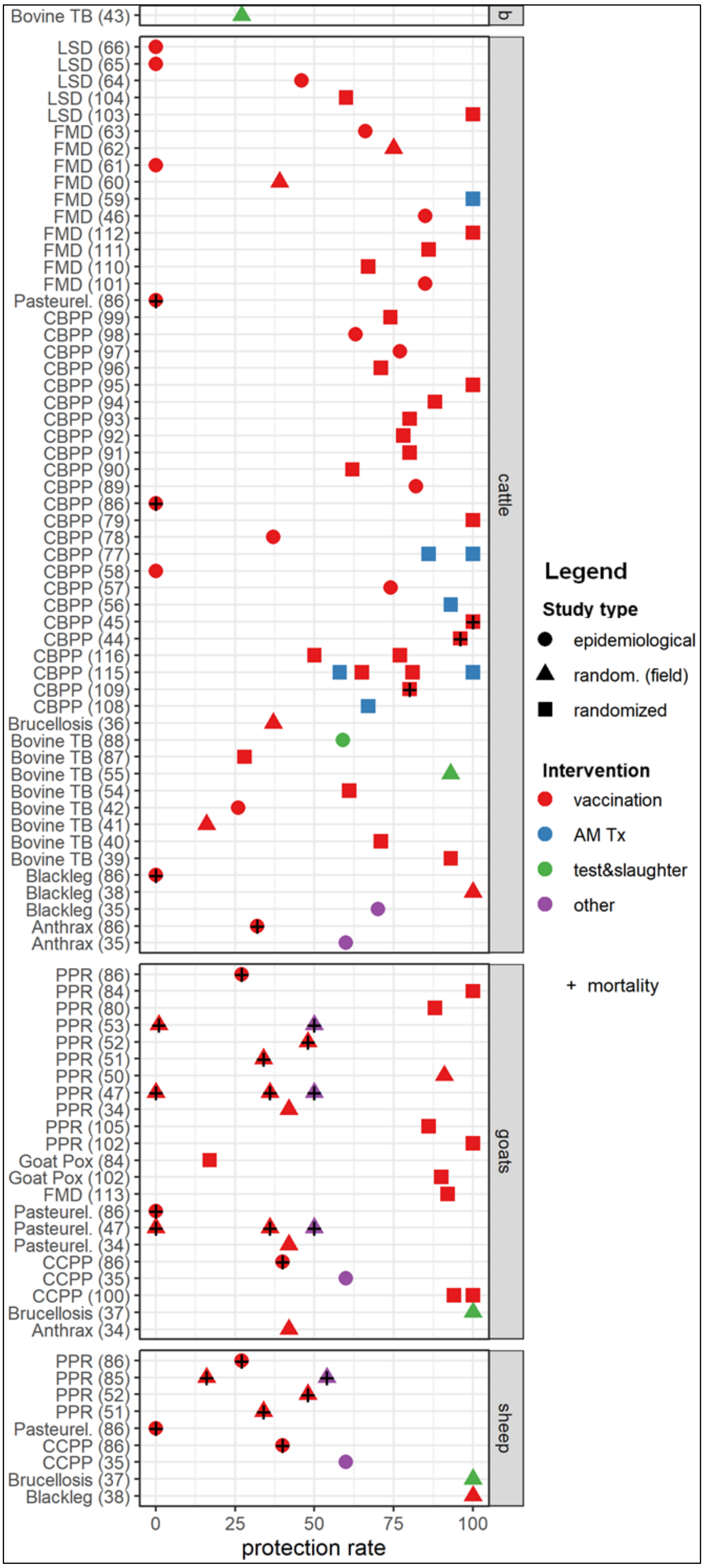

Figure 3: Effectiveness of preventive interventions against morbidity and mortality in ruminant livestock.

The y-axis shows the specific diseases evaluated by species of livestock, with included study references in parenthesis. The x-axis shows the protection rates offered by the interventions against the specified diseases on a percentage scale. Interventions that did not offer protection against a disease in an included study have a 0% protection rate on the scale. Shapes are used to distinguish between study types while colors distinguish between the different preventive interventions evaluated in the included studies. “randomized” represents experimental studies implemented under controlled clinical conditions while “random. (field)” represents experimental studies implemented under natural field conditions. “epidemiological” denotes all other study types except experimental studies implemented in the included studies. ”AM Tx” denotes antimicrobial treatment. “other” denotes the other interventions including deworming and dipping. The position of shapes on the percentage scale denote the protection rates of the interventions against morbidity to the specified diseases of interest in the included studies. ”+” in a shape represents protection rate of the interventions against mortality to the specified disease. “b” denotes a study that evaluated test and slaughter strategy in buffalos.

Anthrax

Three studies evaluated the effect of preventive interventions on anthrax in cattle and goats. Two of the studies assessed mortality rate differences in vaccinated and unvaccinated cattle and goats, while the other study assessed the impact of community animal health workers’ (CAHWs) management of anthrax in rural Ethiopia.

The effectiveness of vaccination could only be assessed in one of the vaccination studies as the other compared mortality rates among goats receiving vaccines against three diseases (pasteurellosis, anthrax and PPR). Thus, only a joint effectiveness of the three vaccines could be evaluated. The overall effectiveness of the vaccines was 34% protection in goats less than 6 months old, and 50% protection in adult goats (Ba et al., 1996). The effectiveness of vaccination in the other study was mixed; vaccination appeared effective during drought years (protection rate = 64%). However, during a normal year’s vaccination, it was not protective (Catley et al., 2009).

The evaluation of effectiveness of CAHWs deployment showed that, the effect of anthrax in pastoralists’ herds reduced by 60% following the activities of CAHWs in the communities (Admassu et al., 2005).

Brucellosis

Both studies on Brucellosis were field trials; one evaluated vaccination as an intervention while the other evaluated a test and slaughter approach. The outcomes assessed were different in the two studies. Both interventions were effective; vaccination offered a 37% protection rate against brucellosis-related abortions and still births in cattle (Camus, 1980) while test and slaughter was 100% protective against brucellosis infections in sheep and goats (Emslie and Nel, 2002).

Blackleg

Three studies evaluated effectiveness of preventive interventions against Blackleg in cattle and sheep. The studies adopted experimental, cross-sectional and retrospective study designs. The interventions evaluated were vaccination and CAHWs deployment. The outcomes of interest varied across the studies. The deployment of animal health workers was effective, reducing the effect of blackleg in pastoralists' herds by 70% following the activities of CAHWs (Admassu et al., 2005). However, the effectiveness of vaccination was unclear. In an experimental study, the authors observed a protective rate of 100% against blackleg related deaths in cattle (Coackley and Weston, 1957). However, a retrospective review of data in another study found vaccination to be ineffective (Catley et al., 2009).

Bovine Tuberculosis

Eight out of the nine studies that evaluated effectiveness of interventions against Bovine tuberculosis (bTB) were done in cattle while the other was done in buffalos. The interventions mainly evaluated were vaccination (n = 6) and test and removal (n = 3). The effectiveness of vaccination was evaluated under controlled conditions in four out of the six studies. Both vaccination and the test and slaughter strategies were protective against bTB infection and/or deaths in all the studies, although the protection rates varied.

In the six studies that evaluated the protection rate of vaccination against bTB infection in cattle (Ellwood and Waddington, 1972; Waddington and Ellwood, 1972; Berggren, 1977, 1981; Ameni et al., 2010; Ameni et al., 2018), an average protective rate of 63% (range: 28% to 93%) under controlled conditions in clinical trials and 21% (range: 16% to 26%) under natural field conditions was reported. The results for the test and removal strategy were not different either. In cattle, test and slaughter strategy provided an average protection rate of 76% (range: 59% to 93%) against bTB infection (Ameni et al., 2007; Roug et al., 2014). However, in buffalos test and slaughter offered a protection rate was 27% (le Roex et al., 2016).

Contagious Bovine Pleuropneumonia

Twenty-three studies evaluated the effectiveness of interventions against contagious bovine pleuropneumonia (CBPP) morbidity and/or mortality in cattle. CBPP is the only disease for which interventions were evaluated in all the sub-Saharan African regions.

The outcomes of interest in these studies varied but all interventions implemented were generally effective. To assess the extent of CBPP morbidity, most of the studies adopted the Hudson and Turner approach (Hudson and Turner, 1963) in lesion scoring.

Three of the studies (experiments) evaluated the protective rate of antimicrobial treatment [danofloxacin (Huebschle et al., 2006), long acting oxytetracycline (Niang et al., 2010) and tulathromycin and gamithromycin (Muuka et al., 2019)] against CBPP infection and infection spread among cattle under controlled conditions in clinical trials. Overall, the antimicrobials used were efficacious against CBPP morbidity; average protection rate was 82% (range: 67% to 93%).

A trial assessed both vaccination and treatment approaches against CBPP infection and deaths. The study reported an average protection rate of 65% against morbidity and 81% against mortality, for the 2 vaccine formulations tested. The authors observed that treatment with oxytetracycline protected infected animals against the extension of lesions in the lungs (protection rate = 58%) (Thiaucourt et al., 2004).

Even though the studies evaluating the effectiveness of vaccination alone (Lindley, 1967; Doutre and Chambron, 1970; Gilbert et al., 1970; Gilbert and Windsor, 1971; Doutre et al., 1972; Masiga, 1972; Domenech, 1979; Gray et al., 1986; Garba et al., 1989; Thiaucourt et al., 2000; Wesonga and Thiaucourt, 2000; Hübschle et al., 2003; Mariner et al., 2006a; Mariner et al., 2006b; Catley et al., 2009; Tambuwal et al., 2011; Nkando et al., 2012; Suleiman et al., 2015; Nkando et al., 2016; Zerbo et al., 2021) reported mixed results, the evidence shows vaccination to be effective against both CBPP morbidity and mortality. All studies evaluating vaccination under controlled conditions (n = 13), were highly protective against CBPP infection and deaths: average protection rate against CBPP infection was 77% (range: 50% to 100%) and mortality was 92% (range: 77% to 100%). In the seven other studies that evaluated vaccination against CBPP, only five showed vaccination to be effective; average protective rate against CBPP infection was 67% (range: 37% to 82%). In the two cross-sectional studies where vaccination was ineffective, prevalence of infections and deaths from CBPP were higher in cattle with a history of vaccination.

Contagious caprine pleuropneumonia

Three studies evaluated effectiveness of interventions (vaccination and community animal health workers deployment) against contagious caprine pleuropneumonia (CCPP) in goats and sheep. Both interventions were effective against CCPP infection in the studies. Protective efficacy of vaccination against morbidity and mortality in goats were 94% and 100% respectively in an experiment under controlled conditions (Rurangirwa and McGuire, 1991). A retrospective study found a lower protective rate of vaccination (40%) against CCPP mortality in sheep and goats (Catley et al., 2009). The study that evaluated CAHWs deployment found the effect of CCPP in pastoralists' herds to reduce by 60% following the activities of CAHWs in the communities (Admassu et al., 2005).

Foot-and-mouth disease

Ten out of eleven studies assessed the effectiveness of vaccination against foot-and-mouth disease. The other intervention evaluated the efficacy of a novel topical anesthetic and antiseptic formulation (Tri-Solfen) against FMD lesions. Only one study assessed intervention effectiveness in goats; the rest were all in cattle.

The comparison of the efficacy of Tri-Solfen and antimicrobial treatment (parenteral oxytetracycline) against FMD lesion healing under controlled conditions in a trial showed a 100% protective rate of both treatments towards clinical recovery, but with a more rapid healing observed for the new formulation compared to the parenteral oxytetracycline group (Lendzele et al., 2020).

Vaccination was highly protective against FMD infection in all the studies done under controlled conditions in clinical trials (n = 4): average protection rates were 84% in cattle (range: 67% to 100%) and 92% in goats (Cloete et al., 2008; Maree et al., 2015; Scott et al., 2017; Lazarus et al., 2020). In the six studies evaluating effectiveness of vaccination against FMD infection in cattle under natural field conditions (Anderson et al., 1974; Chema, 1975; Lyons et al., 2015; Bertram et al., 2018; Nyaguthii et al., 2019; Jemberu et al., 2020b), only one was ineffective. Average protection rate across studies was 70% (range: 39% to 85%). In the cohort study where vaccination was ineffective, incidence of FMD infection during an outbreak was highest in cattle with previous histories of vaccination against FMD; the risk of infection increased with an increase in the lifetime doses of FMD vaccines received by the cattle (Lyons et al., 2015).

Goat pox

Two experiments assessed the efficacy of vaccination against goat pox infection under controlled conditions. The protection rate of vaccination against goat pox infection differed widely in the two studies. While goats vaccinated against goat pox were fully protected in one study (Caufour et al., 2014), the other study reported a protection rate of only 17% (Martrenchar et al., 1997).

Lumpy skin disease

Five studies evaluated the effect of vaccination against lumpy skin disease (LSD) infection in cattle. Vaccination was highly protective against LSD infection in the two studies (Ngichabe et al., 2002; Gari et al., 2015) done under controlled conditions; average protection rate was 80% (range: 60% to 100%). Only one of the other three studies done under natural field conditions found vaccination to be protective against LSD infection; protection rate was 46% (Molla et al., 2017b). The two other cross-sectional studies observed a higher prevalence of infections and deaths in vaccinated compared to the unvaccinated cattle (Ayelet et al., 2013; Ayelet et al., 2014).

Pasteurellosis

Five studies evaluated effectiveness of interventions against pasteurellosis morbidity and mortality in livestock under natural field conditions. Two of these studies assessed in addition the combined effects of multiple vaccines and deworming in a parallel group (Ba et al., 1996) or factorial design (Lancelot et al., 2002). The net effect in both studies was that both treatments were effective in reducing mortality rates in goats, the effect even more profound when vaccination and deworming are combined.

In the three other studies, the effectiveness of vaccination was unclear. Due to differences in the outcomes of interest, a pooled estimate of protection rate could not be derived. One of these studies compared the efficacy of two vaccine formulations and found a modified vaccine to be about 15% more efficacious than the standard vaccine in preventing pasteurellosis infection in cattle (Gummow and Mapham, 2000). In a retrospective study, vaccination was not protective against pasteurellosis related deaths in cattle in both normal and drought years, and in goats and sheep during drought years, but was protective (protection rate = 18%) in sheep and goats when vaccination was done in normal years (Catley et al., 2009). In another experiment, Lesnoff et al. (Lesnoff et al., 2000) showed vaccination alone was ineffective, but deworming alone or vaccination applied jointly with deworming improved productivity (reduced mortality and increased fecundity) in goats.

Peste des petits ruminants (PPR)

Twelve studies evaluated the effectiveness of interventions against PPR morbidity in goats and sheep. Two of these studies described a combined effect of multiple vaccines and had been reported earlier (Ba et al., 1996; Lancelot et al., 2002). In all the other studies, the effects of either PPR vaccination, feed supplementation, deworming and/or pest control on PPR infection and deaths were evaluated.

Overall, vaccination has been shown to be effective in PPR control. Under controlled conditions in clinical trials (n = 4), vaccination provided an average protection of 94% against PPR infection (range: 86% to 100%) and 100% protection against PPR related deaths in goats (Martrenchar et al., 1997; Caufour et al., 2014; Holzer et al., 2016; Jarikre et al., 2019). Under natural conditions, protection is slightly lower; protection rate against PPR infection was 91% (Wosu et al., 1990) and against PPR related deaths, protection rate was 31% on average (range: 27% to 34%) in sheep and goats (Martrenchar et al., 1999; Catley et al., 2009).

The other three studies evaluated the effectiveness of vaccination in addition to other measures including dipping, deworming and feed supplementation. The application of vaccination jointly with deworming provided a protection rate of 48% against mortality in small ruminants (Awa et al., 2000). However, providing feed supplement was more protective against mortality in sheep than vaccination and deworming applied jointly (Njoya et al., 2005). While, dipping was more effective against mortality in goats when applied alone, than when applied jointly with vaccination (Reynolds and Francis, 1988)

Profitability of the interventions

About 25% (n = 21) of the reviewed studies evaluated profitability of implemented interventions; four of these studies evaluated both effectiveness and profitability. The majority (n = 15) of the studies reported benefit cost-ratios (BCR), 3 studies reported marginal rate of return (MRR), 2 reported internal rate of return (IRR) and 1 reported the net return of implementing the intervention(s). The profitability analyses was done only for blackleg, bTB, CBPP, CCPP, FMD, LSD, pasteurellosis and PPR control strategies. Figure 4 shows the profitability of interventions for controlling the infectious diseases of interest. Overall, apart from strategies involving culling of infected animals, all other interventions evaluated provided positive returns on investment. We present below a summary of the profitability for interventions for controlling each of the diseases.

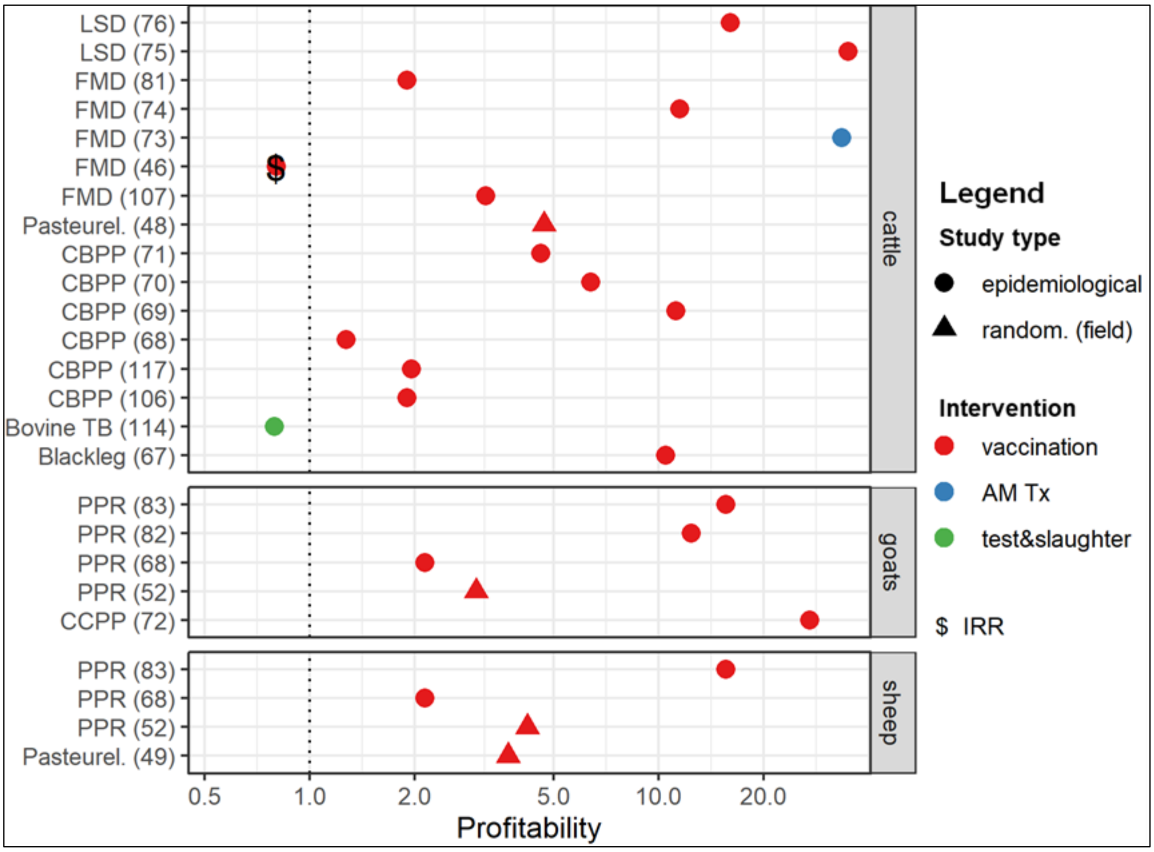

Figure 4: Profitability of preventive interventions in controlling infectious diseases in ruminant livestock.

The y-axis shows the specific diseases evaluated by species of livestock, with included study references in parenthesis. The x-axis shows the profitability of the interventions in controlling the specified diseases on a benefit-cost ratio (BCR) scale. Shapes are used to distinguish between study types while colors distinguish between the different preventive interventions evaluated in the included studies. “random. (field)” represents studies that adopted field trials while “epidemiological” denotes all other study types except experimental studies. ”AM Tx” denotes antimicrobial treatment. The position of shapes on the BCR scale denote the profitability of the interventions in controlling the specified diseases of interest in the included studies. “$” in shapes represents the internal rate of return of an intervention in controlling the specified disease for studies that did not present data for BCRs to be calculated.

Bovine tuberculosis

The profitability of a test and slaughter strategy in controlling bTB morbidity and mortality in both cattle and humans was assessed in one study. The benefit cost ratio was 0.79, thus the costs of control always exceed the benefits if purely monetary estimates were considered (Mwacalimba et al., 2013).

Blackleg

The control of blackleg in cattle was profitable compared to non-vaccination; vaccinating cattle in a 1 year period provides substantial benefits to farmers (MRR = 9; BCR = 10.5) (Ayele et al., 2016).

Contagious bovine pleuropneumonia

Six studies assessed the profitability of interventions for controlling CBPP in cattle. The interventions include vaccination, antimicrobial treatment, surveillance, and a culling of infected animals at home. Except for culling, investments in vaccination, treatment or both treatment and vaccination, and surveillance, were all found to yield significant economic returns (Tambi et al., 2006; Fadiga et al., 2013a; Kairu-Wanyoike et al., 2014; Onono et al., 2014; Alhaji and Babalobi, 2017; Kairu-Wanyoike et al., 2017). Average BCR for implementing a vaccination only strategy was 5.9 (range: 1.3 to 11.2). Average BCR for a jointly applied vaccination and antimicrobial treatment strategy was 2.2 (range: 2.0 to 2.4). Implementing vaccination, antimicrobial treatment and surveillance altogether provides a BCR of 1.3. However, a culling strategy is not profitable (BCR = 0.07).

Contagious caprine pleuropneumonia

One study assessed the profitability of vaccination against CCPP infection in goats at different levels of vaccine efficacy (Renault et al., 2019). BCR at 20% vaccine efficacy was 5.7, 50% was 27.2 and 95% was 61.9. Vaccination was thus profitable in all the scenarios assessed.

Foot-and-mouth disease

Five studies evaluated the profitability of vaccination (n = 4) and antimicrobial treatment (n = 1) in controlling FMD in cattle. In all cases, the results showed that the investments in these interventions would yield high economic returns (Chema, 1975; Barasa et al., 2008; Jemberu et al., 2016; Souley Kouato et al., 2018; Alhaji et al., 2020). However, antimicrobial treatment of FMD lesions yielded higher economic returns (BCR = 33.6) compared to vaccination (BCR = 5.5 on average; range 1.9 to 11.5, IRR = 0.8).

Lumpy skin disease

Two studies assessed the profitability of vaccination in controlling LSD in cattle (Gari et al., 2011; Molla et al., 2017a). In both studies, vaccination was profitable; average MRR = 24.5 (range: 15.1 to 34), BCR = 25.6.

Pasteurellosis

One study compared the profitability of implementing deworming or pasteurellosis vaccination in sheep. Only deworming was found to be profitable (BCR = 3.7) (Lesnoff et al., 2000). Another study compared the profitability of two vaccine formulations in controlling pasteurellosis; both vaccines were profitable (BCR = 4.7) (Gummow and Mapham, 2000).

Peste des petits ruminants

Four studies (Stem, 1993; Awa et al., 2000; Fadiga et al., 2013a; ElArbi et al., 2019) evaluated the profitability of interventions aimed at controlling PPR in sheep and goats. All the interventions evaluated were cost-effective for controlling PPR, yielding significant economic returns on investment. Average BCR for controlling PPR by vaccination only was 14.0 (range: 12.4 to 15.6). Applying vaccination jointly with deworming provides a BCR of 3.1, while vaccination, surveillance and antimicrobial treatment applied jointly in PPR control yields a BCR of 2.1.

3.5 Discussion

In this review, we aimed to summarize veterinary interventions implemented to control infectious diseases in ruminants in SSA, as well as their effectiveness in reducing the occurrence of diseases and deaths in livestock. Our review included both observational and experimental evaluations. Our results highlight vaccination as the main and currently dominant tool in the control of all the infectious diseases assessed. This could be due to the relative success of vaccination in the past as a control measure in eliminating several infectious diseases in livestock like foot-and-mouth disease and bluetongue in developed countries (Conrady et al., 2021) as well as the infectious nature of the pathogens causing these diseases: viruses and bacteria. Particularly in the case of the global efforts against the highly virulent rinderpest disease which is the only animal disease to be eradicated globally after many years of devastative impact on animal health and productivity (Morens et al., 2011). The other control measures including antimicrobial treatment, parasite control, test and slaughter, surveillance, and feed supplementation, were seldom used exclusively, but were usually combined with vaccination to achieve better results.

Our review showed that antimicrobials could limit disease progression in infected animals, thereby preventing further infection spread (Thiaucourt et al., 2004; Huebschle et al., 2006; Mariner et al., 2006a; Niang et al., 2010; Muuka et al., 2019). The test and slaughter strategy was also effective in the control of brucellosis and bovine TB (Emslie and Nel, 2002; Ameni et al., 2007; Roug et al., 2014; le Roex et al., 2016). However, these control measures: antimicrobial treatment and, test and slaughter approaches, may not be feasible for effective disease control in the SSA region. They are either too expensive or impractical to implement, in the case of test and removal (Ducrotoy et al., 2017; Arnot and Michel, 2020), or lack effective regulation to achieve sustainable control, for antimicrobial treatment. Particularly in the case of antimicrobial treatment, a recent review of the PVS Pathway appraisals in African countries found that the veterinary services in 80% of countries in the region, had limited or in some cases no capability to administratively control the registration, import and production, distribution and usage of veterinary medicines and biologicals" (OIE, 2019a). Thus, the retail of antimicrobials are largely out of control, and antimicrobial treatment is widely practiced by farmers, without veterinary advice. Usage rates of antimicrobials range from 80% to 100% of farms in the region, with the main drugs in use being tetracyclines, aminoglycosides, and penicillin groups (Kimera et al., 2020; Mshana et al., 2021). Consequently, there is a significant concern about the safety of livestock products in the region, worsened by a lack of residue testing programmes in more than two-thirds of countries (OIE, 2019a). The high usage rates of antimicrobials coupled with a lack of testing could foster the development antimicrobial resistant pathogens.

Vaccination is currently without doubt, the main intervention tool for controlling infectious diseases in both humans and animals (Pastoret and Jones, 2004; Andre et al., 2008; McVey and Shi, 2010). As noted in previous reviews (Domenech and Vallat, 2012; Baker et al., 2018; Zhang et al., 2018), vaccination is highly effective in controlling most of the infectious diseases of interest in this review. However, given that a large proportion of the studies in our review (39%) were on-station clinical experiments, effectiveness under natural field conditions may be more limited due to extreme weather events, animal undernutrition and human error in vaccine administration among others. Under ideal conditions, different degrees of protection could be achieved by vaccination against specific pathogens, including protection against infection, disease progression and infection spread to other susceptible animals and humans (McVey and Shi, 2010). The production of vaccines however is limited in SSA with only 17 countries producing vaccines in the region for livestock, mainly for local use in the countries (Jaime et al., 2021). About 20 different types of vaccines are produced in the region, a majority being vaccines for poultry especially against Newcastle disease. Vaccines produced for ruminant livestock are mainly against PPR, anthrax, and FMD. The production units are mostly small, with Ethiopia accounting for a large share of vaccines produced (Jaime et al., 2021). These vaccine production shortfalls coupled with huge challenges with distribution infrastructure in the region could affect farmers' access to quality vaccines.

Good quality vaccines are key to any successful disease control strategy. Our review showed that some vaccines are less efficacious and in some cases, are even associated with increased risk of morbidity. While the negative effect of vaccination is difficult to explain, some bottlenecks have been identified to contribute to the reduction in effectiveness of vaccines under field conditions. For example, reasons for vaccination failures in this review were: potentially low vaccine efficacy due to over-attenuation (Gari et al., 2015) or pathogen resistance over time (Lancelot et al., 2002), loss of vaccine potency under unfavorable field conditions like adverse weather events (Wosu et al., 1990; Lancelot et al., 2002) and cold chain failure (Zerbo et al., 2021), and potential mismatch of circulating pathogen strains and the vaccines in use (Martrenchar et al., 1997; Catley et al., 2009; Ayelet et al., 2013; Lyons et al., 2015; Jemberu et al., 2020b). These setbacks are due mainly to poor handling of vaccines in the field (Pambudi et al., 2022), thus emphasizing the importance of the vehicle of vaccination delivery in the disease control strategy. More field evaluations of vaccine effectiveness in controlling livestock diseases under natural conditions are also needed. This will help to identify and address the challenges with deployment of vaccination in the field. There have been efforts to identify tools that minimize the field constraints associated with vaccination mobilization in SSA over the past decades. Some progress has been made in developing tools that address cold chain failures thus far. A good example is the recent development of an inexpensive locally produced passive cooling device that successfully maintained rabies vaccines under field conditions in rural Tanzania (Lugelo et al., 2020). More tools such as this are needed to be scaled-up and deployed especially in rural settings in SSA, if the full dividends of vaccination are to be attained. Additionally, continued surveillance of the changes in the circulating pathogens through serotyping and subtyping as well as vaccine matching remains key to any successful control of infectious diseases (Domenech and Vallat, 2012).

Vaccination adoption and use by smallholder farmers and marginalized pastoral populations remain low in SSA. Factors accounting for this may be demand or supply driven. Significant weaknesses in the organizational structures of veterinary services particularly at the field level, is one of the major challenges identified by the review of PVS Pathway appraisals, as a supply side barrier in Africa. This is due mainly to human, financial and material resource constraints that hinder vaccine supplies and limits operational effectiveness (OIE, 2019a). The human resource capacity is estimated at an average of only seven animal health professionals (two veterinarians and five para-veterinarians) for every 100,000 inhabitants in SSA, compared to an average of 50, in countries like the United States and United Kingdom (Jaime et al., 2021). Thus, a stronger partnership with the private sector and donors would be required to address these supply side barriers in vaccination delivery (OIE, 2019a; Jaime et al., 2021). Demand side barriers are driven mainly by farmers' loss of trust in the health services (Abakar et al., 2018) or a lack of access to vaccination services due to the peculiar location of such communities (Donadeu et al., 2019). Thus, strategies including awareness creation, improving vaccine supply, packaging and storage in the field have been proposed to increase vaccine adoption in developing countries (Donadeu et al., 2019). Additionally, community engagement is also a valuable tool to addressing particularly demand side barriers linked to mistrust of health systems (Abakar et al., 2018; Dione et al., 2019). Also, organizations including the Pan-African Veterinary Vaccine Center (PANVAC) remain crucial to the harmonization of disease control efforts in SSA through the setting of quality standards for animal vaccines (Jaime et al., 2021).

Notwithstanding the benefits of vaccination, the question of its return on investment is particularly key for decision-making. Our review showed clearly that the application of vaccination as a disease control strategy is economically profitable regardless of whether it is implemented at the herd, community, or national levels. However, the profitability may depend on the pathogen, disease burden and quality of vaccines. For example, a test and slaughter strategy for controlling bovine TB in livestock would be more profitable (Abakar et al., 2017), while vaccination of livestock is cost-effective in controlling PPR in livestock (Fadiga et al., 2013a) and brucellosis in both livestock and humans (Roth et al., 2003). Similar results of the cost-effectiveness of vaccination have been reported in other reviews in both human and animal studies (Tambi et al., 1999; Drolet et al., 2018). However, the approaches of the profitability analyses differ. The valuation of the cost-effectiveness of interventions in humans is based on non-monetary metrics, whereas in animals' health, cost-effectiveness analysis is quantified in monetary metrics (Shaw et al., 2017). The profitability of vaccination as control strategy is understandable as vaccines generally decrease the incidence and severity of diseases thereby providing savings in the costs of measures previously used to deal with the disease, including costs of treatment or lost productivity and/or death of affected persons or animals. The sustainability of the funding mechanism for any disease control strategy is crucial, either with a free of cost or cost-recovery approach, to optimize the returns to investment. However, the choice of funding mechanisms should not be mutually exclusive; it should depend on the externalities involved for each peculiar disease (whether its control is for public or private good), and the capacity to pay (National Research Council (US) Committee on Achieving Sustainable Global Capacity for Surveillance and Response to Emerging Diseases of Zoonotic Origin, 2009). The control of diseases that are transboundary in nature, including FMD, CBPP and PPR, must be treated as public good, with a greater share of the investment for their control financed from public sources. Thus, cost-effectiveness and willingness to pay studies on disease control strategies remain essential.

Vaccination could be even more effective and deliver high returns on investment if they could be combined with other strategies like surveillance and helminthic control, as our review revealed. Helminthic control have been shown to be largely effective in improving the productivity of livestock, and provides good returns on investment, particularly in small ruminants (Itty et al., 1997a; Itty et al., 1997b; Itty et al., 1997c). Uncontrolled helminthiases in livestock reduces appetite and antibody production, thereby negatively affecting their immune response to vaccination. Given that helminthiasis is a major problem affecting nutrition of livestock in SSA due to favorable environmental conditions, the inclusion of deworming as part of any disease control package would be both effective in improving animal health and provide good returns on investment, particularly in small ruminants as evident in this review (Lesnoff et al., 2000; Lancelot et al., 2002). Other reviews have similarly highlighted the key role helminthic control plays in animal health and productivity, and proposed new tools to optimize the control efforts by addressing the problem of drug resistance (Morgan et al., 2013; Vercruysse et al., 2018).

The anticipated improvement in livestock productivity with improved disease control in SSA may raise a sustainability concern with respect to the carbon footprint of livestock. Livestock-related contributions to methane emissions are relatively high; about 32% of all human activity related methane emissions (United Nations Environment Programme, 2021). Thus, the livestock sector must also reduce its emissions as part of global efforts to mitigate climate change. But having highly productive livestock, would effectively result in producing the required nutritional requirements of the population with fewer animals (Llonch et al., 2017). We argue that to achieve sustainability and enhance the reduction of greenhouse emissions in livestock, infectious diseases must be controlled effectively. If livestock are largely healthy, fewer animals would be required for food-producing purposes (O'Brien and Zanker, 2007). This phenomenon could be likened to the population dynamics during the demographic transition, where a sustained decline in mortality was the precondition for families to reduce their fertility, no longer needing to have more children than needed in anticipation of losing some children to diseases (Galor, 2012). Moreover, the largely extensive nature of the livestock production system in SSA makes it less dependent on feeding animals with human-edible crops with its attendant loss of biodiversity. Nevertheless, to achieve sustainability in livestock production, in an effective disease control regime, there would be a need for strict land and grassland use controls that would optimize the inputs and outputs in the production of livestock.

Our review had some challenges; the differences in the outcomes of interest or the measure of intervention effectiveness and/or profitability in some of the studies did not allow us to derive a pooled estimate of effectiveness and/ or profitability in all cases. In addition, as the focus of the review was to map the scope of evidence in the literature on what preventive interventions are applied, their effectiveness and/or profitability, an assessment of methodological limitations in the included studies was not done (Peters et al., 2020). It would be interesting to stratify the interventions' effectiveness and profitability by farming system. However, the unavailability of this information in included studies did not permit such analysis. Our review focused on interventions for which reduction in infectious livestock disease occurrence or deaths was a directly measurable outcome or could be inferred indirectly from another reported outcome. Thus, for studies that did not report protective rates or BCRs of the interventions, but had data on morbidity and/or mortality in intervention and control groups, or intervention and disease costs, we were able to compute protection rates and BCRs based on the data published to allow for a comparison of intervention effectiveness and profitability across studies. This review thus, has provided good evidence of the value of veterinary interventions applied in controlling infectious diseases in SSA, in spite of these limitations. Future reviews would benefit from having standardized measures of assessing effectiveness and profitability of interventions in original research articles. It is clear however, that profitability analyses of controlling some of the infectious diseases are lacking. More studies on profitability of control strategies therefore are needed.

3.6 Conclusion

This review shows that vaccination is currently the main strategy for controlling infectious diseases in livestock in SSA. Other strategies such as test and removal or antimicrobial treatment appear more challenging in the resource constrained and less regulated settings of SSA. Helminthic control, particularly in small ruminants, also appears to be effective in improving productivity and profitability of livestock when combined with vaccination. Despite their potential effectiveness and high returns on investment of vaccination as a control measure, factors such as adverse weather events, cold chain failure, and poor surveillance of circulating pathogen strains, could cause vaccines to be ineffective in practice. To achieve effective control of infectious livestock diseases in SSA, vaccination strategies should ideally integrate deworming and continuous surveillance capable of identifying new pathogens of interest. Optimal vaccine delivery tools may also help to minimize the impact of unfavorable field conditions, while maximizing the impact of the control strategy.

3.7 Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

Funding

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Author contributions

Conceptualization, F.S.N., G.I.M., K.K.A., G.F. J.Z. and B.B.; **methodology**, F.S.N., J.A., J.H., G.I.M., K.K.A., J.Z. and B.B.; **software**, F.S.N., J.A. and J.H.; **validation**, F.S.N., J.H., G.I.M., K.K.A., G.F., J.Z. and B.B.; **formal analysis**, F.S.N. and J.H.; **investigation**, F.S.N. and J.A.; **resources**, B.B., J.Z. and G.F.; **data curation**, F.S.N.; **writing—original draft preparation**, F.S.N.; **writing—review and editing**, all authors; **visualization**, F.S.N., J.H., G.F., J.Z. and B.B.; **supervision**, G.I.M., K.K.A., G.F., J.Z. and B.B.; **project administration**, F.S.N. and B.B.; **funding acquisition**, K.K.A. and B.B. All authors have read and agreed to the published version of the manuscript.

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3.8 Supplemental

Supplemental Appendix to

“Effectiveness and profitability of preventive veterinary interventions in controlling infectious diseases of ruminant livestock in sub-Saharan Africa: a scoping review”

Additional file 1: Search terms used on PubMed, Scopus and African Journals Online

PubMed < 1927 to March 10, 2021 > Date searched: May 28, 2021

("Africa South of the Sahara"[Mesh] OR Angola[Mesh:NoExp] OR Benin[Mesh:NoExp] OR Botswana[Mesh:NoExp] OR "Burkina Faso"[Mesh:NoExp] OR Burundi[Mesh:NoExp] OR Cameroon[Mesh:NoExp] OR "Cabo Verde"[Mesh:NoExp] OR "Central African Republic"[Mesh:NoExp] OR Chad[Mesh:NoExp] OR Comoros[Mesh:NoExp] OR Congo[Mesh:NoExp] OR "Cote d'Ivoire"[Mesh:NoExp] OR Djibouti[Mesh:NoExp] OR "Equatorial Guinea"[Mesh:NoExp] OR Eritrea[Mesh:NoExp] OR Ethiopia[Mesh:NoExp] OR Gabon[Mesh:NoExp] OR Gambia[Mesh:NoExp] OR Ghana[Mesh:NoExp] OR Guinea[Mesh:NoExp] OR Guinea-Bissau[Mesh:NoExp] OR Kenya[Mesh:NoExp] OR Lesotho[Mesh:NoExp] OR Liberia[Mesh:NoExp] OR Madagascar[Mesh:NoExp] OR Malawi[Mesh:NoExp] OR Mali[Mesh:NoExp] OR Mauritania[Mesh:NoExp] OR Mauritius[Mesh:NoExp] OR Mozambique[Mesh:NoExp] OR Namibia[Mesh:NoExp] OR Niger[Mesh:NoExp] OR Nigeria[Mesh:NoExp] OR Rwanda[Mesh:NoExp] OR "Sao Tome and Principe"[Mesh:NoExp] OR Senegal[Mesh:NoExp] OR Seychelles[Mesh:NoExp] OR "Sierra Leone"[Mesh:NoExp] OR Somalia[Mesh:NoExp] OR "South Africa"[Mesh:NoExp] OR "South Sudan"[Mesh:NoExp] OR Sudan[Mesh:NoExp] OR Swaziland[Mesh:NoExp] OR Tanzania[Mesh:NoExp] OR Togo[Mesh:NoExp] OR Uganda[Mesh:NoExp] OR Congo[Mesh:NoExp] OR Zaire[Mesh:NoExp] OR Zambia[Mesh:NoExp] OR Zimbabwe[Mesh:NoExp] OR ((Angola[tiab] OR Benin[tiab] OR Botswana[tiab] OR Bobo-Dioulasso[tiab] OR "Burkina Faso"[tiab] OR Burundi[tiab] OR Cameroon[tiab] OR "Cabo Verde"[tiab] OR "Central African Republic"[tiab] OR Chad[tiab] OR Comoros[tiab] OR Congo[tiab] OR "Cote d'Ivoire"[tiab] OR Djibouti[tiab] OR "Equatorial Guinea"[tiab] OR Eritrea[tiab] OR Ethiopia[tiab] OR Gabon[tiab] OR Gambia[tiab] OR Ghana[tiab] OR Guinea[tiab] OR Guinea-Bissau[tiab] OR Kenya[tiab] OR Lesotho[tiab] OR Liberia[tiab] OR Madagascar[tiab] OR Malawi[tiab] OR Mali[tiab] OR Mauritania[tiab] OR Mauritius[tiab] OR Mozambique[tiab] OR Namibia[tiab] OR Niger[tiab] OR Nigeria[tiab] OR Rwanda[tiab] OR "Sao Tome and Principe"[tiab] OR Senegal[tiab] OR Seychelles[tiab] OR "Sierra Leone"[tiab] OR Somalia[tiab] OR "South Africa"[tiab] OR "South Sudan"[tiab] OR Sudan[tiab] OR Swaziland[tiab] OR Tanzania[tiab] OR Togo[tiab] OR Uganda[tiab] OR Zaire[tiab] OR Zambia[tiab] OR Zimbabwe[tiab] OR "Africa South of the Sahara"[tiab] OR "Sub-Saharan Africa"[tiab]))) AND (ruminant[Mesh] OR livestock[Mesh] OR ruminant*[tiab] OR Antelope*[tiab] OR Hippotragine[tiab] OR Buffalo*[tiab] OR Bubalus[tiab] OR Syncerus[tiab] OR Bison[tiab] OR Cattle[tiab] OR Cow[tiab] OR Zebu[tiab] OR Yak[tiab] OR Bos[tiab] OR Deer[tiab] OR Giraffe*[tiab] OR Okapi[tiab] OR Goat[tiab] OR Capra[tiab] OR Sheep[tiab] OR Ovis[tiab] OR Mouflon[tiab]) AND ("Animal Disease*"[Mesh] OR "Abortion, Veterinary"[tiab] OR Brucellosis[tiab] OR "Bang Disease"[tiab] OR Tuberculos*[tiab] OR Mycobacteri*[tiab] OR "Foot-and-Mouth Disease"[tiab] OR Blackleg[tiab] OR "Clostridium chauvoei"[tiab] OR Anthrax[tiab] OR "Bacillus anthracis Infection*"[tiab] OR "Sheep Pox"[tiab] OR "Goat

Pox"[tiab] OR Capripoxvirus[tiab] OR "Pox Virus"[tiab] OR Peste-des-Petits-Ruminants[tiab] OR Pseudorinderpest[tiab] OR Pleuropneumonia*[tiab] OR "Lumpy Skin Disease"[tiab] OR Pasteurellosis[tiab] OR "Shipping Fever"[tiab]) AND ("Public health practice"[Mesh] OR "Communicable Disease Control"[tiab] OR "Animal Culling"[tiab] OR "Disease Notification"[tiab] OR Fumigation[tiab] OR Immunization[tiab] OR Vaccination[tiab] OR "Infection Control"[tiab] OR "Mandatory Testing"[tiab] OR "Mass Drug Administration"[tiab] OR "Contact Tracing"[tiab] OR "Physical Distancing"[tiab] OR Quarantine[tiab] OR "Universal Precautions"[tiab] OR Disinfection[tiab] OR Decontamination[tiab] OR "Mass Screening"[tiab] OR "Primary Prevention"[tiab] OR "Quaternary Prevention"[tiab] OR "Secondary Prevention"[tiab] OR "Tertiary Prevention"[tiab] OR prevent*[tiab] OR reduc*[tiab])

Scopus < 1954 to March 10, 2021 > Date searched: June 25, 2021

(INDEXTERMS("Africa South of the Sahara") OR INDEXTERMS("Angola") OR INDEXTERMS("Benin") OR INDEXTERMS("Botswana") OR INDEXTERMS("Burkina Faso") OR INDEXTERMS("Burundi") OR INDEXTERMS("Cameroon") OR INDEXTERMS("Cabo Verde") OR INDEXTERMS("Central African Republic") OR INDEXTERMS("Chad") OR INDEXTERMS("Comoros") OR INDEXTERMS("Congo") OR INDEXTERMS("Cote d'Ivoire") OR INDEXTERMS("Djibouti") OR INDEXTERMS("Equatorial Guinea") OR INDEXTERMS("Eritrea") OR INDEXTERMS("Ethiopia") OR INDEXTERMS("Gabon") OR INDEXTERMS("Gambia") OR INDEXTERMS("Ghana") OR INDEXTERMS("Guinea") OR INDEXTERMS("Guinea-Bissau") OR INDEXTERMS("Kenya") OR INDEXTERMS("Lesotho") OR INDEXTERMS("Liberia") OR INDEXTERMS("Madagascar") OR INDEXTERMS("Malawi") OR INDEXTERMS("Mali") OR INDEXTERMS("Mauritania") OR INDEXTERMS("Mauritius") OR INDEXTERMS("Mozambique") OR INDEXTERMS("Namibia") OR INDEXTERMS("Niger") OR INDEXTERMS("Nigeria") OR INDEXTERMS("Rwanda") OR INDEXTERMS("Sao Tome and Principe") OR INDEXTERMS("Senegal") OR INDEXTERMS("Seychelles") OR INDEXTERMS("Sierra Leone") OR INDEXTERMS("Somalia") OR INDEXTERMS("South Africa") OR INDEXTERMS("South Sudan") OR INDEXTERMS("Sudan") OR INDEXTERMS("Swaziland") OR INDEXTERMS("Tanzania") OR INDEXTERMS("Togo") OR INDEXTERMS("Uganda") OR INDEXTERMS("Congo") OR INDEXTERMS("Zaire") OR INDEXTERMS("Zambia") OR INDEXTERMS("Zimbabwe") OR ((TITLE-ABS("Angola") OR TITLE-ABS("Benin") OR TITLE-ABS("Botswana") OR TITLE-ABS("Bobo-Dioulasso") OR TITLE-ABS("Burkina Faso") OR TITLE-ABS("Burundi") OR TITLE-ABS("Cameroon") OR TITLE-ABS("Cabo Verde") OR TITLE-ABS("Central African Republic") OR TITLE-ABS("Chad") OR TITLE-ABS("Comoros") OR TITLE-ABS("Congo") OR TITLE-ABS("Cote d'Ivoire") OR TITLE-ABS("Djibouti") OR TITLE-ABS("Equatorial Guinea") OR TITLE-ABS("Eritrea") OR TITLE-ABS("Ethiopia") OR TITLE-ABS("Gabon") OR TITLE-ABS("Gambia") OR TITLE-ABS("Ghana") OR TITLE-ABS("Guinea") OR TITLE-ABS("Guinea-Bissau") OR TITLE-ABS("Kenya") OR TITLE-ABS("Lesotho") OR TITLE-ABS("Liberia") OR TITLE-ABS("Madagascar") OR TITLE-ABS("Malawi") OR TITLE-ABS("Mali") OR TITLE-ABS("Mauritania") OR TITLE-ABS("Mauritius") OR TITLE-ABS("Mozambique") OR TITLE-ABS("Namibia") OR TITLE-ABS("Niger") OR TITLE-ABS("Nigeria") OR TITLE-ABS("Rwanda") OR TITLE-ABS("Sao Tome and Principe") OR TITLE-ABS("Senegal") OR TITLE-ABS("Seychelles") OR TITLE-ABS("Sierra Leone") OR

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African Journals Online < 1984 to March, 2021 > Date searched: June 28, 2021

[(ruminant OR livestock OR Antelope OR Hippotragus OR Buffalo OR Bubalus OR Bison OR Cattle OR Cow OR Zebu OR Yak OR Bos OR Deer OR Giraffe OR Okapi OR Goat OR Capra OR Sheep OR Ovis OR Mouflon) AND (Animal Disease* OR Abortion OR Brucellosis OR Bang Disease OR Tuberculos* OR Mycobacter* OR Foot-and-Mouth Disease OR Black Leg OR Clostridium Chauvoei OR Anthrax OR Bacillus anthracis infection OR Sheep Pox OR Goat Pox OR Capripoxvirus OR Pox Virus OR Peste-des-Petits-Ruminants OR Pseudo Rinderpest OR Pleuropneumonia OR Lumpy Skin Disease OR Pasteurellosis OR Shipping Fever) AND (Public health practice OR Communicable Disease Control OR Animal Culling OR Disease Notification OR Fumigation OR Immunization OR Vaccination OR Infection Control OR Mandatory Testing OR Mass Drug Administration OR Contact Tracing OR Physical Distancing OR Quarantine OR Universal Precautions OR Disinfection OR Decontamination OR Mass Screening OR Primary Prevention OR Quaternary Prevention OR Secondary Prevention OR Tertiary Prevention OR prevent* OR reduce*)]

Table S1: Overview of the studies reviewed

The table details the characteristics of the included studies in addition to the references in parenthesis and reference list at the end, as captured in the manuscript

Author (references[†])	Year	Country	Objective of study	Study design	Data sources
Admassu B. et al. (36)	2005	Ethiopia	Impact assessment of CAHWs work on disease prevalence in cattle, sheep and goats	Cross-sectional study (participatory)	FGDs & interviews
Alhaji NB. et al. (111)	2020	Nigeria	Cost-benefits of FMD control in pastoral local dairy cattle production systems	Cross-sectional study (survey)	Questionnaire
Alhaji NB. Et al. (107)	2017	Nigeria	Cost-effectiveness of vaccination against CBPP infection in cattle	Cross-sectional study (survey)	Questionnaire & interviews
Ameni G. et al. (46)	2007	Ethiopia	Effectiveness of test and segregation on Bovine TB incidence in cattle	Experimental study (field trial)	Physical & laboratory examination
Ameni G. et al. (42)	2018	Ethiopia	Efficacy of vaccination against Bovine TB infection in calves	Experimental study (clinical trial)	Physical & laboratory examination
Ameni G. et al. (41)	2010	Ethiopia	Effectiveness of vaccination against Bovine TB infection in neonatal calves	Experimental study (clinical trial)	Physical & laboratory examination
Anderson EC. et al. (82)	1974	Kenya	Compare prevalence of FMD infection in cattle from vaccinated and unvaccinated areas	Cross-sectional study (survey)	Laboratory examination
Awa DN. et al. (99)	2000	Cameroon	Effectiveness and cost-benefits of deworming and PPR vaccination in goats and sheep	Experimental study (field trial)	Questionnaire
Ayele B. et al. (103)	2016	Ethiopia	Cost-benefits of vaccination against blackleg infection in cattle	Cross-sectional (survey, participatory)	Questionnaire & FGDs
Ayelet G. et al. (90)	2013	Ethiopia	Compare prevalence of LSD infection and deaths in vaccinated and unvaccinated cattle	Cross-sectional study (survey)	Questionnaire, lab & physical examination
Ayelet G. et al. (91)	2014	Ethiopia	Compare prevalence of LSD infection and deaths in vaccinated and unvaccinated cattle	Cross-sectional study Retrospective study	Questionnaire, data review (secondary)
Ba SB. et al. (34)	1996	Mali	Effectiveness of vaccination and deworming on mortality in goats	Experimental study (field trial)	Questionnaire, lab examination
Barasa M. et al. (112)	2008	South Sudan	Cost-benefits of vaccination against FMD in cattle	Cross-sectional (participatory)	Interviews, literature review, observation
Berggren SA. (44)	1981	Malawi	Effectiveness of vaccination against Bovine TB incidence and spread in cattle	Experimental study (field trial)	Questionnaire, lab & physical examination

Berggren SA. (45)	1977	Malawi	Compare incidence of Bovine TB infection in vaccinated and unvaccinated cattle	Cross-sectional study (survey)	Questionnaire & physical examination
Bertram MR. et al. (83)	2018	Cameroon	Effectiveness of vaccination against FMD infection in cattle over 1 year	Experimental study (field trial)	Observation & lab examination
Camus E. (37)	1980	Côte d'Ivoire	Effectiveness of vaccination against abortions and still births in cattle due to Brucellosis	Experimental study (field trial)	Questionnaire, data review & observation
Catley A. et al. (35)	2009	Ethiopia	Effectiveness of vaccination against cattle, goat and sheep mortality in normal and drought years	Cross-sectional study (participatory), Retrospective study	Questionnaire, Interviews, data review, observation
Caufour P. et al. (85)	2014	Ethiopia	Efficacy of vaccination against Capripox and PPR in goats with pre-existing immunity	Experimental study (clinical trial)	Observation, lab & physical examination
Chema S. (80)	1975	Kenya	Effectiveness and cost-benefits of vaccination against occurrence of FMD outbreaks in cattle	Experimental study (before and after)	Observation, data review & lab tests
Cloete M. et al. (75)	2008	South Africa	Efficacy of different vaccine formulations against FMD infection in cattle	Experimental study (clinical trial)	Physical & laboratory examination
Coackley W. & Weston SJ. (39)	1957	Kenya	Efficacy of vaccination against blackleg deaths in cattle and sheep	Experimental study (clinical & field trial)	Data review, physical & lab examination
Domenech J. (55)	1979	Ethiopia	Compare the prevalence of CBPP infection in cattle at different vaccination coverage levels	Cross-sectional study (survey)	Data review & lab examination
Doutre MP. & Chambron J. (68)	1970	Senegal	Efficacy of vaccination against CBPP deaths in cattle at 3, 7 and 14 months post-exposure	Experimental study (clinical trial)	Questionnaire, lab tests & observation
Doutre MP. et al. (69)	1972	Senegal	Efficacy of vaccination against CBPP infection in cattle	Experimental study (clinical trial)	Questionnaire, lab tests & observation
ElArbi AS. et al. (118)	2019	Mauritania	Cost-benefits of different vaccination strategies in controlling PPR in sheep and goats	Cross-sectional study (surveys)	Questionnaire, data review
Ellwood DE. & Waddington FG. (43)	1972	Malawi	Efficacy of vaccination against Bovine TB infection and spread of lung lesions in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Emslie FR. & Nel JR. (38)	2002	South Africa	Effectiveness of a test and slaughter strategy on Brucellosis infection in goat and sheep	Experimental study (field trial)	Data review & lab examination
Fadiga M. et al. (105)	2013	Nigeria	Cost-benefits of targeted interventions in the control of CBPP & PPR in cattle, sheep & goats	Cross-sectional study Retrospective study	Interviews, FGDs, data review
Garba SA. et al. (67)	1989	Nigeria	Efficacy of different vaccine formulations against CBPP infection and deaths in cattle	Experimental study (clinical trial)	Observation, lab & physical examination

Gari G. et al. (88)	2015	Ethiopia	Efficacy of different vaccine formulations against LSD infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Gari G. et al. (115)	2011	Ethiopia	Cost-benefits of vaccination in controlling LSD in cattle	Cross-sectional (survey)	Questionnaire, data review & interviews
Gilbert FR. & Windsor RS. (63)	1971	Kenya	Efficacy of different vaccine formulations against CBPP infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Gilbert FR. et al. (62)	1970	Kenya	Efficacy of vaccination against CBPP infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Gray MA. et al. (64)	1986	Kenya	Efficacy of different vaccine formulations against CBPP infection and deaths in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Gummow B. & Mapham PH. (93)	2000	South Africa	Effectiveness and cost-benefits of different vaccination formulations against Pasteurellosis infection and deaths in cattle	Experimental study (field trial)	Observation, data review & physical examination
Holzer B. et al. (95)	2016	Kenya	Efficacy of different vaccine formulations against PPR infection in goats	Experimental study (clinical trial)	Observation & lab examination
Hübschle OJ. et al. (54)	2003	Namibia	Efficacy of vaccination against CBPP deaths in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Huebschle OJB. et al. (50)	2006	Namibia	Efficacy of antimicrobial treatment against CBPP infection and spread in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Jarikre TA. et al. (96)	2019	Nigeria	Efficacy of different vaccine formulations against PPR infection in goats	Experimental study (clinical trial)	Observation, lab & physical examination
Jemberu WT. et al. (79)	2020	Ethiopia	Effectiveness of vaccination against FMD infection in cattle	Experimental study (field trial)	Observation, interview & questionnaire
Jemberu WT. et al. (113)	2016	Ethiopia	Cost-benefits of different vaccination strategies in controlling FMD in cattle	Retrospective study (secondary data)	Literature and data review
Kairu-Wanyoike SW. et al. (108)	2014	Kenya	Cost-benefits of vaccination in controlling CBPP in cattle	Cross-sectional study (survey)	Questionnaire
Kairu-Wanyoike SW. et al. (106)	2017	Kenya	Cost-benefits of vaccination in controlling CBPP in cattle at household and community levels	Cross-sectional study Retrospective study Longitudinal study	Questionnaire, data review & interviews
Lancelot R. et al. (92)	2002	Senegal	Effectiveness of deworming and vaccination on mean duration of survival of goats within 1 year	Experimental study (field trial)	Questionnaire & physical examination
Lazarus DD. et al. (78)	2020	South Africa	Efficacy of different vaccination doses against FMD infection in goats	Experimental study (clinical trial)	Observation, lab & physical examination

le Roex N. et al. (48)	2016	South Africa	Effectiveness of a test and cull program against Bovine TB infection in Buffalos	Experimental study (clinical trial)	Questionnaire, lab & physical examination
Lendzele SS. et al. (74)	2020	Cameroon	Efficacy of Tri-Solfen therapy vs antimicrobial treatment on FMD wound healing in cattle	Experimental study (clinical trial)	Observation, physical exam, questionnaire
Lesnoff M. et al. (94)	2000	Senegal	Effectiveness and cost-benefits of deworming and vaccination against Pasteurellosis infection in sheep	Experimental study (field trial)	Questionnaire, observation & physical examination
Lindley EP. (72)	1967	Sudan	Efficacy of vaccination against development of CBPP lesions in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Lyons NA. et al. (81)	2015	Kenya	Effectiveness of vaccination against incidence of FMD infection in cattle	Longitudinal study (cohort)	Observation, physical exam, questionnaire
Maree FF. et al. (76)	2015	South Africa	Efficacy of two different vaccine formulations against FMD infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Mariner JC. et al. (71)	2006	Sudan, Tanzania	Effectiveness of different vaccination strategies against CBPP infection and deaths in cattle	Cross-sectional study Retrospective study	FGDs, interviews & literature review
Mariner JC. et al. (70)	2006	Kenya, Sudan, Tanzania	Effectiveness of vaccination against CBPP infection and deaths in cattle	Retrospective study (secondary data)	Literature and data review
Martrenchar A. et al. (86)	1997	Cameroon	Efficacy of vaccination against PPR and Goat pox infection and deaths in goats	Experimental study (clinical trial)	Observation, lab & physical examination
Martrenchar A. et al. (98)	1999	Cameroon	Efficacy of vaccination against PPR deaths in goats and sheep	Experimental study (field trial)	Observation, physical exam, questionnaire
Masiga WN. (65)	1972	Kenya	Efficacy of vaccination against CBPP infection and deaths in different cattle breeds	Experimental study (clinical trial)	Observation, lab & physical examination
Molla W. et al. (116)	2017	Ethiopia	Cost-benefits of vaccination in controlling LSD infection in cattle	Cross-sectional study (survey)	Questionnaire
Molla W. et al. (89)	2017	Ethiopia	Effectiveness of vaccination against LSD infection in cattle	Experimental study Cross-sectional study	Questionnaire, lab & physical examination
Muuka G. et al. (52)	2019	Kenya, Zambia	Efficacy of different antimicrobial treatments against CBPP lung lesion resolution in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Mwacalimba KK. et al. (102)	2013	Zambia	Cost-benefits of a test and slaughter strategy in controlling Bovine TB in cattle	Retrospective study (secondary data)	Literature and data review
Ngichabe CK. et al. (87)	2002	Kenya	Efficacy of vaccination against LSD infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination

Niang M. et al. (51)	2010	Mali	Efficacy of antimicrobial treatment against CBPP infection and deaths in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Njoya A. et al. (100)	2005	Cameroon	Effectiveness of food supplementation and prophylaxis against PPR on deaths in sheep	Experimental study (field trial)	Observation, physical exam, questionnaire
Nkando I. et al. (59)	2012	Kenya	Efficacy of different vaccine formulations against CBPP lung pathology in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Nkando I. et al. (60)	2016	Kenya	Efficacy of different vaccine formulations against CBPP infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Nyaguthii DM. et al. (84)	2019	Kenya	Compare prevalence of FMD infection in vaccinated and unvaccinated cattle	Cross-sectional study (survey)	Questionnaire
Onono JO. et al. (109)	2014	Kenya	Cost-benefits of different intervention packages in controlling CBPP in cattle	Cross-sectional study Retrospective study	Interviews & literature review
Renault V. et al. (110)	2019	Kenya	Cost-benefits of vaccination in controlling CCPP in goats	Longitudinal study (cohort)	Questionnaire, data review & observation
Reynolds L. & Francis PA. (101)	1988	Nigeria	Effectiveness of dipping and vaccination against PPR on kidding and deaths in goats	Experimental study (field trial)	Observation, data review, questionnaire
Roug A. et al. (47)	2014	Tanzania	Effectiveness of a test and removal strategy on Bovine TB prevalence in cattle	Retrospective study (secondary data)	Observations, data & literature review
Rurangirwa FR. et al. (73)	1991	Kenya	Efficacy of vaccination against CCPP infection and deaths in goats	Experimental study (field trial)	Observation, lab & physical examination
Scott KA. et al. (77)	2017	South Africa	Efficacy of different vaccine formulations against FMD infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Souley Kouato B. et al. (114)	2018	Niger	Cost-benefits of vaccination in controlling FMD infection in cattle	Retrospective study (secondary data)	Data review
Stem C. (117)	1993	Niger	Cost-benefits of vaccination in controlling PPR infection in goats	Retrospective study (secondary data)	Observations, data & literature review
Suleiman A. et al. (56)	2015	Nigeria	Compare the prevalence of CBPP infection in vaccinated and unvaccinated cattle	Cross-sectional study (survey)	Questionnaire & lab examination
Tambi NE. et al. (104)	2006	Multiple countries (12)*	Cost-benefits of vaccination and treatment in controlling CBPP infection in cattle	Retrospective study (secondary data)	Data & literature review
Tambuwal F. & Egwu G. (58)	2011	Nigeria	Compare the prevalence of CBPP infection in cattle at different vaccination coverage levels	Retrospective study (secondary data)	Data review
Thiaucourt F. et al. (53)	2004	Cameroon, Kenya	Efficacy of different vaccine formulations and antimicrobial treatment against CBPP infection	Experimental study (clinical trial)	Observation, lab & physical examination

Thiaucourt F. et al. (61)	2000	Kenya,Namibia Cameroon	Efficacy of vaccination against CBPP infection and deaths in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Waddington FG. & Ellwood DC. (40)	1972	Malawi	Efficacy of vaccination against Bovine TB infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Wesonga H. & Thiaucourt F. (66)	2000	Kenya	Efficacy of different vaccine formulations against CBPP infection in cattle	Experimental study (clinical trial)	Observation, lab & physical examination
Wosu LO. et al. (97)	1990	Nigeria	Effectiveness of vaccination across different seasons against PPR infection in goats	Experimental study (field trial)	Observation, physical examination
Zerbo LH. et al. (57)	2021	Burkina Faso	Compare the prevalence of CBPP infection in cattle at different vaccination coverage levels	Cross-sectional study (survey)	Questionnaire & lab examination

*__Countries__: Burkina Faso, Chad, Côte d'Ivoire, Ethiopia, Ghana, Guinea, Kenya, Mali, Mauritania, Niger, Tanzania, Uganda. [†] Numbered references for the included studies are provided in the Supplemental section at the end of this Chapter.

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Chapter 4 Management of diseases in a ruminant livestock production system: a participatory appraisal of the performance of veterinary services delivery, and utilization in Ghana

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4.1 Abstract

Introduction: Sustainable livestock production remains crucial for attainment of food security globally and for safeguarding the livelihoods of many households in low- and –middle income countries. However, the high prevalence of infectious livestock diseases, coupled with inadequate provision and adoption of effective control measures, leads to reduced livestock productivity, increased animal mortalities, and emergence of antimicrobial resistant pathogens. This study sought to assess the management strategies employed by farmers for priority diseases affecting their animals and the utilization and performance of veterinary services.

Methods: We conducted a mixed-method study in three districts in the main livestock rearing belts in Ghana. We used a semi-structured questionnaire to collect data from 350 ruminant livestock farmers and 13 professional veterinary officers (VOs) in surveys. We also conducted seven focus group discussions (FGDs) involving 65 livestock farmers. The survey data were analyzed, and the distribution of priority diseases, management strategies employed by farmers and the performance of veterinary services were described. We conducted a deductive thematic analysis of the FGD transcripts, by generating codes and categories from the raw transcript texts, based on the study goals. We used triangulation to validate findings across the different datasets.

Results: Almost all the farmers (98%) reared small ruminants, with about 25% also rearing cattle. The farmers reported pestes-des-petits-ruminants and mange as the priority diseases affecting sheep and goats, while cattle were mainly affected by foot-and-mouth-disease and contagious bovine pleuropneumonia. About 82% of farmers used treatment, while only 20% used vaccination services. The antimicrobial medicines used in managing the diseases are poorly regulated by the veterinary system and, in most of the cases, wrongly applied by farmers in treating the target diseases. Farmers primarily use services of informal providers (51%), with only 33% utilizing VOs. The farmers perceived VOs to perform highly in terms of medicine availability and quality, treatment effectiveness, advisory services, service affordability, and competence, while the informal providers were better in proximity and popularity with farmers.

Conclusions: Vaccine-preventable diseases are a significant impediment to the livestock industry in Ghana. Although the VOs performed better on most indicators, their services are seldom used by livestock farmers. The inability of the veterinary system to regulate antimicrobials used in animal production contributes to their misuse by livestock farmers, thereby posing a threat to public health and food security. New initiatives that improve the adoption of vaccination and antimicrobial stewardship, are needed to achieve sustainable livestock production.

Keywords: Diseases management, Antimicrobials, Performance of Veterinary Services, Ruminant livestock, Livestock diseases, One Health.

4.2 Introduction

In spite of the strides made in the last decade towards attaining the Sustainable Development Goals (SDGs) the risks for severe food insecurity and extreme poverty have increased in recent years. The main drivers of the recent bottlenecks to food security have been climate change, COVID-19 pandemic, conflicts, global economic crisis and increasing supply chain constraints (FAO et al., 2021). In light of these difficulties, urgent strategies are required to improve country-level productivity in the agricultural sector to address the food system challenges (FAO et al., 2021).

Although more than 50% of people in sub-Saharan Africa (SSA) are employed in the agricultural sector (ILO, 2021), the region's productivity in agriculture is comparatively low globally (Alston and Pardey, 2014). The agricultural sector in many countries in SSA is primarily dominated by crop production, which accounts for more than two-thirds of the production levels in the sector (OECD/FAO, 2016). Livestock production, despite comprising less than a third of total agricultural output, plays a crucial role in the lives of people in SSA. Livestock serve as essential assets, contributing to various aspects of people's lives. They serve as a source of livelihood, protein, and wealth storage against uncertainties. In addition, they also serve as companion animals for many farmers (Otte and Knips, 2005; Brown, 2006; Yurco, 2018; OIE, 2019b). The livestock production system is largely extensive and dominated by small-scale farmers. The animals' productivity thus is affected greatly by weather changes, availability of grazing resources, livestock diseases, security and conflict, and access to veterinary services (Pica-Ciamarra et al., 2007; Valbuena et al., 2015).

Our previous study in Ghana showed that farmers experience significant livestock mortalities primarily due to infectious animal diseases, theft, pasture shortages and conflicts. These factors collectively resulted in an average annual herd loss of 15%, and affecting approximately 80% of livestock farmers (Nuvey et al., 2020). The negative impacts of these adverse events are further exacerbated by inadequate provision of veterinary services, which could enable farmers to better cope with the challenges, due to limited government investment in the veterinary sector (Diop et al., 2011).

The veterinary system plays a crucial role in providing both preventive and curative services to livestock farmers. However, a recent review of the performance appraisal reports on veterinary services across SSA countries revealed that 80% of countries in the region face significant limitations, or in some cases, a complete lack of administrative control over the registration, import and production, distribution and use of veterinary medicines and biologicals (OIE, 2019a). Consequently, the usage rates of antimicrobials in the region are considerably high, varying from approximately 80% to 100% of all farms. The commonly used antibiotics are tetracyclines, aminoglycosides, and penicillin groups (Kimera et al., 2020; Mshana et al., 2021). This high usage of antimicrobial drugs in the absence of formal controls can lead to the persistence of drug residues in livestock products, and promote the development of antimicrobial resistant pathogens.

There is currently no reliable overview on how Ghanaian farmers prevent and manage livestock diseases affecting their herds and how they interact with their veterinary service providers. The previous research on disease management practices in Ghana were narrow in scope; dealing specifically with control of only particular diseases (Morrow et al., 1993; Morrow et al., 1996), or management practices employed by one veterinary provider (Adeapena et al., 2021) or farmers in one agro-ecological zone (Turkson and Naandam, 2003; Omondi et al., 2022). To be able to address the food safety concerns with sustainable policies in Ghana, it is essential to identify the current disease management strategies employed by both farmers and their veterinary service providers, particularly for priority disease conditions. Our study sought to address the identified gaps. We assessed the most important adversities affecting livestock production including main diseases from both the farmers and veterinarians' perspective, and assessed the utilization rate of professional veterinary services and the factors predicting it, as well as evaluated farmers' perception of the performance of their veterinary service providers.

4.3 Materials and methods

Description of study area

This study was conducted in the Mion, Pru East and Kwahu Afram Plains South (KAPS) districts, which represent the northern, middle, and southern farming belts in Ghana. The districts lie in the Guinea Savannah, Transition and Deciduous forest Vegetation zones, which are the main livestock production zones in Ghana (**Figure 5**). The selection of districts was done purposively in collaboration with the regional directors of veterinary services, utilizing a sampling frame of farming districts within the corresponding vegetation zones. The districts were selected based on their strategic location and suitability for conducting field studies. These districts are primarily rural and agrarian. Cattle, sheep, and goats are the predominant ruminant livestock species reared in these districts (GSS, 2014b, c, a). We obtained district maps from which we extracted a sampling frame of villages to obtain a random sample for data collection.

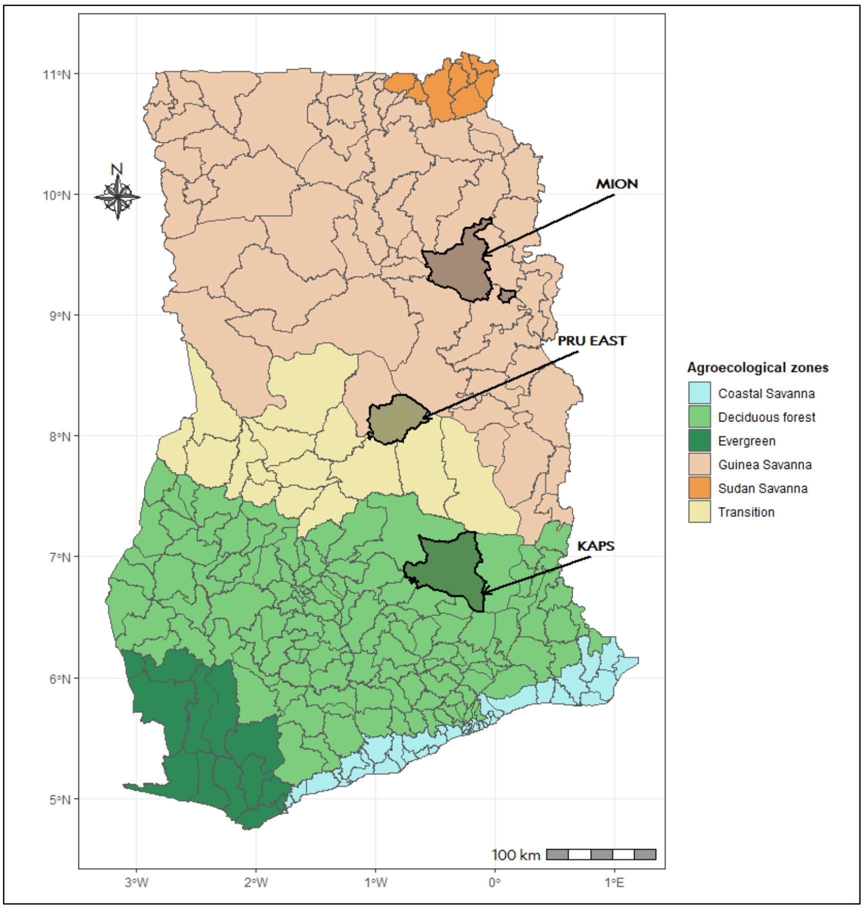

Figure 5: Administrative map of Ghana showing the agro-ecological zones and study districts.

The figure presents the distinct locations of the study districts (shaded areas to which arrows point) within the main agro-ecological zones. MION, PRU EAST, and KAPS denote the Mion, Pru East and Kwahu Afram Plains South Districts respectively.

Study design

This was a cross-sectional study employing a convergent parallel mixed-method approach. This design enables the simultaneous integration of quantitative and qualitative elements of a research project within the same phase of the research process. Although the analysis is performed separately for each method, the results carry equal significance and are jointly interpreted (Creswell and Clark, 2018). We conducted two cross-sectional surveys involving 350 livestock farmers and 13 professional veterinary officers (VOs), and seven focus group discussions (FGDs) involving 65 livestock farmers purposively selected within the districts. The FGD participants were selected based on their knowledge and experience with livestock farming in the districts, as well as their willingness and ability to travel to a designated venue on scheduled dates.

Study population

In the livestock farmers' survey, we firstly created a sampling frame of villages within the study districts. Based on published data from the last census (2010 population and housing census) conducted before the study, we randomly drew 15 villages in the KAPS District, and 10 villages each in the Pru East and Mion Districts, proportional to the number of livestock farming households per study district (GSS, 2014b, c, a). From the selected villages, at least two persons were approached per village to participate in FGDs organized after the surveys in each district. Seven FGDs; three in KAPS District and two each in the Pru East and Mion Districts were conducted involving 65 participants. All the VOs in the study area also participated in a survey to identify key challenges facing livestock production, veterinary service delivery and treatment strategies used for key diseases in the study area. Based on the census data available prior to the study, there was about 29890, 11250, 8740 veterinary livestock units (VLUs) in the KAPS, Mion and Pru East districts respectively. VLUs depict the workload per veterinary officer calculated by dividing the standardized total number of animal heads in tropical livestock units (TLUs) by the number of VOs (Diop et al., 2011). In Ghana, the VOs providing veterinary services in rural areas, where livestock are usually reared, are mainly veterinary paraprofessionals with a diploma degree in animal health as minimum qualification. The VOs work under the supervision of district or regional veterinarians (with a doctor of veterinary medicine qualification) (Diop et al., 2011). All the VOs assigned in the study districts were veterinary paraprofessionals.

Sample size and sampling technique

We determined the sample size using Epi Info Companion version 5.5.9 (Dean et al., 2011) with the following assumptions:

Expected utilization rate of veterinary services was 60% based on a previous study in the Northern region of Ghana, which found in a survey that 57% of livestock farmers used government veterinary services (Mockshell et al., 2014). The acceptable margin of error was 5%-points, at a 95% confidence level. This yielded a minimum sample size of 370 livestock farmers. We recruited 350 livestock farmers from 38 villages using segmentation, with a response rate of 95%. The 5% non-response was mainly due to low number of ruminant livestock keeping households in some of the randomly assigned study villages during enumeration. Within the selected segments of the study villages, all households engaged in ruminant livestock farming were eligible for selection to participate in the survey. Households that provided consent were recruited to partake in the survey. For the VOs survey, all personnel were eligible to participate once informed consent was given. All 13 VOs assigned within the districts were recruited. For the FGDs, we used a purposive sampling approach to recruit farmers during the survey in each district. Overall, 65 farmers consented to participate in FGDs in the three districts.

Data collection and data management

Between November 2021 and January 2022, the enumeration team visited the households keeping ruminant livestock in their homes to administer the questionnaires. The respondents were interviewed face-to-face using tablets equipped with Open Data Kit (ODK) application. The survey instruments were designed to collect data on priority diseases affecting herds, management strategies employed, farmers' perception of the performance of veterinary service providers and other socio-demographic characteristics. The livestock farmers' appraisal of the performance of professional and informal veterinary service providers was assessed using a questionnaire adapted from Admassu et al. (Admassu et al., 2005). We also assessed the utilization of professional veterinary services by farmers, and factors predicting the utilization (**Additional file 1**).

The VOs survey were conducted during the same period at the workplaces of the veterinary personnel using ODK. In their survey, VOs evaluated their own performance on several key functions of veterinary services including the availability of border posts for monitoring animal movements, slaughter places for ensuring meat safety, motor vehicles for delivery of veterinary services, designated laboratories for confirming suspected pathogens, and protocols for regulating the sale of medicines within their respective operational areas. We assessed the availability of communication pathways between the VOs and public health personnel regarding the control of zoonotic diseases in the operational areas. We collected data on the priority diseases or conditions and specific drugs used to treat or manage the affected animals (**Additional file 2**).

The FGDs were conducted concurrently with the other field studies at designated venues in the study districts using a paper-based interview guide in the local language, and the sessions recorded using an audiotape. The farmers discussed in the FGDs the main constraints of livestock production, disease management strategies applied and factors influencing their choices. They also reported the distribution in a farming year, the priority or most common diseases affecting both small and large ruminants in their herds using the proportional piling approach. Specifically, the farmers distribute for each disease that affects their herd, the proportion on average of 10 round counters presumed as their total herd, that get infected during a farming year for each disease.

The survey data was downloaded as Microsoft Excel files from ODK and imported into R version 4.1 (RStudio Team, 2022) for analyses. The interview audio recordings from the FGDs were transcribed in English verbatim, and the transcripts imported into NVivo software version 12 (QSR International Pty Ltd., 2018) for analysis.

Data analyses

We performed descriptive analyses of both farmers and VOs surveys, comparing the distribution of responses by study district. The farmers' herd sizes were converted to tropical livestock units (TLU) to standardize livestock holdings as follows: 1 TLU = 0.75 cattle, or 0.2 pigs, or 0.1 small ruminants, or 0.01 poultry, or 0.02 doves (Rothman-Ostrow et al., 2020). We also compared livestock farmers' perception of the severity of different adversities on herds with the perspectives of the VOs. We assessed the priority diseases affecting ruminant livestock, with farmers and VOs reporting the most recent disease(s) or condition(s) to cause deaths of the animals. We report the frequency of use of the medicines, and the usefulness of the medicine and disease or condition combinations based on the evidence in literature and authors' experience. We also compared how farmers and VOs treat the common or priority diseases affecting livestock in the districts. The performance of the professional and informal veterinary service providers on each of the attributes or indicators were derived by transforming the Likert scale scores into Relative Importance Indices (RIIs) as follows:

$$\textbf{Relative Importance Index } (\boldsymbol{RII}) = \frac{\sum \boldsymbol{W}}{\boldsymbol{A} \times \boldsymbol{N}}$$

Where W is the weight given to each attribute or indicator by the respondents (ranging from 1 to 5), A is the highest weight (i.e., 5 in this case), and N is the total number of respondents.

Using a pre-specified model, we evaluated the relationship between professional veterinary service utilization (any use in the past 12 months), and farmers' sex, educational attainment, herd size, wealth status, resilience level, livestock rearing experience, distance to VOs, perception of disease severity at herd-level, and level of social support received, adjusting for village-level clustering, at the 95% confidence level in a binary logistic regression model. We determined the relative wealth of households using an index of a household's ownership of selected assets, such as televisions, refrigerators and bicycles, presented as wealth quintiles (ICF, 2019). Resilience was assessed using the Resilience scale (RS-14). The RS-14 consists of 14 items rated on a 7-point Likert-scale. The total scores are computed and higher scores indicate higher resilience (Wagnild, 2009). The availability of social support to farmers was assessed using a 5-point Likert scale, which measured the level of support farmers received from various facets of society including family, friends, law enforcement, credit institutions, community leaders and religious leaders, to aid them in livestock farming. Herd size and social support level were categorized into tertiles (three quantiles) to compare veterinary service utilization within homogenous levels. The choice of covariates for the model was pre-specified, and was informed mainly by literature and previous research on the determinants of veterinary services utilization (Onono et al., 2013; Faizal and Kwasi, 2015; Gizaw et al., 2021). Potential violations of the model assumptions were assessed by calculating Pregibon leverages, by visual inspection of residual versus fitted and QQ-plots, and by examination of variance inflation factors.

The analysis of FGD transcripts was conducted from a social constructivism perspective recognizing that agricultural (livestock) production is shaped by the social and cultural dynamics of those involved. We sought to find convergence on the social concerns regarding the challenges faced by farmers in rearing ruminant livestock, and strategies they employ to tackle or manage these challenges. We conducted a deductive thematic analysis of the transcripts, by generating codes and categories from the raw transcript texts, based on the study goals. The results are presented in a narrative form supported by verbatim quotes. Where necessary, clarification phrases are placed in square brackets to enhance the understanding of the quotes. We present also the frequency distribution of the reported proportions of large and small ruminant herds affected by the priority diseases. We used triangulation to validate the findings across the different datasets.

4.4 Results

Socio-demographic characteristics of study participants

Table 4 presents the socio-demographic characteristics of all study respondents stratified by study area. On average, the farmers completing the survey (N = 350) were 45 years old (SD = 14 years), with no significant differences in age between the study districts. Furthermore, the farmers reported an average of 9 years livestock rearing experience (IQR = 6 – 15 years), with farmers keeping an average of 2.9 TLUs of livestock (IQR = 1.4 – 7.8 TLUs); including cattle, goats, sheep, pigs, chicken, guinea fowls, ducks, and doves in their herds. Majority of the farmers (95%) own the animals reared. The livestock farming experience and herd sizes were not significantly different between the study districts. The farmers' resilience similarly did not differ significantly between the study districts, with farmers having average resilience score of 80.5 out of 98 (IQR = 74 – 85). More than two-thirds (71%) of the farmers were male, with the proportion significantly different between districts. About half of the farmers had received no formal education (51%), with the level of educational attainment being significantly different between the study districts. The average number of individuals in farmer households was 8 (IQR = 6 – 11 individuals), and the average distance between the households and professional veterinary officers (VOs) was 8 kilometers (IQR = 1.9 – 12.4 kilometers). The household sizes and distance to VOs were significantly different between the districts. Households' wealth index also differed significantly between study districts with Mion (59%) and Pru East (69%) Districts having the highest proportion of the poorest and least poor households respectively. Significant differences were observed in the availability of social support between the study districts, with more than half of farmers reportedly receiving low levels of social support. The primary sources of social support reported, in order of availability, were from family, friends, religious bodies, community leaders, credit associations, and law enforcement bodies.

For farmers participating in the focus group discussions (FGDs) (N = 65), average age was 45.5 years (SD = 13.0 years). On average, the farmers keep 3.6 TLUs in their herds (IQR = 1.7 – 25.5 TLUs). The majority of the participants were male (85%).

There were no significance differences observed in the age, herd size and sex distributions of farmers participating in the FGDs between the study districts. On average, majority of the farmers (60%) participating in the FGDs had at least some basic formal education, with educational attainment levels being significantly different between the study districts.

The VOs in the study districts were 36.1 years old (SD = 8.6 years) on average, with a majority (85%) being males. They have undergone an average of 3 years (IQR = 3 – 4 years) of veterinary training and worked on average for 2 years (IQR = 2 – 9 years) in the veterinary services. The age, sex, years of training and work experience did not differ significantly between the personnel by study district.

Table 4: Socio-demographic characteristics of the study participants by study district

Characteristic	KAPS	MION	PRU EAST	Percent (%)	Statistical significance
FARMER SURVEY (N = 350)	**n = 149**	**n = 98**	**n = 103**		***p*-value**
Age (years)	46.0 (36.0, 56.0)	41.0 (34.0, 51.0)	46.0 (34.0, 57.0)		0.247
Household size (persons)	7 (5, 10)	10 (7, 15)	8 (6, 13)		0.021
Livestock farming experience (years)	9.0 (5.0, 16.0)	10.0 (6.0, 17.0)	9.0 (5.0, 15.0)		0.415
Distance to veterinary service (km)	12.0 (8.0, 14.4)	6.9 (1.6, 12.7)	1.9 (0.6, 5.6)		<0.001
Resilience level	78.0 (73.0, 84.0)	82.5 (78.0, 87.0)	81.0 (75.0, 86.0)		0.431
Sex					0.001
Female	57	16	29	29.1	
Male	92	82	74	70.9	
Educational attainment					<0.001
No formal education	41	85	52	50.9	
Up to 12 years education	72	6	29	30.5	
Higher education	36	7	22	18.6	
Wealth status					<0.001
Poorest	21	41	8	20.0	
Below average	41	25	8	21.1	
Average	36	14	16	18.9	
Above average	37	10	23	20.0	
Least poor	14	8	48	20.0	
Social support availability					0.012
Low	77	44	59	51.4	
Medium	43	30	13	24.6	
High	29	24	31	24.0	
Herd size (TLU)					0.011
Small (1st tertile: 0.3 – 1.8 TLUs)	55	41	21	33.4	
Medium (2nd tertile: 1.9 – 5.48 TLUs)	51	28	38	33.4	

Large (3rd tertile: 5.5 – 182.3 TLUs)	43	29	44	33.2	
FARMER FGD (N = 65)	**n = 30**	**n = 15**	**n = 20**		
Age (years)	46.0 (37.0, 54.0)	41.0 (36.0, 52.0)	49.0 (35.5, 56.0)		0.763
Herd size (TLU)					0.297
Small (1st tertile: 0.9 – 2.1 TLUs)	9	7	6	33.8	
Medium (2nd tertile: 2.2 – 11.6 TLUs)	10	5	7	33.8	
Large (3rd tertile: 11.7 – 157.2 TLUs)	11	3	7	32.4	
Sex					0.300¥
Female	7	1	2	15.4	
Male	23	14	18	84.6	
Educational attainment					0.025¥
No formal education	16	3	7	40.0	
Up to 12 years education	5	10	7	33.8	
Higher education	9	2	6	26.2	
VETERINARY OFFICER SURVEY (N = 13)	**n = 3**	**n = 5**	**n = 5**		
Age (years)	32.0 (32.0, 43.0)	33.0 (32.0, 41.0)	30.0 (29.0, 38.0)		0.454
Veterinary training (years)	3.0 (3.0, 5.0)	3.0 (3.0, 4.0)	3.0 (3.0, 4.0)		0.467
Work experience (years)	2.0 (2.0, 15.0)	2.0 (2.0, 9.0)	2.0 (2.0, 7.0)		0.440
Sex					1.000¥
Female	0	1	1	15.4	
Male	3	4	4	84.6	

Numbers (n) of participants, including farmers and veterinary personnel by data collection approach, falling into each study district; KAPS denotes participants from Kwahu Afram Plains South District, MION denotes participants from the Mion District and PRU EAST denotes participants from Pru East District in the Southern, Northern and Middle farming Belts of Ghana respectively. Percent (%) denotes the proportion of study participants within each characteristic explored. TLUs denotes farmers' herd sizes standardized in tropical livestock units (1 TLU = 1 cattle, or 3 pigs, or 5 small ruminants, or 25 poultry, or 50 doves). For continuous variables, the median value with corresponding lower and upper quartile values reported in parentheses are presented. *P*-values from Kruskal-Wallis equality-of-populations rank test for continuous variables, and *p*-values from Chi-square tests for categorical variables are presented. ¥ denotes Fisher's exact test probabilities for expected observations less than 5 persons in at least one of the cells.

Severity of adverse events affecting livestock farming

Table 5 presents the top five ranked adverse events based on severity of impact on herds by farmers and their VOs stratified by study district. Overall, the adverse event ranked to have the most severe effect on livestock production by the majority of the participants (all livestock farmers and most of the VOs) across all the study districts was animal diseases. The severity ranking of the other adverse events were mainly district dependent. Pasture shortages was also ranked highly in all the districts although in the more arid Mion District than the other districts. Bush fires were ranked third by farmers in the Mion District, but is less of a challenge in the other two districts. While theft of animals was ranked second by farmers in the Pru East District, conflicts with other land users was ranked second by the farmers in the KAPS District.

The VOs perception of adverse events' effect on livestock production was mainly district dependent. While the personnel in the KAPS and Mion Districts ranked animal diseases to have the most severe effect on livestock production, VOs in the Pru East ranked it fourth. The highly ranked challenge in the Pru East District by VOs was theft of animals. A majority of the personnel across the districts perceived livestock farmers' conflicts with other land users, and ingestion of foreign objects like polythene rubbers by animals to have moderate to severe effects on livestock production. The perceptions of the severity of the adverse events generally were different from the farmers' and the veterinary personnel's perspective in the study district, except for the impact of animal diseases on herds.

Table 5: Most important adversities affecting livestock production based on reported severity of impact on herd by study district

FARMER SURVEY (N = 350)	KAPS (n = 149)	MION (n = 98)	PRU EAST (n = 103)
ADVERSE EVENTS		**RANKING**	
Animal diseases	1st	1st	1st
Pasture shortages	3rd	2nd	3rd
Conflict with other land users	2nd	-	=5th
Theft of animals	4th	-	2nd
Bush fires	-	3rd	=5th
Water shortages	-	5th	
Swallowing of foreign bodies	5th	4th	4th

VETERINARY OFFICER SURVEY (N = 13)	KAPS (n = 3)	MION (n = 5)	PRU EAST (n = 5)
ADVERSE EVENTS	**RANKING**		
Animal diseases	1st	=1st	=4th
Pasture shortages	=4th	=1st	=4th
Conflict with other land users	=2nd	=2nd	=2nd
Theft of animals	=4th	=2nd	1st
Bush fires	=4th	-	-
Water shortages	-	-	-
Swallowing of foreign bodies	=2nd	=3rd	=2nd

Numbers (n) of participants, including farmers and veterinary personnel included in surveys, falling into each study district; KAPS denotes participants from the Kwahu Afram Plains South District, MION denotes participants from the Mion District and PRU EAST denotes participants from the Pru East District in the Southern, Northern and Middle farming Belts of Ghana respectively. The adverse events included in the table are events for which ranked first to fifth per study district. Rankings range from 1st = Most severe impact on herds to 5th = Least severe impact on herds. Rankings are derived as the sum of the products of the number of participants (n) and the reported severity level (no effect = 1, moderate effect = 2, and severe effect = 3) for each adverse event, standardized by sample size per study district. Rankings with "=" before the rank denote tie rank scores for adverse events within each study district. We omitted rankings below the 5th rank within each study district. The other adverse events include poor market for livestock, flooding and ectoparasite infestations.

In the FGDs, the farmers reported animal diseases as the main challenge facing the livestock farmers. The reported challenges were mainly animal-health related, with major concerns about the effects of the diseases on herd productivity and livelihoods, lack of animal health infrastructure, low access to, and inadequacy and high cost of animal health service provision.

> *"For us we have a big problem with diseases in our animals. When it comes to cattle, there is a disease called 'suffer' [Foot-and-Mouth Disease (FMD)], it worries us a lot. There are also other diseases but the 'lung disease' [Contagious Bovine Pleuropneumonia (CBPP)] is very serious. When they are infected, it brings out all other diseases that are hidden in the cattle. …, as for it when it enters the cattle kraal, hmm masa, unless you solve it, you cannot have peace of mind, …, you will weep before it goes. … When they contract the lung disease [CBPP], the pregnant cows do have premature*

births. Also, the milk production goes down drastically, [long pause], you can't even get some of the milk. It will not be enough for the calves before you think of the farmer" ***(Male farmer, 46 years old, Mion District)***

"Formerly, it would have been after 2 to 3 years before you inject your cattle once, but now within 1 month you could treat one cattle about 3 times for diseases" ***(Male farmer, 49 years old, KAPS District)***

Other challenges reported were in relation to pasture and water shortages, housing challenges for the herds, and the cost of resolving conflicts occasioned by animals' destruction of farms.

"The diseases are the single major problem for all of us. I think NH [referring to another FGD participant] also said something about feeding. When it gets to the dry season, there is bush burning everywhere. The pasture that cattle and goats will feed on, all of them, off [burnt]. When that happens, the animals begin to lose weight. So when something small [disease] infects them, then they begin to die. .... Hmm, also, the issue of housing, like our sister said; where the animals will sleep [is a problem]" ***(Female farmer, 46 years old, KAPS District)***

"One major problem for us livestock farmers in this community especially the cattle and goat farmers is that, during the dry season, we [livestock farmers] do not get access to feed for the animals. As a result, it leads to a fight between livestock farmers and the crop farmers especially yam growers. Because the animals sometimes end up destroying the [crop] farms" ***(Male farmer, 53 years old, Pru East District)***

To identify the most common or priority livestock diseases affecting ruminant livestock production, we inquired about the most recent disease cause of death in the past 12 months for farmers reporting a mortality of their ruminant livestock within the study period. About 82% (282/344) of the farmers who rear small ruminants reported animal mortalities compared to 78% (68/87) for the farmers rearing cattle. Specifically for the ruminant livestock species kept (cattle, sheep, and goats), the farmers reported an average of 10% mortality of their herds to diseases (IQR = 23%) in past 12 months. On the most likely disease to have caused the death, 40% of the small ruminant farmers reported Peste-Des-Petits-Ruminants (PPR), while 5% reported mange.

Among farmers rearing cattle, 31% reported the recent mortality to be due to Contagious Bovine Pleuropneumonia (CBPP) with about 5% due to Foot-and-Mouth Disease (FMD) infection. In the local languages, farmers refer to PPR, Mange, CBPP and FMD as “ayamtuo yareɛ”, “krusakrusa”, “akoma yareɛ” and “suffer” respectively. The other non-specific factors reported to lead to mortalities were birth-related including abortions and birth complications during parturition, causing about 1% of reported deaths in small ruminants and 4% of reported deaths in cattle.

The VOs similarly provided the disease(s) likely to have caused the most recent reports of ruminant livestock mortality they received from the livestock farmers in their respective operational areas. In small ruminants, PPR was the most likely cause of death in small ruminants, reported by farmers to a majority of the VOs (69%). While in cattle, CBPP was most likely the cause of death reported to the VOs (31%).

In FGDs, farmers identified the most common diseases affecting their herds to include CBPP and FMD in cattle and, PPR and mange in goats and sheep. Based on this, the farmers reported the average distribution of each disease in their herds in a farming year, using proportional piling. Overall, the reported FMD prevalence was 50% on average (IQR = 50%), while CBPP prevalence was 40% (IQR = 20%) on average in cattle herds in a farming year. For the small ruminants, an average PPR prevalence of 50% (IQR = 40%) and average mange prevalence of 10% (IQR = 20%) among herds in a farming year were reported (**Figure 6**).

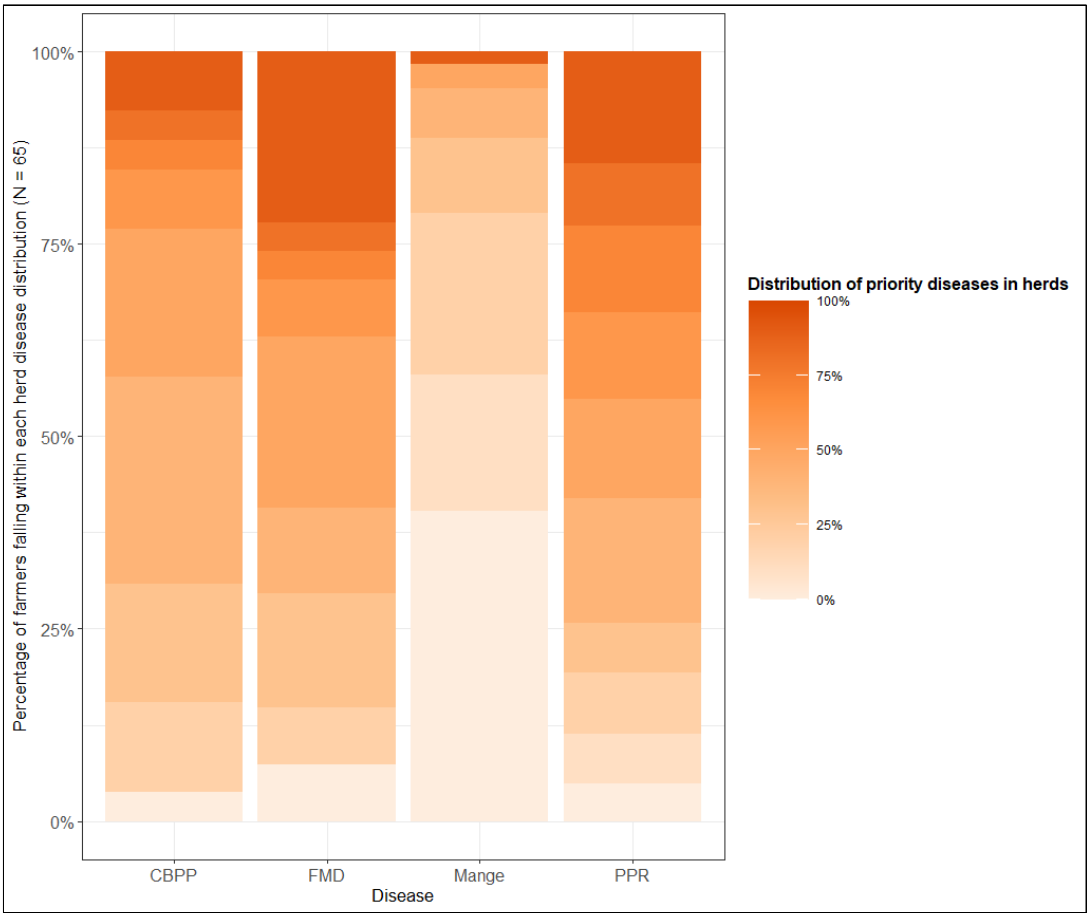

Figure 6: Distribution of common infectious diseases in ruminant livestock.
The figure shows the typical distribution of key infectious diseases in a farming year in farmers' herds based on proportional piling by 65 experienced farmers purposively selected to participate in focus group discussions. The gradient of color shows the reported distribution of the diseases on a percentage scale (from 0 to 100%) with light coloration depicting low prevalence and deep coloration depicting high prevalence. The y-axis shows the proportion of the farmers reporting a specified prevalence level of each disease condition in their herds. Each column bar on the x-axis depicts the two most common diseases for large and small ruminant farmers respectively.

Management strategies for common livestock diseases

We found treatment for sick animals (82%), deworming (54%) and treatment of wounds (47%) as the most common disease management strategies the farmers utilized. Only 20% of farmers reported vaccinating their herds in the study year (**Figure 7**). We assessed for each disease management strategy utilized by the farmers, the most recent veterinary service provider that rendered the service. Among farmers who used any of these services, the treatment services for sick animals were done almost evenly by informal providers 37% (106/286), professional veterinary officers 35% (96/286) and farmers themselves 29% (84/286). The VOs 39% (73/188) mostly did deworming of the animals, while the farmers and informal providers do about 30%

each of the deworming of livestock. Similarly, the treatment of wounds was done mainly by the VOs 42% (69/166); 36% (60/166) of farmers reported treating wounds themselves, with informal providers delivering 22% of wound treatment services for farmers.

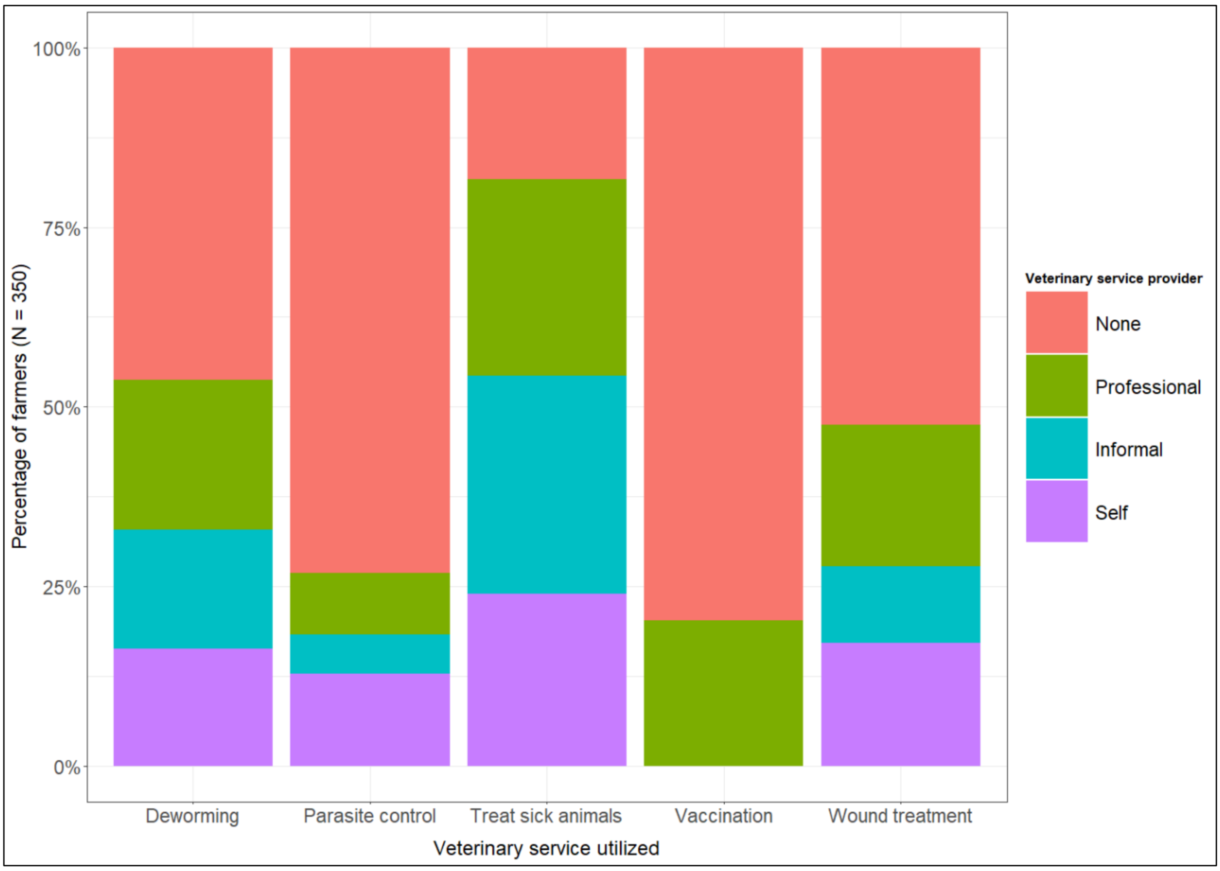

Figure 7: Veterinary services use preferences of ruminant livestock farmers in Ghana.

The figure presents the distribution of most recent usage of key veterinary services requiring the application of medicines by farmers and the service providers used. The y-axis shows the proportion of farmers utilizing the services by provider type. The x-axis presents the services evaluated. The divisions and colors in the stacked bars depict the proportion of each service use accounted for by a service provider.

As shown in **Figure 8**, among livestock farmers who used antimicrobials, the most frequently applied compounds are tetracyclines, penicillins and antiparasitic medicines to manage the diseases or conditions of their animals. The tetracyclines commonly used by the farmers were Oxytetracycline injections, and Tetracycline Hydrochloride capsules. Antiparasitic medicines used commonly were Ivermectin injections, and Albendazole suspensions. With respect to penicillins, farmers commonly used Procaine Penicillin or Procaine Penicillin with Dihydrostreptomycin (PenStrep) injections, and Amoxicillin Trihydrate capsules (See **Additional File 3**). However, after disaggregation of the application of the medicines, we found that although most farmers use tetracyclines and penicillins for most of the common conditions, the majority of the reported applications of these medicines were not useful (**Figure 9 Panel A**). On the other hand, whereas the VOs also use tetracyclines and antiparasitic medicines quite frequently, the reported applications of the medicines were mostly useful for the conditions (**Figure 9 Panel B**).

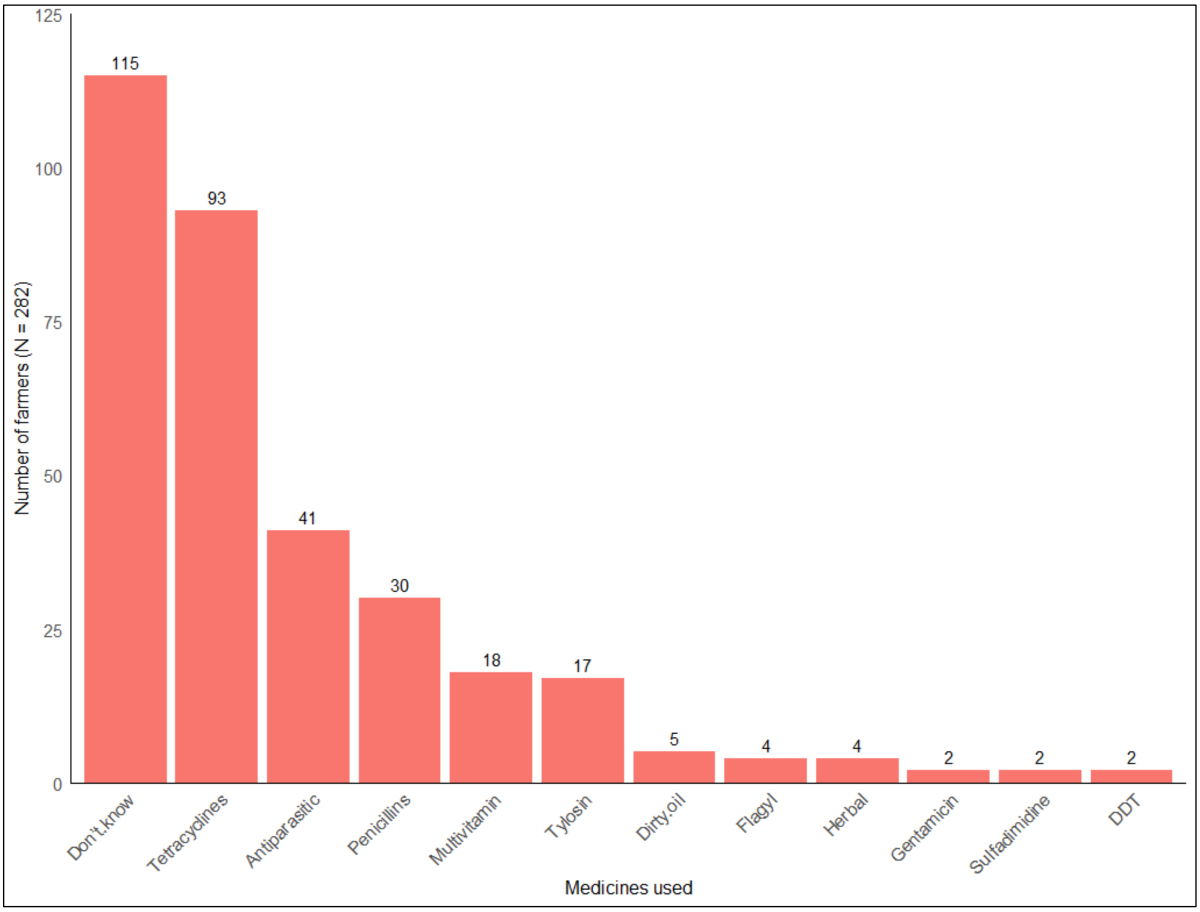

Figure 8: Medicines commonly used by livestock farmers for managing common diseases.

The y-axis shows for each medicine used, the number of farmers (N = 282) who reported self-treating a disease or condition in their herds during the study year. The x-axis presents the medicines the farmers reported using or have medicine sachets, vials or bottles available during the survey to be captured. Farmers that used medicines but could not recall the medicine names nor provide the medicine sachets, vials or bottles are depicted as “Don’t know” on the column bar. The reported and captured medicines were grouped in medicine classes if possible, and usage frequencies presented in the column bars.

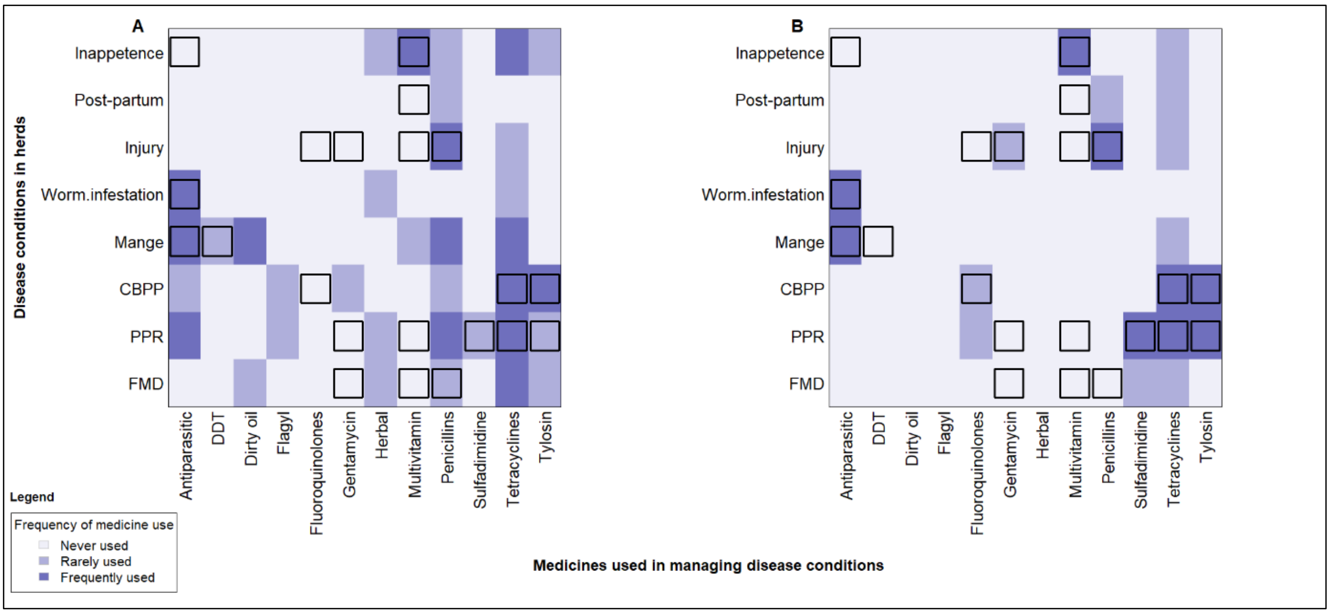

Figure 9: Frequency and utility of use of medicines by livestock farmers and veterinary officers for managing common diseases and conditions in ruminant livestock.

The figure compares the medicines and the reported frequency of use in managing each disease or condition by livestock farmers and professional veterinary officers. **Panel A** and **Panel B** depicts farmers' and veterinary officers' application of the medicines respectively. Square shapes (☐) in cells depict a useful medicine and disease or condition combination. The color gradient shows the frequency of use of each of the medicines by the study participants, ranging from no use (light color) to frequent use (deep color) respectively. The y-axis presents the disease or conditions treated while the x-axis presents the medicines applied.

In FGDs, we found that the diseases are treated also with traditional medicines including ethanol, herbal preparations and used automobile engine oils. The orthodox medicines for treatment are accessed from veterinary drug stores, human drug stores, livestock markets or from medicine vendors who roam the communities. Non-orthodox medicines are usually self-made or accessed from livestock markets or community herbalists.

"… there is not a specific drug, we use different drugs [in FMD treatment], …, everybody tries something. So if you are lucky and a particular treatment works, then you stick with it and it becomes a norm. I remember that a cattle disease [FMD] affected our cattle and someone advised me to buy some medicines to apply, …, The person told me to buy "battery water" [Sulphuric acid] and add a bit of salt to it, …" ***(Male farmer, 37 years old, KAPS District)***

> *"…if it [FMD] is serious, we call the veterinary officers to come to assess the affected animal. But sometimes when it is less severe, we buy 'DDT' [Acaricide] and mix it with "tupaye" [Tetracycline] and we use the mixture on their affected hooves"* ***(Female farmer, 30 years old, Pru East).***

> *"…I use procaine penicillin for treating the diarrheal disease [PPR] in both sheep and goats. For the skin rashes [mange], I use 'dirty oil' [used automobile engine oil] for it"* ***(Male farmer, 41 years old, Mion District)***

For the factors influencing the disease management strategies adopted by the livestock farmers, we found that for the most part, either informal providers administer the treatments or the farmers treat the diseases on their own, due to lack of easy access to professional veterinary officers or reduced severity of the diseases. Few farmers seek professional veterinary officers in the first instance of a disease problem in their herds. The choice of medicines for treating diseases, were greatly influenced by farmers' past experiences with the use of specific medicines, peer to peer referrals for specific treatment strategies or medicine vendors in communities or livestock markets. The medicines are administered by injections, orally, in drinking water or directly into the mouths with syringes, and topical application on lesions and wounds.

> *"Usually, I go to those who sell drugs in 'gariki' [livestock market in the district] and explain to them the symptoms the animal is showing. They are the ones that gave me a certain drug [to use for PPR infected small ruminants]. … Some of the drugs are pills, and some too are like milk in a gallon [anthelmintic] and you have to draw it with a syringe to administer it to the infected animals. Some of the drugs are also green in color [anthelmintic tablets], and we give these to them [orally]* ***(Male farmer, 50 years old, Pru East District)***

> *"For the diarrheal disease [PPR], we use our own mind [knowledge] to manage. Like my brother said, when the goats are having the diarrhea [PPR] and we don't get the veterinary officer, we go and buy 'Tupaye' [Tetracycline],…, and then open a lot of them and put in water; and then open the mouth of the goat and give it to it to drink"* ***(Male farmer, 43 years old, KAPS District)***

> *"When there is the CBPP outbreak, I call the doctor [veterinary officer] to assess them, and he gave the animals some injections. Sometimes too, if the cattle are not feeding well, the herdsmen will let me know and then we get penicillin injections [procaine penicillin] to be given to the cattle [by the herdsmen]"* ***(Female farmer, 46 years old, Mion District)***

The treatment measures employed have varied effectiveness for the conditions they are applied; sometimes they are effective but in most cases, the treatment effects are short-lived.

> *"When we use the dirty oil for mange, we see immediate effect of the scaly skin peeling off and new hair regenerate in the affected area in a short while. But it doesn't cure the disease in the animal's system because it won't be long enough and the animals [goat and sheep] would develop the mange again"* ***(Male farmer, 41 years old, Mion District)***

> *"For the animals that the disease is not advanced, when you administer them [drugs bought from livestock market], it seem to work… but it sometimes recurs. And for those that the disease is already advanced, it doesn't cure them, and they end up dying* ***(Male farmer, 60 years old, Pru East District)***

Utilization of veterinary services

Overall, only 33% (116/350) of the surveyed farmers utilized professional veterinary services during past 12 months compared to 51% (177/350) utilizing the services of informal veterinary service providers. The proportion of farmers using professional veterinary services was significantly different between the study districts ranging from 54% (56/103) in the Pru East District to 21% (32/149) in the KAPS District (p<0.001). We present the predictors of farmers' utilization of professional veterinary services in **Table 6**. In our pre-specified model, we found the odds of farmers utilizing the services to be improved significantly by increasing years of experience with livestock rearing, increase in farmer resilience, increase in herd size, being male, educational attainment, increasing wealth status, increasing severity of perceived effect of diseases on herds and high levels of social support availability in the univariable analyses. The odds of farmers utilizing the services significantly reduced with increase in distance between farmers and professional veterinary officers.

After adjusting for the farmers' livestock rearing experience, resilience level, sex, and social support availability, the utilization of professional veterinary services was significantly influenced by distance between farmers and their veterinary personnel, farmers' herd size, educational attainment, wealth status, and perceived severity of disease effect on herds (Pseudo $R^2 = 0.22$, $p < 0.001$). We evaluated and found that our model was more effective than the null model, and fit the data well (Hosmer – Lemeshow goodness-of-fit $\mathcal{X}^2(10) = 7.75$, $p = 0.46$). We did not find evidence that the model assumptions were violated in our post estimation analysis; the residuals scatter randomly, the Pregibon leverage was below the recommended threshold and the predictors were not strongly correlated.

After adjusting for the other predictors, the odds of farmers utilizing professional veterinary services decreased by a factor of 0.91 with each 1-kilometer increase in distance from a service provider (aOR = 0.91, 95% CI = 0.85 – 0.98, $p = 0.01$).

The odds of farmers using professional veterinary services were 2.1 times higher if they had large herd size (5.5 – 182.3 TLUs) (aOR = 2.11, 95% CI = 1.08 – 4.11, $p = 0.03$) compared to if they had small herds (0.3 – 1.8 TLUs). Farmers with basic education were also twice more likely to use services compared to if they had no formal education (aOR = 2.08, 95% CI = 1.07 – 4.06, $p = 0.03$). There was also a three-fold increase in the odds of utilizing the services if the farmer's wealth status was above average (aOR = 2.62, 95% CI = 1.02 – 6.73, $p = 0.04$) and 3.6 times higher for the least poor households (aOR = 3.61, 95% CI = 1.27 – 10.2, $p = 0.02$), compared to the poorest households. The odds of a farmer utilizing professional veterinary services increases with increasing perception of disease risk to their herd. The odds increased by a factor of 3.6 if farmers perceived diseases effect to be moderate (aOR = 3.64, 95% CI = 1.24 – 10.7, $p = 0.02$), and by a factor of 4.0 if the perceived effect of diseases on the herds was severe (aOR = 4.00, 95% CI = 1.51 – 10.6, $p = 0.005$), compared to when farmers perceive no diseases effect on their herds.

Table 6: Factors influencing livestock farmers' utilization of professional veterinary services in Ghana

	Unadjusted model		Adjusted model	
Variables	**cOR (95% CI)**	**P-value**	**aOR (95% CI)**	***p*-value**
Livestock farming experience (years)	1.04 (1.01, 1.07)	0.014	1.03 (0.98, 1.07)	0.248
Distance to veterinary service (km)	0.91 (0.87, 0.95)	<0.001	0.91 (0.85, 0.98)	0.016
Resilience level	1.04 (1.01, 1.07)	0.008	1.03 (1.00, 1.07)	0.078
Herd size (TLUs)				
Small (1st tertile: 0.3 – 1.8 TLUs)	ref		ref	
Medium (2nd tertile: 1.9 – 5.48 TLUs)	1.74 (0.95, 3.19)	0.071	1.15 (0.58, 2.28)	0.691
Large (3rd tertile: 5.5 – 182.3 TLUs)	4.09 (2.28, 7.32)	<0.001	2.11 (1.08, 4.11)	0.028
Sex				
Female	ref		ref	
Male	2.22 (1.30, 3.80)	0.004	1.67 (0.90, 3.09)	0.105
Educational attainment				
No formal education	ref		ref	
Up to 12 years education	1.70 (1.02, 2.83)	0.041	2.08 (1.07, 4.06)	0.031
Higher education	1.65 (0.90, 3.00)	0.103	1.42 (0.60, 3.37)	0.424
Wealth status				
Poorest	ref		ref	
Below average	0.77 (0.33, 1.81)	0.556	0.78 (0.29, 2.05)	0.612
Average	1.28 (0.57, 2.88)	0.551	1.38 (0.54, 3.51)	0.496
Above average	3.00 (1.41, 6.37)	0.004	2.62 (1.02, 6.73)	0.046
Least poor	6.77 (3.16, 14.5)	<0.001	3.61 (1.27, 10.2)	0.016
Perceived effect of diseases on herd				
No effect	ref		ref	
Moderate effect	3.53 (1.36, 9.13)	0.009	3.64 (1.24, 10.7)	0.018
Severe effect	4.45 (1.81, 10.9)	0.001	4.00 (1.51, 10.6)	0.005
Social support availability				
Low	ref		ref	
Medium	0.73 (0.41, 1.32)	0.301	1.50 (0.77, 2.90)	0.233
High	2.07 (1.21, 3.52)	0.008	1.83 (0.85, 3.94)	0.123

Multivariable model evaluation		$\mathcal{X}^2$	df	***p*-value**
Wald test	*Pseudo* R^2=0.22	88.76	16	<0.001
Goodness-of-fit test				
Hosmer – Lemeshow (H–L)		7.75	10	0.463

Variables included as predictors of livestock farmers' utilization of professional veterinary services in Ghana. Crude odds ratio (cOR) with 95% confidence intervals (CI) and associated *p*-values for the unadjusted model, and adjusted odds ratio (aOR) with 95% CI and associated *p*-values for the adjusted model, accounting for village-level clustering during sampling are reported. 'ref' denotes the reference category. $\mathcal{X}^2$ are chi-squared statistics of a Wald test comparing the full multivariable model versus the null model, and Hosmer – Lemeshow (H–L) goodness-of-fit test of the model fit with respective degrees of freedom (df) and *p*-values.

The discussions with farmers similarly showed that, utilization of professional veterinary services was influenced mostly by the affordability of the service, farmer proximity and/or personal access to the veterinary personnel or in cases of complications from diseases or other conditions of the livestock. The professional veterinarians usually are sought after to address the situations that the farmers or informal providers could not successfully handle.

> *"When the veterinary officer comes to treat them, we are mostly unable to afford the cost. So, we usually buy the medicines ourselves. So, when we give the animals the injection [treatment] over time, and it gets to a point that it is difficult or beyond us, that is when we call him"* ***(Male famer, 49 years old, KAPS District)***

> *"My issue is, even when you have money to buy drugs, there is no veterinary post available where you can get the drugs needed. You see, rearing animals also requires a market, but we don't have a slaughterhouse where you can send the animals to sell. And the veterinary officers here don't even have any place to store the drugs, ... So, unless, you go and request, and he will give you maybe two weeks, when he would have gone to Accra [Capital of Ghana] and bought the drugs to come and administer. So, by the time he returns with the drugs for you, the sickness would have worsened, ..., you see. And the veterinary officers are also few* ***(Male famer, 72 years old, KAPS District).***

> *"…for my cattle, I don't use any medicine [self-treatment]. I'm close to the veterinary officer in the community so whenever there's any infection of my cattle, I quickly call him to come and treat them for me"* ***(Male farmer, 41 years old, Mion District)***

Appraisal of Veterinary Services Performance

We assessed the farmers' general perceptions of the performance of the veterinary service providers they had ever used. **Figure 10** compares the relative importance indices (RII) for the performance attributes of VOs and their informal provider counterparts from farmers' perspective. The VOs performed best on the efficacy of the medicines administered (RII = 0.86) and performed worse on the affordability of services rendered (RII = 0.66). The informal providers performed best on the availability of drugs (RII = 0.78) and worse on the provision of education or advisory services to the farmers (RII = 0.58). Except for the proximity to the farmers, popularity, and high usage of informal providers' services among the farmers, the VOs were rated highly on all the other attributes. Thus, comparatively, VOs performed better with respect to the availability of medicines when attending to farmers, quality of medicines administered, positive outcome of the treatments administered, provision of health education, affordability of the services rendered, and trust of competence to address the animal health issues in the communities. The informal providers on the other hand were viewed to be closer to the farmers and their services were popular, and highly used by most of the farmers.

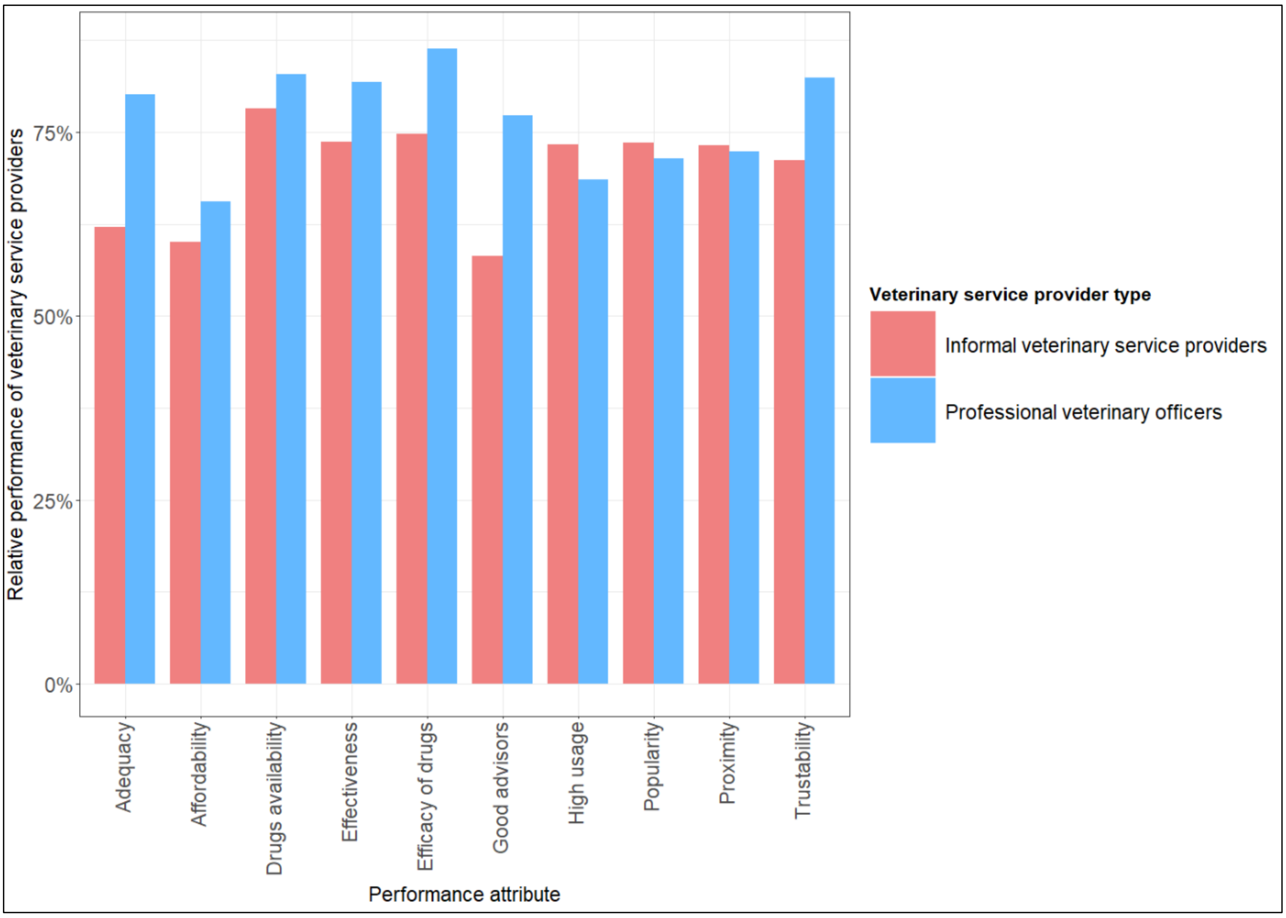

Figure 10: Farmers' appraisal of the performance of their veterinary service providers.

Figure 10 presents the appraisal of farmers of the performance of the veterinary service providers that they ever used on 10-item 5-point Likert scale. The y-axis depicts the relative performance of the providers on each attribute. The Relative Importance Index (RII) of each attribute are depicted by the height of the bars, stratified by colors for each provider type.

The VOs evaluated themselves on the availability of key tools required to deliver their services effectively in a survey. Only 54% (7/13) of the VOs have personnel stationed at border posts to monitor animal movements in their operational areas. About 62% (8/13) reported having slaughter places in their operational areas and having official motorcycles for their work. None of the VOs reported having a designated laboratory to confirm suspected pathogens or any means to control the sale and use of medicines in the respective districts. Most of the VOs (54%) reported that they do not have any form of communication with public health personnel in the districts; 31% (4/13) had informal communications, while only 15% (2/13) had formal communications with public health personnel concerning diseases of zoonotic potential.

In the FGDs with the livestock farmers, we found farmers who had access to the professional veterinarians to be largely satisfied with the services provided to them. The veterinarians provide advice on ways to improve herd health, treat animals, and sometimes purchase medicines for farmers who provide them funds. However, there is generally a dissatisfaction regarding the timeliness of veterinarians' response to the farmers call for help.

> *"What I have noticed is that when he [veterinary officer] comes and once the animal is sick, he does everything possible to help us out. Even if the money to pay is not available at the time he came, he will still consider you. … He considers us a lot"* ***(Female farmer, 46 years old, KAPS District)***

> *"…the doctors that attend to us here are very few [3 veterinary officers in KAPS]. So, if you call him [veterinary officer] to come, maybe it is not only you who needs the doctor; another person also calls him today and tomorrow. So, if he goes from one farm to another, by the time he or she would come to you, it would be too late. … But because it is the work you are doing; you need to try to do something to ensure that the animals are healthy by making provision to inject the animal. If you fail to do something, by the time the veterinary doctor comes, the animal will die"* ***(Male farmer, 66 years old, KAPS District)***

> *"When we call upon the veterinary and they are not able to come on time, we go to town to where they sell the cattle medicines [veterinary drug store]. And when we get there, we describe to them the type of sickness affecting them [livestock], and they give medicines to come and inject the animals"* ***(Female farmer, 30 years old, Pru East District)***

4.5 Discussion

In this study, we aimed to identity the main challenges affecting ruminant livestock production in Ghana, evaluate the management strategies applied to deal with diseases and appraise the performance of veterinary services in meeting livestock farmers' demands for their services. We adopted a convergent parallel mixed-method design to achieve this goal. Our results suggest that animal diseases are the main challenge to livestock production with pestes-des-petits-ruminants (PPR) and mange, and contagious bovine pleuropneumonia (CBPP) and foot-and-mouth disease (FMD), as the main diseases affecting farmers producing small and large ruminants respectively. Farmers mostly utilized treatment services, with the services provided mainly by informal veterinary service providers in the communities, public professional veterinary officers (VOs) or farmers themselves. The choice of management strategies was informed by farmers' access to VOs, past experiences with the diseases, peer influence, severity of the disease in herd and suggestions by medicine vendors. The antimicrobials mostly used were tetracyclines, penicillins and antiparasitic medicines, although most of the reported applications of these medicines by the farmers were not useful for the conditions or diseases. Overall, farmers were satisfied with the veterinary services provided them, with VOs scoring highly on drugs availability and quality, effectiveness of treatments, education offered, services affordability and community's trust of their competence to deliver the services compared to the informal providers.

These findings are intuitive, as previous research among sections of the target population similarly identified animal diseases as the primary impediment to the productivity and wellbeing of livestock farming households. Additionally, the previous studies showed that farmers self-treat diseases, and sell diseased animals as coping strategies in response to the lack of adequate veterinary services (Mockshell et al., 2014; Nuvey et al., 2020; Nuvey et al., 2021). The discordance between the perceived effects of the adverse events on livestock production between the farmers and their VOs was logical, given the reported shortfalls in the veterinary workforce and service delivery to livestock farmers in Ghana (Diop et al., 2011). Under the current global environment with heightened risks of disease spillovers particularly from animals to humans, the need for the effective control of infectious diseases in animals cannot be overemphasized. Previous reviews have shown vaccination to be both effective and profitable in controlling infectious diseases in animals (Charlier et al., 2022; Nuvey et al., 2022a). With a high prevalence of diseases such as CBPP, FMD and PPR among herds in spite of the availability of effective vaccines, there is a compelling need to identify reasons for the low uptake of vaccination by farmers. Additionally, further studies should also determine livestock farmers' valuation and willingness to pay for vaccines to protect their livestock against the negative effects of diseases while ensuring sustainability of the disease control interventions.

There is extensive evidence in the literature on the links between increased antimicrobial use in agriculture and emergence of antimicrobial-resistant pathogens (Kimera et al., 2020; Mshana et al., 2021). Our results show that in addition to the high rate of antimicrobial use in livestock production in Ghana, including tetracyclines, penicillins and antiparasitic preparations like ivermectin, most application of antimicrobials by farmers were not useful for treating the target diseases. This finding is concerning given the limited capacity of the veterinary services to control the types and quality of antimicrobials that are sold and used in many African countries (OIE, 2019a). The results of our survey with VOs clearly corroborate this limitation in our setting, where the VOs reported the non-availability of mechanisms in the districts to regulate the sale and use of veterinary medicines, in addition to other limitations to control animal movements across operational area borders that facilitate the spread of infectious diseases in animals. The limitations in the veterinary services control of veterinary drug marketing could be attributed to the liberalization of the marketing of veterinary medicines in Ghana following the structural adjustment programmes (Turkson, 2001). In the light of these findings, the risks to public health because of ecosystem pollution with pharmacological preparations as well as the development and spread of antimicrobial-resistant pathogens, are enormous and require urgent strategies to deal with the animal diseases problem in the livestock sector.

Although the VOs were rated highly by farmers who have ever used their services on most of the attributes assessed, they performed poorly in proximity or accessibility to farmers in comparison with the community-based informal veterinary service providers. Thus, we found a high reliance of farmers on their peers and informal veterinary service providers for animal health services. These informal providers, however, operate outside the purview of the formal veterinary system. Moreover, there is a lack of trust and willingness to integrate such informal providers into the veterinary systems in many African countries (Riviere-Cinnamond, 2005). Community-based animal health workers (CAHWs) as they are popularly known, have been shown to play crucial roles in augmenting professional veterinary personnel in delivering animal health services particularly in rural areas in other settings in Africa (Martin, 2001; Admassu et al., 2005; Bugeza et al., 2017). With better training and supervision, CAHWs could be a valuable asset to the livestock sector particularly in resource-limited settings like Ghana, which have significant shortfalls in veterinary professionals.

Furthermore, we found in our model that utilization of veterinary services was predicted mainly by the social circumstances and human capital of farmers as well as some health system factors. Strategies aimed at improving utilization of veterinary services must focus on these social, human capital, and health system aspects. There is a need therefore for more engagement between policy makers, like the Ministry of Food and Agriculture and Veterinary Services Directorate, and communities towards the development of the veterinary workforce and the co-creation of solutions to address the challenges with animal health services delivery in Ghana. Such solutions must strive for better antimicrobial stewardship in animal production to tackle the emergence of antimicrobial resistant pathogens. Immediate actions to promote effective governance and increased funding for veterinary services are imperative. These measures are indispensable for advancing sustainable livestock production and better animal, human and ecosystem health.

Our study had some limitations. Despite efforts to obtain a representative sample of the different agro-ecological zones in Ghana, our study did not account for the two other minority agro-ecological zones, namely the Evergreen and Coastal Savannah zones. Even though these zones are not typical areas for livestock production in Ghana, it would have been interesting to observe the disease management strategies as well as veterinary services performance in these minority agro-ecological zones. In spite of this missing perspective, we do not expect the parameters evaluated to be markedly different in these agro-ecological zones. Additionally, we relied largely on reported information in our surveys and focus group discussions with study participants. Nevertheless, the triangulation of results from the different methods employed show some validity of our instruments. Our study thus has provided valuable information on the key challenges confronting livestock production, disease management strategies utilized by farmers and appraisal of veterinary services performance in Ghana. Additionally, interviewing the informal providers in the veterinary system would have provided a better understanding of their activities and role in the animal health service delivery. However, this was not covered within the scope of this study. Future studies should address the role of informal providers in the veterinary system from their perspective.

4.6 Conclusion

Our study shows that animal diseases including PPR and Mange in small ruminants, and CBPP and FMD in cattle remain a key bottleneck to the productivity of livestock and wellbeing of livestock dependent populations in Ghana. Disease management strategies adopted by farmers are influenced mainly by accessibility to professional veterinarians, severity of diseases on herds, peer influence, experience with diseases and suggestions by drug vendors. The antimicrobials applied in the treatment for most of the animal diseases and conditions by the farmers are not useful. Although the farmers are largely satisfied with the performance of their professional veterinary service providers in terms of drugs availability and quality, effectiveness of treatments, health education, service affordability and competence to deliver veterinary services, informal veterinary service providers are widely used due to their proximity to farmers in the communities. Given that the main diseases reported have available effective vaccines for their control and vaccination utilization is low among the farmers, our findings underscore the urgent need to improve the adoption and use of vaccination services by farmers, as well as better antimicrobial stewardship and veterinary services governance to properly regulate the animal health service delivery in Ghana.

4.7 Declarations

Ethics approval and consent to participate

The study was reviewed and approved by the Ghana Health Service Ethics Review Committee, Ethics and Research Management Department – Accra, Ghana (approval number: GHS-ERC 006/09/20). In the study districts, permission was obtained from all the relevant authorities prior to data collection. The study participants provided written informed consent and the data generated are kept as confidential records. All the methods were carried out in accordance with relevant guidelines and regulations (Such as Declaration of Helsinki).

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

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Author contributions

Conceptualization, all authors; **methodology**, all authors; **validation**, G.I.M., J.Z., J.H., G.F, B.B., K.K.A.; **formal analysis**, F.S.N.; **investigation**, F.S.N.; **resources**, B.B., J.H., J.Z. and G.F.; **data curation**, F.S.N.; **writing—original draft preparation**, F.S.N.; **writing—review and editing**, all authors; **visualization**, F.S.N., and J.H.; **supervision**, G.I.M., J.Z., G.F., B.B. and K.K.A.; **project administration**, F.S.N. and B.B.; **funding acquisition**, J.Z., B.B. and K.K.A. All authors have read and agreed to the published version of the manuscript.

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4.8 Supplemental

Supplemental Appendix to

“Management of diseases in a ruminant livestock production system: a participatory appraisal of the performance of veterinary services delivery, and utilization in Ghana”

Additional file 1: Survey instrument for livestock farmers' survey

The survey instrument for livestock farmers’ survey can be accessed via the following link:

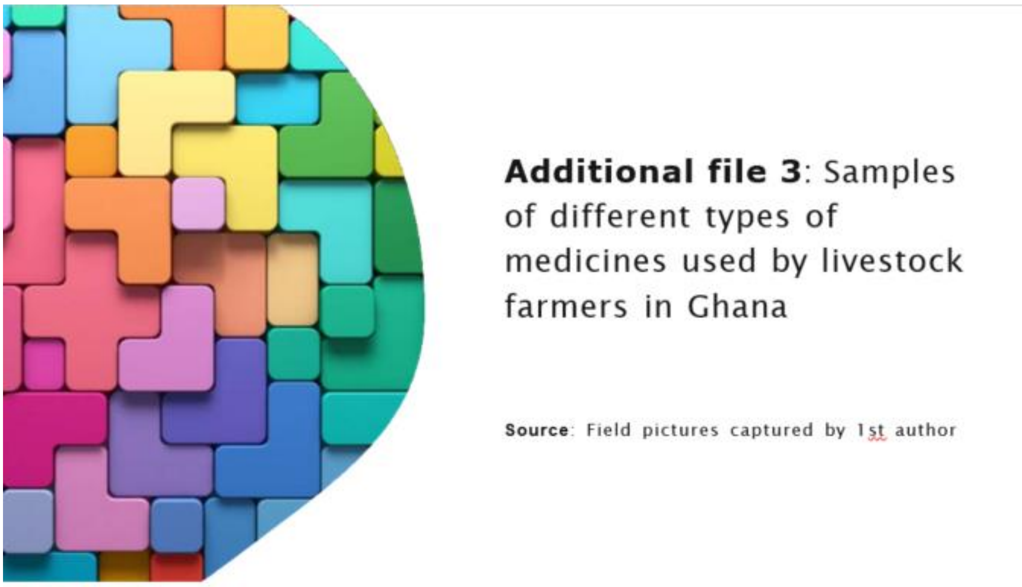
https://doi.org/10.21203/rs.3.rs-2380836/v1

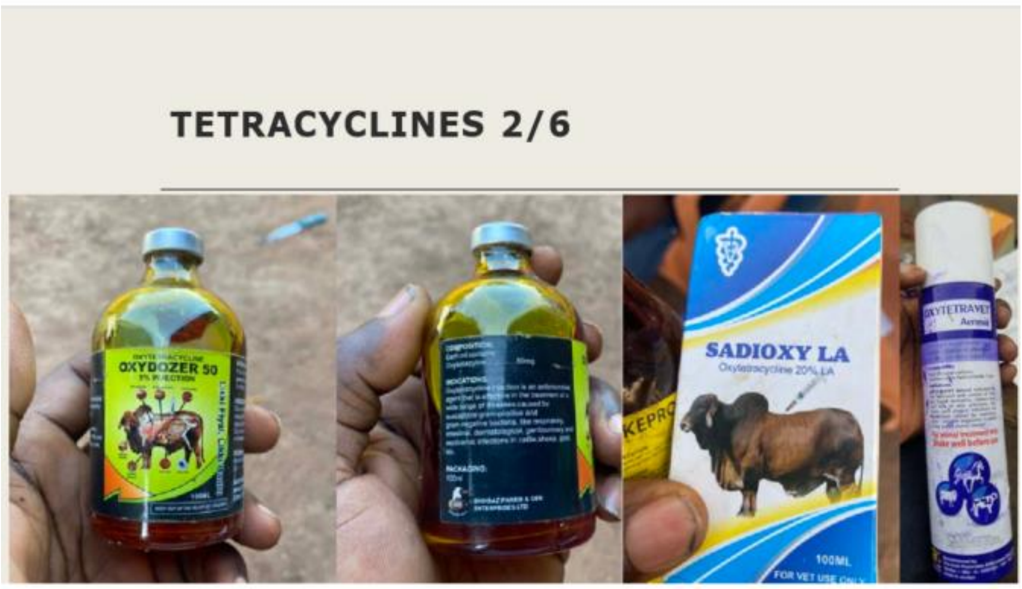
Additional file 2: Survey instrument for veterinary service providers' survey

The survey instrument for veterinary service providers’ survey can be accessed via the following link:

https://doi.org/10.21203/rs.3.rs-2380836/v1

Additional file 3: Samples of different classes of medicines used by livestock farmers in Ghana

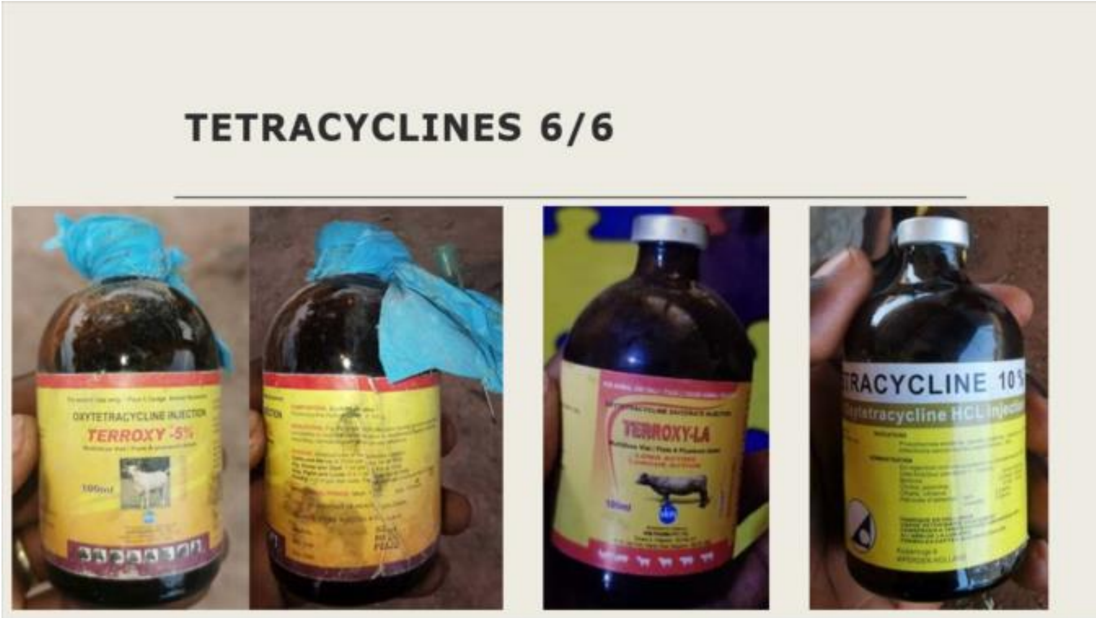





TETRACYCLINES 3/6
Temadox L.A.
100ml
PANTEX-
OXYTETRA 200 LA
PANTEX
ANNYTROX LA
100ml


TETRACYCLINES 4/6
SADIOXY LA
OXY 20% LA INJ
Dopharma
MARTHA


TETRACYCLINES 5/6
OXYTETRACYCLINE
CLINE 10%
100ml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OXYTETRACYCLINE INJECTION
TERROXY-5%
TERROXY-LA
TRACYCLINE 10%


PENICILLINS 1/2
PROCAINE PEN
FOR INJECTION
ICILLIN
Eskay
TROGE
FORTIFIED PROCAINE PENICILLIN 4 mega
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HAMBURG - GERMANY
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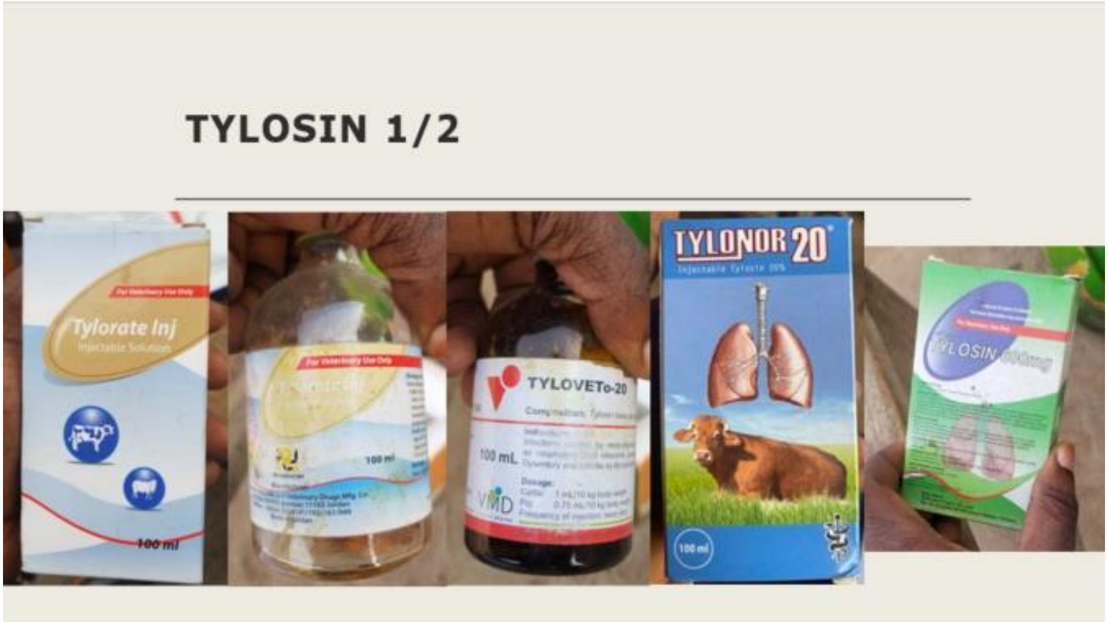
TYLOSIN 1/2
Tylorate Inj
Injectable Solution
100 ml
TYLOVETo-20
100 mL
TYLONOR 20
100 ml


TYLOSIN 2/2
TYLONOR 20
Injectable Tylosin 20%
MANTHA
TYLOSIN BOLUS
FOR VETERINARY USE ONLY


OTHER ANTIBIOTICS
METRONIDAZOLE
METRONIDAZOLE

ANTIPARASITIC MEDICINES 1/6

ANTIPARASITIC MEDICINES 2/6

ANTIPARASITIC MEDICINES 3/6

ANTIPARASITIC MEDICINES 4/6

ANTIPARASITIC MEDICINES 5/6

ANTIPARASITIC MEDICINES 6/6

MULTIVITAMINS 1/2

MULTIVITAMINS 2/2

HERBAL/ TRADITIONAL MEDICINES


OTHER MEDICINES
1 Ltr.
10%
TRADE ON
DEXANOR
Dexamethasone injection 0.2 %
Aqueous solution for parenteral use.
100 ml
M-DEXAME 0.4%
Injectable solution
For Animal Use Only
Oxytocin-20

Chapter 5 Access to vaccination services for priority ruminant livestock diseases in Ghana: Barriers and determinants of service utilization by farmers

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5.1 Abstract

Introduction: Livestock diseases are a major constraint to agricultural productivity, frequently causing significant livelihood losses for farmers, and negatively affecting public food safety and security. Vaccines provide an effective and profitable means for controlling most infectious livestock diseases, but remain underutilized. This study sought to assess the barriers and determinants of vaccination utilization for priority livestock diseases in Ghana.

Methods: We conducted a mixed-method study involving a quantitative survey with ruminant livestock farmers (N=350) and seven focus group discussions (FGD) involving 65 ruminant livestock farmers. The survey data were analyzed, and distribution of barriers to vaccination access described. We evaluated the determinants of vaccination utilization (any use of vaccination against contagious-bovine-pleuropneumonia (CBPP) and peste-des-petits-ruminants (PPR) in 2021) using logistic regression analyses at the 0.05 significance level. FGD transcripts were analyzed deductively. We used triangulation to achieve convergence across the different datasets and analyses.

Results: The farmers kept an average (median) of 2.5 tropical livestock units (TLUs) of ruminant livestock (IQR=1.3–7.0) that were on average 8 kilometers (IQR=1.9–12.4) away from professional veterinary officers (VOs). Only 16% (56/350) of herds were vaccinated against the diseases. Most farmers (274/350) had limited knowledge on vaccines against CBPP and PPR infections, 63% (222/350) perceived low risk of these diseases to their herds. About half of farmers reported experiencing outbreaks of either disease in the study year (2021). Farmers scored on average 80.5 out of 98 (IQR=74–85) on the RS-14 resilience scale. After adjusting for farmers' livestock rearing experience, herd size, sex, wealth status, distance to VOs, previous disease outbreaks, and perceived risk of the diseases, vaccination utilization was negatively associated with limited knowledge (aOR=0.19, 95%CI=0.08–0.43), and positively associated with personal exposure to outbreaks in the study year (aOR=5.26, 95%CI=2.01–13.7) and increasing resilience (aOR=1.13, 95%CI=1.07–1.19). FGDs revealed farmer misconceptions about vaccines, costs of vaccines, and timely access to vaccines from VOs as additional barriers.

Conclusions: Acceptability, affordability, accessibility, and availability of vaccine services represent the main barriers to vaccines utilization by ruminant livestock farmers in Ghana. Given that limited knowledge regarding the value of vaccination and shortfalls in veterinary service supply are of central importance for both the demand and supply side, more collaboration between the different stakeholders in a transdisciplinary manner to effectively address the low vaccination utilization problem is needed.

Keywords: Livestock, Livestock diseases, Livestock farmers, Vaccination access

5.2 Introduction

The production in the livestock sector accounts for about 40% of the agriculture sector's gross domestic product in West Africa; the main species reared being ruminants (cattle, sheep, and goats) and poultry (OECD and ECOWAS, 2008). Ruminants are mostly domesticated mammals with digestive systems that depend on pre-gastric retention of digesta associated with fermentation of plant materials by symbiotic microorganisms (Stover et al., 2016). Mobility in search for optimal grazing resources for the animals, known as transhumance, is an essential part of livestock farming, particularly for cattle farmers. Although these animal movements can be predicted due to their seasonality, the national borders have not been able to adequately prevent unapproved animal movements in the region. Thus, there is a high level of interaction between the transhumance and local herds, leading to the frequent introduction and spread of pathogens across borders (Motta et al., 2017; Apolloni et al., 2019).

Livestock diseases impose significant costs on the livestock sector through animal deaths, disease control costs, and restrictions on animal trade (Grace et al., 2015; Nuvey et al., 2022a). At the individual farmer level, the diseases cause significant livelihood losses for households (Pradère, 2014; Huntington et al., 2021), affecting their domestic food security (Dominguez-Salas et al., 2019; Nuvey et al., 2022b), and psychosocial wellbeing (Mort et al., 2005; Nuvey et al., 2020). While the public is affected by potentially unsafe livestock products entering the food chain, due to the misuse of antimicrobials in livestock production (Kimera et al., 2020; Mshana et al., 2021), and heightened food insecurity from a reduction in the productivity of diseased animals (Herrero et al., 2013). For the most part, the livestock diseases with the most severe impact are transboundary in nature (Islam et al., 2013; Clemmons et al., 2021). These transboundary diseases are highly contagious animal diseases, whose epidemiology may differ across countries; they occur mainly as epidemics, but could also become endemic in the ecosystems of affected countries (Otte et al., 2004). In the West African region, the diseases with the highest impact on countries includes Newcastle disease (ND) in poultry, peste-des-petits-ruminants (PPR) in sheep and goats, contagious bovine pleuropneumonia (CBPP) in cattle, and African swine fever (ASF) in pigs (Otte et al., 2004; Fadiga et al., 2013b).

In Ghana, the livestock sector provides employment for about 10% of the country's population, with about 20% of livestock holders being women. About 80% of livestock farmers are rural dwellers, who keep 60% of the 18 million heads of livestock (GSS, 2021a). Livestock production is dominated by smallholder farmers practicing the extensive system of rearing. Aside from poultry (74%), ruminant livestock rearing constitute the other significant proportion (21%) of livestock holdings of households engaged in livestock production (GSS, 2020a). The livestock sector in Ghana similar to other countries in the West African region, faces challenges with transboundary animal diseases. In a previous study, the livestock farmers and veterinary service providers identified FMD and CBPP in cattle, and PPR and Mange in sheep and goats as priority diseases affecting ruminant livestock productivity, causing an average of 10% (and up to 70%) of herd losses per year. The farmers mainly use treatment services for managing diseases, most of which service is provided by informal persons who are not supervised by the veterinary system or the treatment is done by farmers themselves. In addition, the medicines applied by the farmers are not useful for the conditions treated in most cases (Nuvey et al., 2023c). An effective control of these priority livestock diseases is therefore critical to sustaining the livelihoods and wellbeing of farmers on one hand, and the food safety and security of the population on the other hand.

Preventive veterinary services particularly vaccination have been shown to be both effective and profitable in controlling livestock diseases (Charlier et al., 2022; Nuvey et al., 2022a). However, vaccines supply and utilization rates by farmers in many sub-Saharan African countries including Ghana remain very low (Donadeu et al., 2019;

OIE, 2019a). Among the reported priority diseases: FMD and CBPP in cattle, and PPR and Mange in sheep and goats based on previous research in Ghana (Nuvey et al., 2023c), only CBPP in cattle and PPR in sheep and goats have approved vaccines by the veterinary system in Ghana for their control (Diop et al., 2011). We therefore sought in this study to identify ways to improve the utilization of these vaccines by farmers to mitigate the occurrence and impact of these priority diseases. Identifying the barriers and determinants of farmers' utilization of vaccination services in the Ghanaian context is needed, to inform policy actions towards achieving this goal.

5.3 Materials and methods

Description of study area

The study was conducted in the Mion, Pru East and Kwahu Afram Plains South (KAPS) Districts, which are representative of the northern, middle and southern farming belts of Ghana. The three districts lie in the Guinea Savannah, Transition and Deciduous forest Vegetation zones respectively that are the main livestock production zones in Ghana (GSS, 2014b, c, a) (**Figure 5**). Ghana has a population of 31 million people; with a sex ratio of 97 males for every 100 females, of which about 60% are economically active. A higher share of males (64%) than females (53%) engage in economic activity in the country. Unemployment rate is 13% among the economically active population (GSS, 2021a). The annual average household per capita income is GHC 11,694 (USD 1949) [GHC is Ghanaian Cedis: USD 1 ≈ GHC 6 at the time of the survey (Bank of Ghana, 2021)]; with significantly higher per capita income for urban dwellers [GHC 16,373 (USD 2729)] compared to rural dwellers [GHC 5880 (USD 980)] (GSS, 2019). The agricultural sector contributes about 20% to the country's gross domestic product. For most households, agricultural activity mainly entail the cultivation of crops and livestock rearing (GSS, 2020b).

The selected districts are mainly rural and agrarian, with about one-third of the livestock holdings of households being ruminant species. The primary ruminant livestock species reared by farmers are cattle, sheep, and goats. The primary non-ruminant livestock species reared are poultry, pigs, and rabbits. The majority of the livestock rearing (53%) is for income generation – the rest is directly consumed by the household. The livestock production system is largely extensive and dominated by small-scale farmers (GSS, 2020a). In Ghana, vaccination services for livestock are provided mainly by professional veterinary officers (VOs), and is usually done from farm to farm. The VOs providing veterinary services including vaccination in rural areas, where livestock are usually reared, are mainly veterinary paraprofessionals with a diploma degree (equivalent to three years of training) in animal health as a minimum qualification. The VOs work under the direct supervision of district or regional veterinarians (usually with a doctor of veterinary medicine qualification) (Diop et al., 2011).

Study design

This was a cross-sectional study which employed a convergent parallel mixed-method research approach. This study design enabled us to conduct both quantitative and qualitative elements of the research project during the same phase of the research process. Although the analysis of data is conducted separately for each method, the results have equal weighting and are interpreted jointly (Creswell and Clark, 2018). We conducted a cross-sectional survey involving 350 ruminant livestock farming households, as well as seven focus group discussions (FGDs) involving 65 ruminant livestock farmers purposively selected within the study area. A household refers to a person or group of persons who normally live together and are catered for as one unit; members may or may not be related. Any member of the household who takes responsibility for the upkeep of the livestock kept by the household was eligible to participate in the study.

Study population

In the survey, we firstly obtained district maps and created a sampling frame of villages within the study area to be sampled for data collection. Based on the population and housing census data available prior to the study, there were about 80880, 54694, 47230 tropical livestock units (TLUs) of ruminant livestock species in the KAPS, Mion and Pru East Districts respectively, with an average of about 10 holdings per household. We randomly drew 15 villages in the KAPS District, and 10 villages each in the Pru East and Mion Districts, proportional to the number of livestock farming households per district (GSS, 2014b, c, a). From the selected villages, at least two persons were approached per village to participate in FGDs organized after the surveys in each study district. Seven FGDs were conducted involving 65 participants in the study area.

Sample size and sampling technique

The sample size was determined using Epi Info version 7 (Dean et al., 2011) with the following assumptions: Expected vaccination utilization rate of 10% was estimated based on previously reported vaccination utilization rates in the West African region (Dione et al., 2017; ElArbi et al., 2019). The acceptable margin of error was 5%, at a 95% confidence level. With an assumed average of eight subjects per cluster (m) and an intra-cluster correlation coefficient (ICC) of 0.2, the design effect of the study was 2.4 To reach a margin of error of 5%, a sample size of 350 livestock farmers was required. We recruited 350 livestock farmers from 38 villages using random segmentation. In villages where sufficient households were not realized, the adjoining village was selected for sampling of the remainder of households missed. For the FGDs, we used a purposive sampling approach to recruit farmers during the survey in each district. The farmers who consented to participate in FGDs in the three districts were 65.

Data collection and data management

The enumeration team visited the households rearing ruminant livestock in their homes to conduct the survey between November 2021 and January 2022. The survey questionnaires were administered to the respondents' face-to-face in one of four Ghanaian languages (English, Akan, Dagbani or Ewe) using tablets with Open Data Kit (ODK) application. The survey instruments collected data on farmers' previous and current history of experiencing outbreaks of the priority diseases (CBPP and PPR) in herds, perception of the risk of the diseases to herds, utilization of vaccination services, barriers to service utilization, knowledge of vaccines to protect herds against the diseases, and other socio-demographic characteristics of the participating farmers. Knowledge level was assessed based on farmers' responses to questions on the vaccines' functions and effectiveness, required frequency of use, protection offered to animals, and places to acquire the vaccines when needed. Correct responses yielded a score of 1 while wrong responses yielded a score of zero (0). Perception of the diseases risk to herds was assessed on a five-item Likert scale with responses ranging from 1 to 5; higher scores denote higher risk perception of the diseases to a herd, one item's score (Q4) is reversed to achieve a similar direction of perception score (**Additional file 1**).

The FGDs were conducted during the same period at designated venues in the study districts using a paper-based interview guide, and the FGD sessions were recorded using an audiotape. The farmers discussed in the FGDs their experiences with the outbreaks of the priority diseases, awareness of vaccines for protecting herds against the priority diseases, vaccine utilization and effectiveness in protecting livestock, main constraints of vaccination access and utilization, and the potential measures to improve vaccine uptake.

The survey data were downloaded in Microsoft Excel format from ODK and imported into Stata version 16 (StataCorp, 2019) for analyses. The interview audio recordings from the FGDs were transcribed verbatim in English, and the transcripts were imported into NVivo software version 12 (QSR International Pty Ltd., 2018) for analysis.

Data analyses

We performed descriptive analyses of the survey data, comparing the distribution of farmers' responses by study district. The farmers' herd sizes were converted to tropical livestock units (TLU) to standardize livestock holdings as follows: 1 TLU corresponds to 0.75 cattle and 0.1 small ruminants (sheep and goats) (Rothman-Ostrow et al., 2020). We determined the relative wealth of households using an index of a household's ownership of selected assets, such as televisions, refrigerators and bicycles (ICF, 2019). Resilience was assessed using the Resilience scale (RS-14) (Wagnild, 2009). The RS-14 is a 14 item Likert-scale with scores ranging between 1 and 7, and higher scores indicative of higher resilience. We used the median split approach to categorize knowledge and perception scale scores (Iacobucci et al., 2015), with scores above the median corresponding to good knowledge and good perception respectively, and lower scores otherwise. We adapted the access framework proposed by (Obrist et al., 2007), for each of the reported barriers to vaccination utilization, to determine the applicable dimension of access they fit. Based on the observed distribution in each dimension, we could determine the access dimension(s) to be prioritized for interventions to improve vaccination utilization by ruminant livestock farmers. We compared the access dimension distribution among the households by study district.

In a pre-specified model, we evaluated the relationship between vaccination use (any use of vaccination in the past 12 months) to protect livestock against contagious bovine pleuropneumonia (CBPP) and peste-des-petits-ruminants (PPR), and farmers' sex, herd size, wealth status, resilience level, experience with livestock rearing, distance to VOs, perception of the diseases risk to herds, previous and current history of outbreaks of the diseases in herds, and knowledge level of vaccination against the diseases, adjusting for clustering at the village level, at the 95% confidence level in a logistic regression model. We presented crude (cOR) and adjusted odds ratios (aOR) with their respective 95% confidence intervals (CI) for univariable and multivariable analyses respectively.

The analysis of FGD transcripts was performed from a social constructivism viewpoint, as we understood agricultural (livestock) production to entail the social and cultural creations of those involved. We sought to find convergence on farmers' perception of the risk of the priority diseases to their herds, level of knowledge on vaccination against the diseases, the challenges that farmers face in accessing vaccination services, and to identify ways to address these challenges to improve vaccination uptake. We conducted thematic analysis of the transcripts deductively, by generating codes and categories from the raw transcript texts, based on the study objectives. We present the results as narratives supported by verbatim quotes with clarification phrases where required for quotes, placed in square brackets.

5.4 Results

Characteristics of the study respondents

Table 7 presents a summary of the obtained household survey data in the study area. On average (median), farmers participating in the survey (N = 350) were 45 years old (IQR = 35 to 54). The farmers reported rearing livestock for an average 9 years (IQR = 6 to 15), with households keeping on average of 2.5 TLUs of ruminant livestock (IQR = 1.3 to 7.0); including cattle, goats, and sheep in their herds. More than two-thirds (71%) of the farmers were male. The farmer households were 8 kilometers (IQR = 1.9 to 12.4) away from the professional veterinary officers (VOs) on average. Households' wealth index differed significantly between study districts (p<0.001), with Mion (59%) and Pru East (69%) Districts having the highest proportion of the poorest and least poor households respectively. Furthermore, the farmers scored an average resilience score of 80.5 out of 98 (IQR = 74 to 85), with the average resilience scores highest in the Mion District (82.5), and lowest in the KAPS District (78.0).

Table 7 also shows that the farmers scored an average of 19 out of 25 (IQR = 17 to 21) on the perception scale, and 3 out of 5 (IQR = 2 to 3) on the knowledge scale. Only 22% (76/350) of the farmers had good knowledge of vaccines (score above the median knowledge score) to protect their herds against contagious bovine pleuropneumonia (CBPP) and/ or peste-des-petits-ruminants (PPR) infections. Also, only 37% (128/350) of the farmers perceived a high risk of CBPP and/or PPR infections to their herds. About 47% (164/350) of households experienced either CBPP (49%, 43/87) or PPR (46%, 155/338) outbreaks in the study year.

The farmers participating in the focus group discussions (FGDs) (N = 65) reared on average 3.6 TLUs (IQR = 1.7 – 25.5 TLUs) of ruminant livestock per herd. Most of the participating farmers were male (85%), and about (60%) of the farmers had at least some basic formal education.

Utilization of vaccination services against priority diseases

We found that only 18% (65/350) of households had ever vaccinated their herds against CBPP and/or PPR before the study year. In the study year (2021), only 16% (56/350) of farmers had vaccinated their herds against these priority diseases (**Table 7).** The previous and present vaccination utilization rates were significantly different between the study districts (p<0.001).

Table 7: Summary of data collected from household survey by study district (N = 350)

Characteristic		**KAPS**	**MION**	**PRU EAST**
Socio-demographic characteristics	**n**	**Median (IQR)**	**Median (IQR)**	**Median (IQR)**
Livestock farming experience (years)		9 (5.0 – 16.0)	10 (6.0 – 17.0)	9 (5.0 – 15.0)
Distance to veterinary service (km)		12.0 (8.0 – 14.4)	6.9 (1.6 – 12.7)	1.9 (0.6 – 5.6)
Resilience level		78 (73.0 – 84.0)	82.5 (78.0 – 87.0)	81 (75.0 – 86.0)
Knowledge of CBPP and/or PPR vaccines		3 (2.0 – 4.0)	3 (3.0 – 3.0)	3 (3.0 – 4.0)
Perception of CBPP and/or PPR disease risk		19 (17.0 – 21.0)	18 (17 – 20)	18 (16.0 – 21.0)
		% (n/N)	**% (n/N)**	**% (n/N)**
Sex				
Female	102	38% (57/149)	16% (16/98)	28% (29/103)
Male	248	62% (92/149)	84% (82/98)	72% (74/103)
Wealth status quintiles				
Poorest	70	14% (21/149)	42% (41/98)	8% (8/103)
Below average	74	28% (41/149)	26% (25/98)	8% (8/103)
Average	66	24% (36/149)	14% (14/98)	15% (16/103)
Above average	70	25% (37/149)	10% (10/98)	22% (23/103)
Least poor	70	9% (14/149)	8% (8/98)	47% (48/103)
Herd size (Tropical Livestock Units)				
Small (1st tertile: 0.3 – 1.6 TLUs)	127	42% (62/149)	43% (42/98)	23% (24/103)
Medium (2nd tertile: 1.7 – 4.2 TLUs)	107	31% (46/149)	24% (24/98)	35% (36/103)
Large (3rd tertile: 4.3 – 181.9 TLUs)	116	27% (41/149)	33% (32/98)	42% (43/103)
Utilization of CBPP and PPR vaccination[a]				
Past herd vaccination against CBPP and/or PPR	65	29% (43/149)	13% (13/98)	9% (9/103)
Current herd vaccination against CBPP and/or PPR	56	4% (6/149)	14% (14/98)	35% (36/103)
History of CBPP and/or PPR outbreak in herds[b]				
Previous history of CBPP and/or PPR outbreak	159	35% (52/149)	48% (47/98)	58% (60/103)
Present history of CBPP and/or PPR outbreak	164	31% (46/149)	41% (40/98)	76% (78/103)

Percentages (%) are the proportion of ruminant livestock farmers within each characteristic explored per study district sub-sample (N). Numbers (n) of households, falling into each sub-category of assessed characteristics within the study districts; KAPS: households from the Kwahu Afram Plains South District, MION: households from the Mion District and PRU EAST: households from the Pru East District in Ghana. For continuous variables, the median with corresponding lower and upper quartile values are reported in parentheses. CBPP denotes contagious bovine pleuropneumonia infection in cattle, and PPR denotes peste-des-petits-ruminants infection in sheep and/ or goats. [a] For the utilization of CBPP/PPR vaccinations, non-use of the vaccines by a household in the past years (before 2021) and non-use of the vaccines in the study year (2021) were the reference categories respectively in each case. [b] For the herd history of CBPP/PPR outbreak, non-experience of an outbreak in herd in the previous years (before 2021) and non-experience of an outbreak in the study year (2021) were the reference categories respectively.

We present the determinants of current vaccination utilization by the farmers in **Table 8**. In our pre-specified univariable models, we found positive associations between farmers utilizing vaccination and years of experience with livestock rearing (cOR = 1.04, 95% CI = 1.01 – 1.08, p=0.02), farmers' resilience (cOR = 1.12, 95% CI = 1.06 – 1.18, p<0.001), herd size (cOR = 2.34, 95% CI = 1.59 – 3.44, p<0.001), male sex (cOR = 2.10, 95% CI = 1.01 – 4.33, p=0.04), wealth status (cOR = 1.58, 95% CI = 1.27 – 1.98, p<0.001), and previous (cOR = 3.68, 95% CI = 1.96 – 6.87, p<0.001) and current history (cOR = 5.32, 95% CI = 2.70 – 10.5, p<0.001) of disease (CBPP and/or PPR) outbreak in a herd. There was a negative association between vaccination use and distance between the livestock farming households and VOs (cOR = 0.90, 95% CI = 0.86 – 0.95, p<0.001), perception of low risk of CBPP and/or PPR infection to herds (cOR = 0.47, 95% CI = 0.27 – 0.84, p=0.01), and limited knowledge of CBPP and/or PPR vaccines (cOR = 0.18, 95% CI = 0.10 – 0.33, p<0.001).

After adjusting for the covariates described above, we found positive associations between vaccination use and farmers' resilience (aOR = 1.13, 95% CI = 1.07 – 1.19, p<0.001), and personal experience of an outbreak of the diseases (CBPP and/or PPR) in the study year (aoR = 5.17, 95% CI = 1.96 – 13.7, p<0.001). Farmers' with limited knowledge of vaccines were less likely to use was vaccination services to protect their livestock herds against the diseases (aOR = 0.18, 95% CI = 0.07 – 0.42, p<0.001).

Table 8: Determinants of livestock farmers' utilization of vaccination services against priority ruminant livestock diseases in Ghana

	Unadjusted model		Adjusted model	
Variables	**cOR (95% CI)**	**P-value**	**aOR (95% CI)**	**P-value**
Livestock farming experience (years)	1.04 (1.01, 1.08)	0.02	1.02 (0.97, 1.08)	0.40
Distance to veterinary service (km)	0.90 (0.86, 0.95)	<0.001	0.93 (0.85, 1.01)	0.08
Resilience level	1.12 (1.06, 1.18)	<0.001	1.13 (1.07, 1.19)	<0.001
Herd size (TLU)				
Small (1st tertile)	ref		ref	
Medium (2nd tertile)	2.01 (0.83, 4.85)	0.12	0.94 (0.35, 2.52)	0.90
Large (3rd tertile)	5.26 (2.39, 11.6)	<0.001	1.34 (0.45, 3.99)	0.60
Sex				
Female	ref		ref	
Male	2.10 (1.01, 4.33)	0.04	1.43 (0.63, 3.24)	0.39

Wealth status				
Poorest	ref		ref	
Below average	0.94 (0.31, 2.83)	0.91	1.61 (0.47, 5.77)	0.45
Average	1.07 (0.35, 3.23)	0.91	1.26 (0.35, 4.53)	0.73
Above average	1.33 (0.47, 3.79)	0.60	1.03 (0.27, 3.94)	0.96
Least poor	5.32 (2.12, 13.3)	<0.001	2.51 (0.84, 7.51)	0.10
Herd history of CBPP/PPR outbreak*				
History of CBPP/PPR outbreak in herd	3.68 (1.96, 6.87)	<0.001	1.16 (0.48, 2.81)	0.74
Present (2021) CBPP/PPR outbreak in herd	5.32 (2.70, 10.5)	<0.001	5.17 (1.96, 13.7)	0.001
Knowledge of CBPP and/or PPR vaccines				
Good	ref		ref	
Limited	0.18 (0.10, 0.33)	<0.001	0.18 (0.07, 0.42)	<0.001
Perception of CBPP and/or PPR disease risk				
High	ref		ref	
Low	0.47 (0.27, 0.84)	0.01	1.76 (0.95, 3.24)	0.07

Variables included as predictors of the current utilization of professional veterinary services by livestock farmers in Ghana. Crude odds ratio (cOR) with 95% Confidence Intervals (CI) and the associated *p*-values for the unadjusted model and adjusted odds ratio (aOR) with 95% CI and the associated *p*-values for the adjusted model, accounting for clustering during sampling of respondents. 'ref' denotes the reference category. ***** For the herd history of CBPP/PPR outbreak, non-experience of an outbreak in a household's herd in the past years (before 2021) and non-experience of an outbreak in the study year (2021) were the reference categories respectively in each case.

In the FGDs we similarly found that farmer knowledge of vaccination against these priority diseases and self-conviction or willingness to protect assets (resilience), influences greatly the utilization of vaccination services. Thus, mere provision of information about vaccination availability to the farmers is not sufficient. There are also significant misconceptions about vaccine effectiveness, particularly during an active disease outbreak. Thus, farmers generally only seek to protect their animals when they hear about or experienced the disease outbreaks.

> *"For me I have only heard about the vaccine that prevents CBPP... I know that it will be good for us to take that CBPP vaccine, but if the disease [CBPP] is already in the kraal [an enclosure or pen where the farmers' animals or herd is kept] and you go ahead to vaccinate them, it would kill most of them. So, for me, I have stopped vaccinating my cattle, because if they are already infected and you vaccinate [them], some may die."* **(Male farmer, 46 years old, KAPS District)**

> *"Some time back, the veterinary officer reached out and explained to us about the vaccine that could protect our animals before the disease [PPR] comes. During that time when he [veterinary officer] said that, I also vaccinated my animals…, it protected them against the disease [PPR]."* ***(Male farmer, 40 years old, Pru East District)***

> *"I also do similar as she [another farmer participant] said. If the disease doesn't infect your animals…, even if the veterinary officer is talking about vaccinating them against the disease, you are not too worried about it. But when you see the infection with your own eyes [pauses]... For me, I don't normally do it unless I see that the disease has infected them… Even when he [veterinary officer] brings the vaccines and asks us to vaccinate the animals, most of the farmers don't take it seriously. We'll hear the announcement that we should mobilize ourselves to come and vaccinate our animals, but we don't take it seriously… So, we the farmers; we do not have that spirit [willingness] to vaccinate our animals."* ***(Male farmer, 59 years old, KAPS District)***

Despite the low patronage of vaccination services, we found that many of the farmers that utilize the vaccination services mostly had positive outcomes of protection for their animals, comparing those with and without vaccination use. Few farmers reported negative outcomes.

> *"With that medicine [vaccine], if you inject the animals before the disease [PPR] comes, it [vaccine] protects them from being infected by the disease, and also from dying from it. But now that we don't inject them with that medicine [vaccine] before it [PPR] comes, it kills many of our animals."* ***(Male farmer, 54 years old, KAPS District)***

> *When he [veterinary officer] vaccinates them [sheep and goats] against the diarrheal disease [PPR], and there is an outbreak, to be honest, even if the animal is infected, it won't die. And the phlegm [mucous discharge] that comes out of their head [via nostrils], is reduced. At times, when the disease comes, it often doesn't affect them. And even if they get infected by it, it takes only about two to three days and then it resolves. So, it [vaccine] protects them [sheep and goats] against the different kinds of diseases that*

we mentioned. So, as for the vaccination, it is very very important, ahaa.” ***(Female farmer, 46 years old, KAPS District)***

*“Vaccinations are usually very helpful; they protect the animals very well against those diseases [CBPP and PPR]. Even when you’re doubtful whether there is an outbreak among your animals or not, and you call for vaccination, only those animals which have already contracted the disease are badly affected, and those vaccinated before contracting the disease are usually safe.” (**Male farmer, 41 years old, Mion District)**.*

“What I observed is that the older ones [bucks, does, ewes, and rams] that I vaccinated were not affected by the disease [PPR] when it came. But the young ones [kids and lambs] that were given birth to afterwards, it was not yet time for them to be vaccinated, so they were the ones that the disease normally infected...” ***(Male farmer, 32 years old, Pru East District)***

Barriers to the utilization of vaccination services

We applied the access framework proposed by Obrist et al. 2007, to identify the barriers to farmers accessing vaccination services against infectious livestock diseases in general. Our results showed that the main bottlenecks were in the acceptability (59%), affordability (53%), accessibility (42%), and availability (34%) dimensions of the access framework (**Table 9**). The barriers were somewhat district specific. The proportion of households reporting challenges for each dimension was highest in the KAPS district in all the dimensions except for affordability (**Figure 11**). Affordability as a barrier was highest for farmers in the Pru East District (63%), compared to the other districts. The Mion District had acceptability as the main barrier (64%). In the KAPS District, accessibility was the main barrier (69%), followed by acceptability (64%), availability (60%), and affordability (56%). Adequacy was not much of a barrier for the farmers. We also found the barriers to vaccination access to be gendered; whereby the proportion of female farmers reporting barriers to access was higher in all dimensions compared to males. We did not find marked differences in barriers to access stratified by age categories and marital status of the farmers (**Additional file 2**).

Table 9: Barriers to households' access to vaccination against ruminant livestock diseases

Access dimension	Measure	Proportion
Acceptability	Information on service is unaligned with values and practices of users Service is not perceived by users as valuable to livestock farming	59% (210/350)
Affordability	Users had inadequate funds (money) to use the service when provided Users had inadequate time to participate when services were provided	53% (187/350)
Accessibility	Service provider is distant (far) from the users Service provider is unreachable to users when service was needed	42% (148/350)
Availability	Service is unavailable with the provider when required by the user Service offered by the provider is insufficient to meet the user's needs	34% (119/350)
Adequacy	Quality of service provided did not meet the user's expectation User is dissatisfied with the attitude of service provider	4% (17/350)

Measures depict the indicators obtained in survey as barriers to service utilization. Service refers to vaccination against contagious bovine pleuropneumonia (CBPP) in cattle, and/or peste-des-petits-ruminants (PPR) infection in sheep and/ or goats. Service providers are public employed veterinary officers delivering veterinary services in study districts. Users are ruminant livestock farming households (rearing any of cattle, sheep and or goat) in the study districts. Prevalence denotes the proportion of households reporting at least one of the indicators as barriers to their access to vaccination in any given farming year.

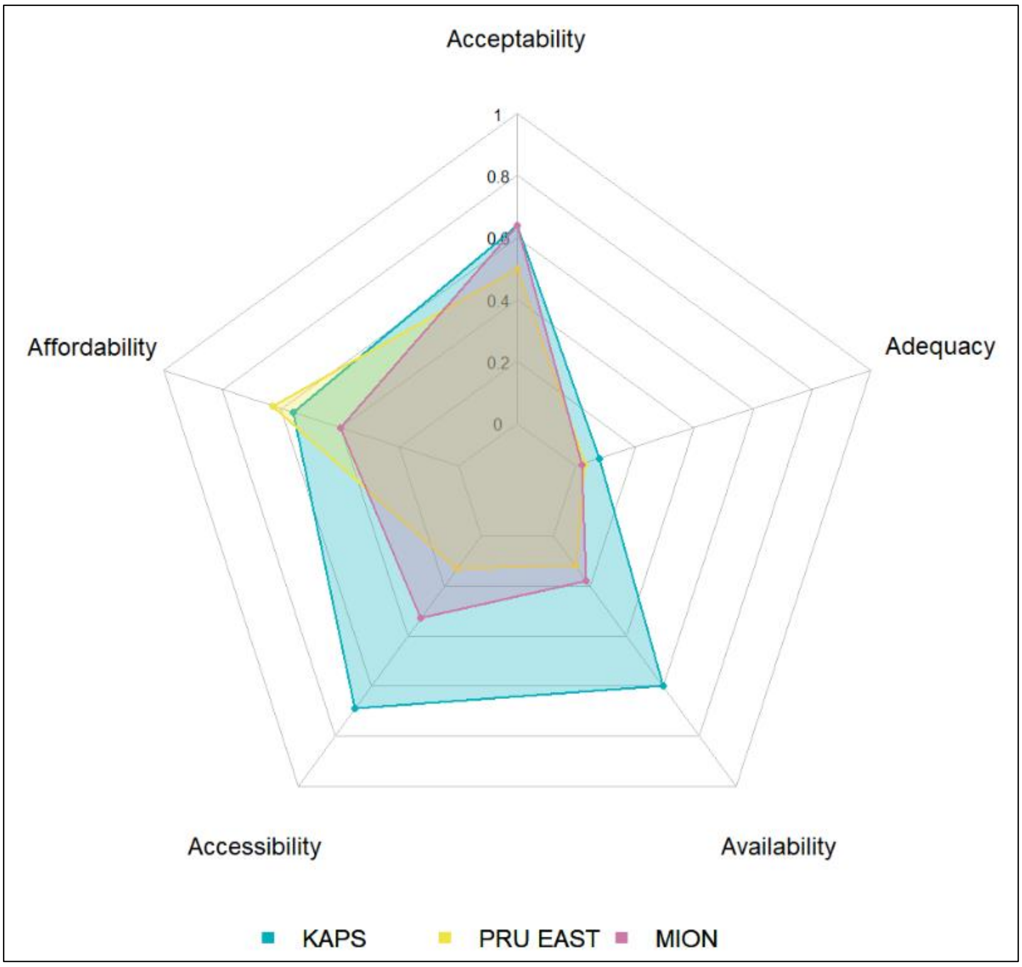

Figure 11: Access dimensions influencing vaccination utilization by livestock farmers in Ghana by district.

The figure shows the access dimensions influencing farmers' utilization of vaccination services against infectious diseases in livestock in Ghana. The color differences depict each study district. The point positions on the radar chart corresponds to the proportion of farmers reporting barriers that fall within each of the access dimensions.

The discussions with the farmers similarly affirm the demand side barriers of acceptability and affordability. Farmers frequently do not consider vaccination against infectious diseases as a part of livestock farming. Even when the farmers are informed and willing to utilize vaccination, the requirement by VOs to have sufficient animals per vial of vaccine [100 cattle for CBPP, and 50 sheep or goats for PPR] before vaccine vials are administered, is a disincentive for farmers whose herds are not sufficiently large, unless they can get other farmers to participate or offer to pay for the unused doses of vaccines. There are also farmers who nevertheless, do not consider vaccination a priority enough to spend their resources on it. In the study year, average vaccination costs per animal were GHC 6 (USD 1) and GHC 5 (USD 0.83) for CBBP and PPR respectively.

"…If the animal is not sick, why should I spend my money to vaccinate the animal? Myself sitting here, I'm sick, and I need money to treat myself [laughs], and to talk of the animal. If the animal gets infected by the disease [PPR] today, I don't have money, so why should I use money to vaccinate an animal that is not ill [diseased]. How about me myself?" ***(Male farmer, 40 years old, KAPS District)****.*

"Majority of us have no education on the importance of preventive veterinary services like vaccination… Some farmers do think their cattle are healthy and need no treatment. So, when the time comes and the veterinary people [officers] talk about that [vaccination], it appears as though they [veterinary officers] are basically trying hard to make money from us the farmers rather than the intended protection the veterinary officers' vaccination would offer against animal losses. It's a big challenge." ***(Male farmer, 41 years old, Mion District)****.*

"I remember that some time ago an announcement was made that we should come together as livestock farmers for a vaccination exercise. They said that, when a vial of vaccine is opened, unless he [veterinary officer] uses all [vaccine doses] in a day. We were told that for some of the medicine [vaccine], it must be used to inject hundred (100) animals [cattle] and for others, fifty (50) animals [goats and sheep]. So, as we were thinking about it, whether to participate, someone [a farmer] was saying that the veterinary officer had gone to buy his medicines that he was planning to come and sell…, but because they were about to expire; and he doesn't know what to do with them, that was why he wanted to come and inject our animals. It made some of us who were willing then to vaccinate our animals to have a change of mind. So that is part of the reasons why some [farmers] don't vaccinate their animals before the diseases come." ***(Male farmer, 37 years old, KAPS District)***

"Usually, the veterinary officers come to inform us about these vaccines. But when you go to ask them [veterinary officers], they tell you that after opening the vaccine vial, he needs to inject a lot of the animals at a go, from one animal to another until the vial is finished, so it doesn't go to waste..., It can be that on a date [scheduled] we all agreed to inject [vaccinate] our animals,

maybe your friend [farmer] does not have the money to do it,…, so he [veterinary officer] would not be able to administer it [vaccine] to your animals" ***(Male famer, 60 years old, Pru East District)***

Aside the demand side barriers, some farmers also reported supply side barriers regarding the accessibility, availability, and adequacy of the vaccination services offered.

"Sometimes, even if one [a farmer] gets the money today [for vaccination] but is not able to access the veterinary officers, you will end up spending the money. Later when they [veterinary officers] show up, what can you do? You will not be able to participate in the vaccination for the animals." ***(Female famer, 46 years old, Mion District)***

"In times past, the veterinary officers would come around to vaccinate our animals yearly. But nowadays it is no longer so…, in fact because the veterinary officers are few, we don't get them [animals] vaccinated regularly… Because we don't get the vaccines on time… You need access to the vaccine every year to give them [animals], so you can protect them. By the time the next vaccination period is approaching, the veterinary officer would say he is going to Accra [360km from district] to get the vaccines, so organize yourself and get other people to also take the vaccine. But where am I going to get them? Maybe the other farmer is doing something on his own and I also on my own. But if it was possible that if you have only 20 cattle, the veterinary officer can just vaccinate your animals and do similar for other farmers, then all the time we could vaccinate to protect them [animals]. But we don't get it that way." ***(Male farmer, 46 years old, KAPS District)***

"For me I have a veterinary man [officer] who usually treat my animals for me. So maybe on the day the veterinary officers come for a vaccination exercise, I may have already spent the money on treating the animals or the veterinary man who sees my animal is not part of the exercise…, so therefore I would not be able to participate in the vaccination." ***(Male farmer, 53 years old, Mion District)***

The farmers argued that increased community engagements by VOs on the value of vaccinations and discounting of vaccination costs, and legislation by local authorities, as well as community mobilization by farmers, would improve vaccination adoption and use.

> *"When there is a vaccination exercise, we only want to have the information about the exercise in good time. The veterinary officers should give the scheduled times that they would always call on us for education on the vaccination exercises. When veterinary officers organize it and get us involved, then we can spread the message among ourselves… I believe that if the education is done on media platforms like radio and television, it would be great. Because even if a farmer is not able to get the time to listen to the education, at least some people in the community who are fortunate to follow the discussion on the media platform, can share what they heard or learnt for others to benefit as well. If that is done, all the farmers who never paid attention to vaccination would bring back their attention and enhance the patronage…. Because for example, if I know the importance [of vaccination] and I have to vaccinate my animals against a disease and I have 3 animals, I can sell one to cater for [protect] the other two."* ***(Male farmer, 41 years old, Mion District)***

> *"Nowadays you can't get the medicine [vaccine] free [like in the past]. But they [veterinary officers] should give us a moderate price. If the price is moderate, we can easily afford... So, if government can help us so that the medicine [vaccine] will come; and if every year, we are supposed to pay a certain amount of money to the government so that they [veterinary officers] will vaccinate our animal for us, that is better. For you to pay money, for your animal to stay healthy, is better than when the diseases infect the animals, and you don't get money to buy medicines to treat them, then they all die. That would mean that we are working in vain. If we are able to pay something small every year, for them to come to inject the animals for us, I think that would help us."* ***(Male famer, 54 years old, KAPS District)***

> *"Like he [another farmer participant] said, I think we those livestock farmers living in one area [village], have to form a union or an association. So that when we have this group, then we could say, all those who have these kind*

of animals, we want to vaccinate the animals this year so that they are not infected by these diseases… When the association meets and decides on a particular date, then we can go and call the veterinary officer, for him to come and vaccinate our animals. When we join and there is understanding, it would help us all… Because when you leave your own animals and someone else vaccinates their own, the disease could infect your animals and could spread to other animals in the area, or in some cases, it could affect all of us.” ***(Female farmer, 62 years old, Pru East District)***

“I also do support the suggestion that it should be made compulsory that everyone undertakes the vaccination of their animals. I believe if we have a mandatory regulation that it is enforceable in the community,… so that if you don’t vaccinate your animals, you would be caught and sanctioned,…, you won’t be permitted to keep livestock, and your farm would be closed to serve as a deterrent.” ***(Male famer, 48 years old, KAPS District)***

5.5 Discussion

Infectious livestock diseases significantly reduce the productivity in the livestock sector, which negatively affects farmers’ livelihoods and wellbeing, and public food safety and security. Although vaccination has been shown to be effective and provide high returns on investment, farmers’ utilization of vaccination services for livestock diseases remain very low in many sub-Saharan African countries. In this study, we aimed to identity the barriers and determinants of farmers’ utilization of vaccination against priority diseases for the livestock sector in Ghana. We implemented a convergent parallel mixed-method design to achieve this goal. Our results suggest that the utilization of vaccination services by farmers is mainly influenced by the service costs, and farmers’ experience of disease outbreaks in herds, knowledge level of vaccines, and resilience to adversity and motivation levels.

Previous studies among livestock farmers in East Africa made similar findings, where factors including cultural norms, farmers’ knowledge of disease and vaccines, history of disease occurrence in herds, vaccine costs, and distance to vaccine sources influenced households’ utilization of vaccination services (Mutua et al., 2019; Mukamana et al., 2022; Williams et al., 2022). A study also showed that socio-cultural factors including age, sex, ethnicity, marital status, geographic location, physical ability and education influence access to vaccination in Uganda (Acosta et al., 2022). We found similar influences on vaccination access of sex, farmers' experience, wealth status, and distance to veterinary services in our unadjusted model. Although the acceptability, affordability, accessibility, and availability of vaccines mainly constrain farmers' access, the increased engagement of professional veterinary officers (VOs) with the farmers on the usefulness of vaccinations and discounting of vaccination costs as well as community mobilization, have been proposed to have the potential to improve uptake and utilization of vaccination services. In addition to these, farmers proposed implementation of legislation to compel participation. This approach however is likely to be counterproductive if awareness and confidence in vaccines are not improved first (Brewer et al., 2017).

Farmers' decision to utilize vaccination could be treated as a discrete choice problem based on the random utility theory (Hensher et al., 2005), whereby the utility a farmer derives from participating in a vaccination exercise would be the sum of the utility derived from the characteristics of the vaccination program. Thus, it is intuitive that all things being equal, improving farmers' awareness on vaccination as an effective and profitable control measure against infectious diseases could address most of the demand side barriers of access (acceptability and affordability). More so, we found the limited knowledge of the effectiveness of vaccines, particularly during active disease outbreaks as the main driver of farmers' misconceptions about vaccines and unwillingness to invest resources in vaccinating their herds during the FGDs. The farmers showed in the survey and FGDs that they were more knowledgeable particularly on where the vaccines for protecting the herds could be accessed and on the concept of herd immunity offered by vaccination.

Government subsidies are often used to incentivize adoption of vaccination in some contexts (Mongoh et al., 2008; China, 2017; Greenville, 2020; Roch and Conrady, 2021; EU Parliament, 2022). However, given the current resource constraints of the veterinary system in Ghana, we argue that public funding of such subsidies would not be possible currently to achieve optimal vaccination coverage. Moreover, previous research has showed that motivational risk communication strategies that increase farmer awareness and willingness are equally effective in increasing farmer vaccination uptake compared with the provision of financial compensation in the form of subsidies (Sok and Fischer, 2020). Future studies in Ghana could address the costing issue by evaluating farmers' valuation and willingness to pay for vaccines, to inform pricing policy that would incentivize use.

The main supply side barriers were related to availability of vaccines and accessibility of VOs to farmers when required, and could be addressed by increasing budgetary allocation to veterinary services, which would help reduce the human resource gap in the veterinary sector. The recent review of the performance of veterinary services of African countries showed that funding for operationalizing veterinary services was very poor for 78% of countries (OIE, 2019a). The public resource allocations to the veterinary system certainly have to be improved if the sector is able to attain its goals, particularly in disease control. In a recent review of the livestock vaccine supply chain, Acosta et al. (Acosta et al., 2019) argued that addressing farmer willingness to vaccinate through increased awareness creation alone, without a commensurate effort to address the supply side challenges would be ineffective in optimizing the vaccination coverage. This underscores the need for increased collaborative and transdisciplinary approaches, involving scientists, policy makers and communities, working together to address the key challenges.

The access framework proposed by (Obrist et al., 2007) also enables the evaluation of the equitability of people's access to health services. We found marked differences in the distribution of the barriers to access in the study districts. The Kwahu Afram Plains South (KAPS) District had a higher proportion of farmers reporting challenges in almost all the access dimensions. This could be explained by the relatively large veterinary workload in KAPS, more than two times that of the other districts. The veterinary livestock units, which is calculated by dividing the standardized total number of animal heads in tropical livestock units by the number of VOs was about 30000 in KAPS compared to about 11500 and 9000 in Mion and Pru East Districts respectively. The Veterinary Services Directorate in Ghana should thus endeavor to maintain an equitable distribution of the available staffing resources to districts.

Our study had some limitations. Despite our best efforts to obtain a representative sample of the different agro-ecological zones in Ghana, this study did not account for the two other minority agro-ecological zones namely the Evergreen and Coastal Savannah zones. Even though these zones are not typical areas for livestock production in Ghana, determining the barriers faced in their contexts would have improved the representativeness of our findings. In spite of this omitted perspective, we do not expect the parameters evaluated to be markedly different in these agro-ecological zones. Additionally, even though we relied mainly on reported information in this study, we believe that the triangulation of results from the different methods show validity of our instruments. Our study thus, has provided valuable information on the barriers and determinants of vaccination utilization in a developing country context, which would inform strategies to address low coverage of preventive vaccination in livestock.

5.6 Conclusion

Our study shows that limited knowledge of the effectiveness and profitability of vaccines, lack of timely access to vaccines and the cost of vaccination services discourage farmers' utilization of vaccination to protect their livestock herds against priority infectious diseases, while increased resilience to adversity as well as the experience of diseases in herds are positively associated with vaccination use. Thus, acceptability, affordability, accessibility, and availability of vaccine services represent the main access dimensions constraining vaccination adoption and use. Misconceptions about vaccines cannot be addressed by information provision of vaccine effectiveness alone. These strategies need to include thorough engagement with community members, and should be sensitive to gender issues relating to vaccination access. Farmer proposals with potential to address the problem would include increased engagement of communities by veterinary service providers on the value and effectiveness of vaccines, discounting of vaccination costs, and farmer community mobilization. Given that limited knowledge of the effectiveness of vaccination and veterinary services supply shortfalls in the districts drive the observed demand and supply side challenges respectively, greater collaboration between the different stakeholders in a transdisciplinary manner to effectively address the low vaccination utilization problem is needed.

5.7 Declarations

Ethics approval and consent to participate

The study was reviewed and approved by the Ghana Health Service Ethics Review Committee (approval number: GHS-ERC 006/09/20). In the study districts, permission was obtained from all the relevant authorities prior to field data collection. The study participants provided written informed consent and the data generated are kept as confidential records. All the methods in this study were carried out in accordance with relevant guidelines and regulations (such as Declaration of Helsinki).

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this published article, and its supplementary files.

Competing interests

The authors declare that they have no competing interests.

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Author contributions

Conceptualization, all authors; **methodology**, all authors; **validation**, G.F., J.H., G.I.M., K.K.A., B.B. and J.Z.; **formal analysis**, F.S.N.; **investigation**, F.S.N.; **resources**, B.B., J.H., J.Z. and G.F.; **data curation**, F.S.N.; **writing—original draft preparation**, F.S.N.; **writing—review and editing**, all authors; **visualization**, F.S.N., and J.H.; **supervision**, G.F., G.I.M., K.K.A., B.B. and J.Z.; **project administration**, F.S.N and B.B.; **funding acquisition**, K.K.A., B.B. and J.Z. All authors have read and agreed to the published version of the manuscript.

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5.8 Supplemental

Supplemental Appendix to

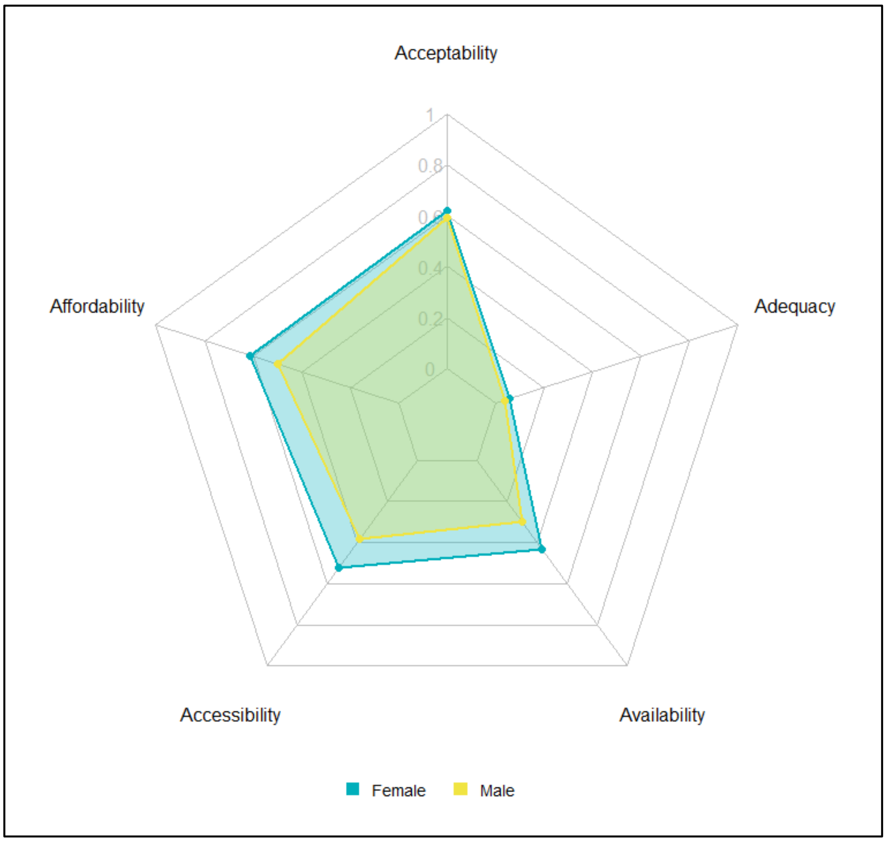
“Access to vaccination services for priority ruminant livestock diseases in Ghana: Barriers and determinants of service utilization by farmers”

Additional file 1: Survey instrument

The survey instrument can be accessed via the following link:

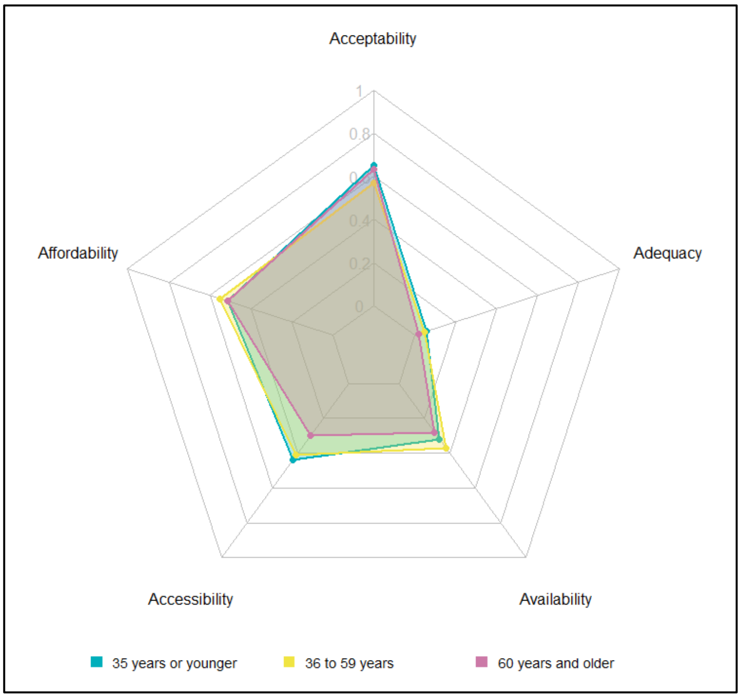
https://ars.els-cdn.com/content/image/1-s2.0-S0167587723000831-mmc1.xlsx

Additional file 2: Access dimensions influencing vaccination utilization by livestock farmers in Ghana



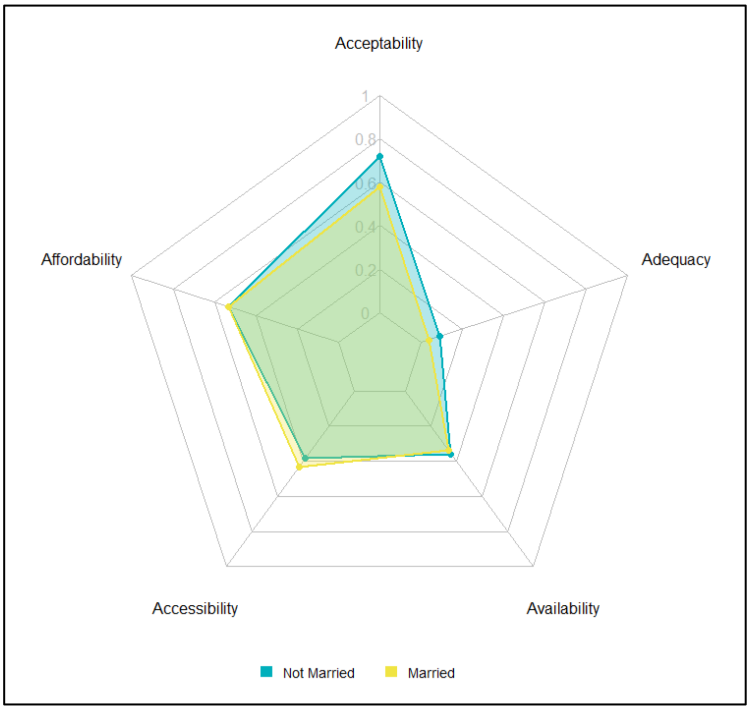
Access dimensions influencing vaccination utilization by livestock farmers in Ghana by sex.

The color differences depict each level (sub-category) of sex of the respondents. The point positions on the radar chart corresponds to the proportion of farmers reporting barriers that fall within each of the access dimensions.



Access dimensions influencing vaccination utilization by livestock farmers in Ghana by age.

The color differences depict each level (sub-category) of age of the respondents. The point positions on the radar chart corresponds to the proportion of farmers reporting barriers that fall within each of the access dimensions.



Access dimensions influencing vaccination utilization by livestock farmers in Ghana by marital status.

The color differences depict each level (sub-category) of marital status of the respondents. The point positions on the radar chart corresponds to the proportion of farmers reporting barriers that fall within each of the access dimensions.

Chapter 6 Farmers’ valuation and willingness to pay for vaccines to protect livestock resources against priority infectious diseases in Ghana

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6.1 Abstract

Introduction: Livestock vaccination coverage rates remain low in many lower and middle income countries despite effective vaccines being commonly available. Consequently, many preventable infectious livestock diseases remain highly prevalent, causing significant animal mortalities and threatening farmers' livelihood and food security. This study sought to assess farmers' maximum willingness to pay (WTP) for contagious bovine pleuropneumonia (CBPP), and peste-des-petits-ruminants (PPR) vaccination of cattle, and sheep and goats, respectively.

Methods: Overall, 350 ruminant livestock farmers were randomly selected from three districts located in the northern, middle and southern farming belts of Ghana. We implemented a double-bounded dichotomous contingent valuation experiment, where farmers indicated their WTP for vaccinating each livestock specie(s) owned at randomly assigned price points. WTP responses were analyzed using maximum likelihood estimation, and factors influencing WTP were assessed using censored regression analysis accounting for village-level clustering.

Results: Mean WTP for CBPP vaccination was USD 1.43 or Ghanaian Cedi (GHC) 8.63 (95% CI: GHC 7.08–GHC 10.19) per cattle. Mean WTP for PPR vaccination was USD 1.17 or GHC 7.02 (95% CI: GHC 5.99–GHC 8.05) per sheep, and USD 1.1 or GHC 6.66 (95% CI: GHC 5.89–GHC 7.44) per goat. WTP was positively associated with resilience, limited knowledge about vaccines (assessed prior to WTP experiment), farmland size, and male gender, after adjusting for other covariates. To attain 70% vaccination coverage in Ghana, vaccination costs should be no larger than GHC 5.30 (USD 0.88) for CBPP per cattle and GHC 3.89 (USD 0.65) and GHC 3.67 (USD 0.61), respectively, for PPR vaccines per sheep and goat.

Conclusions: Ruminant livestock farmers in Ghana value vaccination highly, and are, on average, willing to pay vaccination costs that exceed the prevailing market prices (GHC 6 for CBPP and GHC 5 for PPR vaccination) to protect their livestock resources. To achieve 70% coverage, only minor subsidies would likely be required. These results suggest that effective disease control in these settings should be possible with appropriate distribution strategies.

Keywords: Contagious bovine pleuropneumonia, Pestes-des-petits-ruminants, Stated preferences, Dichotomous choice contingent valuation, Willingness to pay, Vaccination, Ghana, Livestock farmer.

6.2 Introduction

Livestock production serves as a key livelihood source for many households in lower and middle income countries (LMICs). In many developing economies, livestock production is an essential component of public food security and economic growth. For farming communities, livestock is not only a food resource, but also an asset with potentially high returns that can be used to absorb economic shocks in difficult times (FAO et al., 2021; OECD and FAO, 2021). At the same time, livestock productivity is significantly hampered by infectious animal diseases, which are usually transboundary in nature (Clemmons et al., 2021; FAO et al., 2021).

In many countries in sub-Saharan Africa (SSA), transboundary animal diseases (TADs) are highly prevalent, causing significant herd mortality (Grace et al., 2015). Efforts by the veterinary system to address the disease risks have not been very effective to date, at least partially due to inadequate public and private investment in animal health services (Cheneau et al., 2004). To ensure their animals survival, farmers commonly use antimicrobials for treatment without professional veterinary advice (Alhaji and Isola, 2018; Nuvey et al., 2023c). In addition, veterinary medicines supply and use is poorly regulated. A recent review showed that 80% of countries in Africa lack the capacity to administratively control the registration, import and production, distribution and usage of veterinary medicines (OIE, 2019a). As a result, the overwhelming majority of farms use antibiotics on a regular basis (Kimera et al., 2020), contributing to antimicrobial residue contamination in food, and the development of related antimicrobial resistant pathogens (Kimera et al., 2020; Zinsstag et al., 2023a). In principle, effective control of infectious diseases can be achieved by rapid diagnostic tools for pathogen surveillance and effective vaccination deployment (Torres-Velez et al., 2019; Nuvey et al., 2022a). However, neither strategy is currently used adequately in practice in many LMICs (Donadeu et al., 2019; OIE, 2019a).

The main vaccine utilized for controlling CBPP in Ghana and other SSA countries is the live attenuated *Mycoplasma mycoides mycoides* (*Mmm*) T1/44 vaccine. The recommended dosage is 1ml per cattle, administered subcutaneously. Vaccination is advised annually for cattle aged at least 6 months (OIE, 2018a; Alhaji et al., 2020). The primary vaccine used for preventing PPR is the live attenuated peste-des-petits-ruminants virus (PPRV) 75/1 vaccine. For goats and sheep, the recommended dosage is 1ml, administered subcutaneously. The vaccination is currently advised annually for goats and sheep aged at least 3 months, although the vaccine confers about three years of immunity on herds (Sen et al., 2010; OIE, 2018b). The most common adverse reactions observed after administering the *Mmm* T1/44 and PPRV 75/1 vaccines are fever and localized inflammatory reactions at the injection sites.

In Ghana, infectious diseases including foot-and-mouth disease (FMD) and contagious bovine pleuropneumonia (CBPP) in cattle, and peste-des-petits-ruminants (PPR) in sheep and goats, result in average herd losses of 10% per year, with some farmers losing up to 70% of their herds despite excessive use of antibiotics and other medicines (Nuvey et al., 2023c). Although effective CBPP and PPR vaccines have been approved and are available in Ghana (Diop et al., 2011), less than 20% of farmers currently vaccinate their herds on a regular basis (Nuvey et al., 2023a). In Ghana, veterinary vaccines are distributed through the regional veterinary directorates, where licensed veterinary officers acquire doses for vaccinating herds in their respective operational zones. Individual farmers bear the vaccination expenses for their animals, paying the veterinary officers directly. The veterinary officers submit a monthly report on the administered vaccine doses and number of animals vaccinated, to the veterinary services directorate. Additionally, periodic campaigns funded by donor agencies, offer free vaccination services to farmers who rear livestock in some of the most economically deprived regions in Ghana (Diop et al., 2011; Omondi et al., 2022). A previous study in Ghana identified acceptability, affordability, accessibility and availability as key barriers to vaccination utilization by ruminant livestock farmers (Nuvey et al., 2023a). However, relatively little is known currently regarding what farmers are actually willing to invest to prevent diseases.

By eliciting WTP, we can better understand the demand for livestock vaccines and inform government policy to improve vaccination access and uptake, and so achieve more effective control of the infectious diseases affecting livestock productivity. Stated preference surveys are usually applied to assess individual's preferences and valuation of public goods or commodities not exchanged in regular markets. They are also used where a market exists for goods but the existing transactions do not reveal the aspects of demand of interest to stakeholders (Venkatachalam, 2004; Hanley and Barbier, 2009). Contingent valuation methods have been previously applied in low-resource settings to assess farmers' WTP for vaccination strategies (Kairu-Wanyoike et al., 2014; Campbell et al., 2019; Wanyoike et al., 2019; Jemberu et al., 2020a).

Given farmers' limited knowledge on vaccines, and low utilization of vaccination services in the study area (Nuvey et al., 2023a), a contingent valuation approach is a useful tool to elicit farmers' valuation and WTP for vaccines to protect livestock herds against highly prevalent infectious diseases, compared to revealed preference methods. This paper aims to assess farmers' valuation and willingness to pay (WTP) for vaccination using a contingent valuation approach. To this end, we attempt to elicit farmers' (maximum) WTP for CBPP vaccines in the case of cattle owners, and the WTP for PPR vaccines by sheep and goat owners, as well as to determine the maximum price chargeable to achieve national 70% coverage targets.

6.3 Materials and methods

Description of study area

This study was conducted in the Mion, Pru East and Kwahu Afram Plains South (KAPS) Districts, which are representative of the northern, middle and southern farming belts of Ghana. The districts lie in the Guinea Savannah, Transition and Deciduous forest Vegetation zones, which are the primary livestock production zones in Ghana (**Figure 5**) (GSS, 2014b, c, a). The selection of districts was carried out purposively in collaboration with the regional directors of veterinary services, using a sampling frame of farming districts located within these vegetation zones. The districts were chosen based on their strategic positioning and appropriateness for conducting field studies. Agriculture contributed about one-fifth of the national gross domestic product of Ghana in 2019 with the livestock sector accounting for 14% of this production (GSS, 2020b). The selected districts are mainly rural and agrarian, with about one-third of the livestock holdings of households being ruminant species. The primary ruminant livestock species reared by farmers are cattle, sheep, and goats. The main non-ruminant species reared are poultry, pigs, and rabbits (GSS, 2020a). Majority of livestock rearing (53%) is for income generation – the rest is directly consumed by the households, or used for other socio-cultural purposes. The livestock production system is largely extensive and dominated by small-scale farmers (GSS, 2020a).

Study design

This was a cross-sectional contingent valuation study analyzing newly collected data from 350 ruminant livestock farmers. The data were collected within a larger project that employed a convergent parallel mixed-methods design to assess the effectiveness and performance of veterinary services in Ghana, described in further details in an earlier paper (Nuvey et al., 2023a). Vaccines for contagious bovine pleuropneumonia (CBPP) and pestes-des-petits-ruminants (PPR) were selected as focal vaccines based on an earlier study in which farmers and veterinary personnel identified them as priority diseases affecting livestock in the study area, as well as the availability of approved vaccines for these diseases (Diop et al., 2011).

Study population

The target population included all ruminant livestock farmers in the study area. We obtained district maps from the District Directorates of Food and Agriculture, and created a sampling frame of villages within the study area. Based on the population and housing census data available prior to the study (2010 population and housing census), there were 80880, 54694, and 47230 tropical livestock units (TLUs) of ruminant livestock species in the KAPS, Mion and Pru East Districts respectively, with an average of 10 TLUs per household. We randomly drew 15 villages in the KAPS District, and 10 villages each in the Pru East and Mion Districts, proportional to the number of livestock farming households per district (GSS, 2014b, c, a). A household refers to a person or group of persons who normally live together and are catered for as one unit; members may or may not be related. Any member of the household who takes responsibility for the upkeep of the household's livestock was eligible to participate in the study.

Sample size and sampling technique

The sample size determination and sampling procedure for the survey are described in detail in an earlier work. The earlier study sought to estimate the uptake of livestock vaccines, and the barriers to vaccination uptake among ruminant livestock farmers in Ghana (Nuvey et al., 2023a). In summary, 350 livestock farmers were recruited from 38 villages in the three study districts, proportional to the size of ruminant livestock owning households using segmentation. In selected segments of the study villages, all households who keep ruminant livestock were eligible to be selected and the households providing consent were recruited to participate in the survey.

Household recruitment, data collection and data management

The enumeration team visited the households keeping ruminant livestock to administer the questionnaires between November 2021 and January 2022. The survey questionnaire was administered to the respondents face-to-face using tablets with Open Data Kit (ODK) application (Hartung et al., 2010). The data collected included farmers' perception of disease risk to herd, farmers' knowledge of vaccines to protect animals against CBPP and PPR, herd histories of outbreaks of the diseases, and herd vaccination histories against the diseases, farmers' resilience level, farmers' responses to the two vaccine bids and amounts offered, and other husbandry and socio-demographic characteristics. Livestock farmers' resilience was assessed using a Resilience scale (RS-14). The RS-14 consist of 14 items using a 7-point Likert scale; the score ranges between 14 and 98, with higher scores indicate higher resilience (Wagnild, 2009). Knowledge levels were assessed based on farmers' responses to questions on the vaccines' functions and effectiveness, required frequency of use, protection offered to animals, and places to acquire the vaccines when needed. Correct responses were assigned a score of 1 while wrong responses scored as zero (0). Perception of the diseases risk to herds was assessed on a five-item Likert scale with responses ranging from 1 to 5; higher scores denote higher risk perception of the diseases to a herd. The questionnaire used for the survey has been previously published (Nuvey et al., 2023a). The questions on knowledge of vaccines and disease risk perception were completed before the WTP experiment was done.

Assessing Willingness to Pay

We implemented a double-bounded dichotomous choice approach that assesses the individual's WTP at two randomly assigned price points. Although the double-bounded contingent valuation approach can potentially suffer from anchoring effects due to a predetermined starting bid for all respondents (Hanley and Barbier, 2009), the random selection of the second point provides substantial gains in the precision of the WTP estimates compared to single-bounded valuation approaches (Hanemann and Kanninen, 2001). The initial and follow-up prices were determined based on prior engagements with farmers and veterinary officers in the study area. The details of the experiment and bid amounts and questions are provided in an appendix to this paper (**S1 File**).

Prior to the bids being offered to the respondents, farmers were provided information on the diseases (in this case CBPP for cattle owners, and PPR for sheep and/ or goat owners); and on the availability, utility, and value of the vaccines for protecting herds against each disease as well as adverse effects of vaccines. This information was conveyed to respondents by trained study enumerators in order to create a credible and understandable hypothetical market scenario (**S1 File**). Providing such relevant information enhances the credibility and reliability of a contingent valuation study (Yoo and Kwak, 2009). Respondents stated preferences have been shown to be more demand-revealing, when people think that their responses are consequential, either in terms of the price of the good or the chance that it will be supplied to them (Needham and Hanley, 2019). To address the issue of consequentiality associated with contingent valuation as well as to manage expectations, the farmers in the study were informed prior to the start of the choice experiment that the vaccines were neither being provided nor sold in the study, but that the main purpose was to assess the need and demand for livestock vaccines. Outcome consequentiality was thus a feature of the hypothetical market.

After describing the hypothetical market scenario, each farmer was encouraged to ask questions for clarification. Once all questions were answered, and the farmer reported that they fully understood the information, the elicitation procedure started. Each farmer was presented with an initial bid (vaccine price) from which they had the choice to agree to pay the amount offered for vaccinating their herd or not by indicating yes or no to this initial bid, with a benefit of protecting the vaccinated animals against the disease for one year. The initial bid amounts offered was determined based on the average price of prevailing vaccination costs in the study area. The vaccination cost includes the cost of the vaccine per animal plus the service charge of the government veterinary personnel for each disease [i.e., GHC 6.00 (USD 1.00) for CBPP vaccination in cattle and GHC 5.00 (USD 0.83) for PPR vaccination in sheep and goats] [GHC is Ghanaian Cedis: USD 1 ≈ GHC 6 at the time of the survey (Bank of Ghana, 2021)]. Depending on a farmer's choice (acceptance or rejection to pay the initial bid price), a second increased or decreased follow up bid was offered, as either a 25%, 50% or 75% increment or reduction of the initial bid. A higher price was offered if a farmer agreed to pay the initial offer, and a decrease otherwise. The higher price or discount offer was randomly selected by the farmers. The enumerator then makes the selected offer with the increment or reduction based on the response to the initial bid, the farmers' choice was recorded, in addition to the percentage increase or discount offered (See **S2 File** for an illustration of the offer sequence for the CBPP vaccine). A double-bounded contingent valuation model was constructed using maximum likelihood to determine WTP for each specific vaccine.

Data processing and analyses

The data were downloaded in Microsoft Excel format and imported into Stata version 16 (StataCorp, 2019) for analyses. We performed descriptive analyses of the survey data, comparing the distribution of responses by study district. Herd sizes were converted to tropical livestock units (TLU) to standardize livestock holdings, 1 TLU corresponds to 0.75 cattle and 0.1 small ruminants (sheep and goats) (Rothman-Ostrow et al., 2020). The relative wealth of households was determined using an index of household's ownership of selected assets, such as televisions, refrigerators and bicycles, and then dividing households into five quintiles (ICF, 2019). We derived the disease risk to herd perception score as the sum of the Likert scale scores. One item score on the perception scale (Q4) is reversed to achieve a similar direction of scores. We used the median split approach to categorize knowledge and perception scale scores, with scores above the median corresponding to good knowledge and good perception respectively, and lower scores otherwise (Iacobucci et al., 2015). Species-specific herd and farmland sizes were categorized into tertiles (three quantiles) to compare WTP within homogenous levels.

Farmers' responses to the two bids follow four basic patterns: 1) the farmer was not willing to purchase the CBPP or PPR vaccine both at initial bid price or at the discounted price (‘‘no", ‘‘no"); 2) the farmer was not willing to purchase the CBPP or PPR vaccine at the initial bid price but was willing to purchase at the discounted price (‘‘no", ‘‘yes"); 3) the farmer was willing to purchase CBPP or PPR vaccines at the initial bid price but not at the increased price (‘‘yes", ‘‘no"); or (4) the farmer was willing to purchase the CBPP or PPR vaccine at both the initial bid price and the increased price (‘‘yes", ‘‘yes"). Thus, there are four possible intervals where a farmer's WTP would fall: $(0, B_d)$, (B_d, B_i), (B_i, B_h), (B_h, ∞). Where, B_i is the initial bid price, B_d is the discounted follow up bid price, and B_h is the increased follow up bid price. Reported WTP is thus censored below the observed discounted follow up bid price (B_d) and above the increased follow up bid price (B_h) for farmers unwilling, and willing to purchase at both the initial and follow up bid prices respectively – we accounted for this directly in our empirical models (Verbeek, 2008). For all farmers with intermediate WTP, we used the interval midpoint as WTP estimate. We first fitted a model without any covariates to estimate the unconditional WTP with 95% confidence intervals for each vaccine separately. We used censored regression as suggested by (Verbeek, 2008), but we accounted in addition for potential correlations within communities. The WTP for a specific vaccine of the ith farmer (WTP_i) rearing livestock in the jth community is unobserved, and could be expressed as shown in the equation below; where x_{ij} are the varying personal characteristics of the individual farmers in each community, including resilience level, sex, farmland size, herd size, wealth status, perception of disease risk to herd, knowledge of vaccines, history of disease outbreaks, and vaccination history against diseases.

$$\boldsymbol{Willingness\ to\ pay\ (WTP_i) = x_{ij}\beta + \varepsilon_{ij}}$$

The dataset and analyses procedures are presented in an appendix to this paper (**S3 Files**). We report the mean WTP and its 95% confidence intervals for CBPP vaccination of cattle (N = 87), PPR vaccination of sheep (N = 165), and PPR vaccination of goat (N = 316) herds.

We evaluated the relationship between explanatory variables including farmers' resilience level, sex, farmland size, herd size, wealth status, perception of the diseases risk to herds, knowledge level on vaccines, history of the diseases outbreak and vaccination history against the diseases, that may affect farmers WTP for vaccination against CBPP infection in cattle and PPR infection in sheep and goats, adjusting for village-level clustering, at the 95% confidence level in a censored regression model. Our main hypothesis was that these covariates' influence on WTP is zero. We performed sensitivity analysis to assess the robustness of the findings, and examined model residuals to determine if key assumptions of model fit were met.

We derived vaccine and species-specific demand curves based on the cumulative proportion of livestock farmers willing to pay at all price points. Using the demand curves, we estimated the prices at which national vaccination coverage targets for infectious livestock diseases - 50% (intermediate target) and 70% (final target) (OIE and FAO, 2015) - could be attained.

6.4 Results

Socio-demographic and livestock husbandry characteristics of study respondents

Table 10 presents the socio-demographic characteristics of the study respondents (N = 350) stratified by district. The median age of the farmers was 45 years (IQR = 35 – 54), and 71% of farmers were male. The median household size was 8 persons (IQR = 6 – 11). The respondents cultivated on average 7 acres of farmland (IQR = 3 – 15) in addition to rearing livestock. About 51% (178/350) of the farmers had received no formal education. Households' wealth index was significantly different between the districts. In the Mion District, 67% of households were in the poorest two quintiles, while the same was true only for 42% of households in KAPS and for 16% of households in the Pru East Districts. Almost 80% (278/350) of the farmers engaged in farming as their primary source of livelihood, 9% (33/350) engaged primarily in business or trading, 5% (19/350) were primarily employed in the formal sector. The other respondents primarily engaged in artisanal work (4%) including carpentry, tailoring, driving, and masonry, among others, or are students (2%). The majority of the farmers (74%) reported earning less than GHC 1500 (USD 250) [GHC is Ghanaian Cedis: USD 1 ≈ GHC 6 (2021)] annually from the sale of livestock and/or livestock products. About 19% (67/350) of the farmers were unwilling to disclose income earned or did not know.

Table 10: Socio-demographic characteristics of ruminant livestock farmers by study district

Characteristic	KAPS	MION	PRU EAST
	Median (IQR)	**Median (IQR)**	**Median (IQR)**
Resilience level (out of 98)	78 (73 – 84)	82.5 (78 – 87)	81 (75 – 86)
Age (years)	46 (36 – 56)	41 (34 – 51)	46 (34 – 57)
Household size (persons)	7 (5 – 10)	10 (7 – 15)	8 (6 – 13)
	% (n/N)	**% (n/N)**	**% (n/N)**
Sex			
Female	38% (57/149)	16% (16/98)	28% (29/103)
Male	62% (92/149)	84% (82/98)	72% (74/103)
Wealth status quintiles			
Poorest	14% (21/149)	42% (41/98)	8% (8/103)
Below average	28% (41/149)	26% (25/98)	8% (8/103)
Average	24% (36/149)	14% (14/98)	15% (16/103)
Above average	25% (37/149)	10% (10/98)	22% (23/103)
Least poor	9% (14/149)	8% (8/98)	47% (48/103)

Educational attainment			
No formal education	28% (41/149)	87% (85/98)	51% (52/103)
Up to high school education	48% (72/149)	6% (6/98)	28% (29/103)
Tertiary education	24% (36/149)	7% (7/98)	21% (22/103)
Main source of employment			
Farming (livestock, crop and fish farming)	77% (115/149)	95% (93/98)	68% (70/103)
Business	12% (18/149)	1% (1/98)	13% (14/103)
Artisanal worker	5% (8/149)	2% (2/98)	5% (5/103)
Formal sector employed	5% (7/149)	1% (1/98)	11% (11/103)
Student	1% (1/149)	1% (1/98)	3% (3/103)
Farmland size (acres)			
Small (0 – 5 acres)	63% (94/149)	16% (16/98)	28% (29/103)
Medium (6 – 11 acres)	21% (31/149)	43% (42/98)	21% (22/103)
Large (12 – 99 acres)	16% (24/149)	41% (40/98)	51% (52/103)
Annual livestock farming-related income			
Less than GHC 1500	59% (88/149)	94% (92/98)	78% (80/103)
GHC 1500 or more	8% (12/149)	1% (1/98)	10% (10/103)
Don't know/ refused to disclose earnings	33% (49/149)	5% (5/98)	12% (13/103)

Percentages (%) are the proportions of ruminant livestock farmers within each characteristic explored per study district sub-sample (N). Numbers (n) of farmers, falling into each sub-category of characteristics within the study districts; Kwahu Afram Plains South (KAPS), Mion and Pru East Districts. For continuous variables, the median with corresponding lower and upper quartile values (IQR) are reported in parentheses. GHC is Ghanaian Cedis: USD 1 ≈ GHC 6 (2021).

Table 11 presents further details on the husbandry characteristics of ruminant livestock farmers. Farmers had a median 9 years (IQR = 6 – 15) of livestock rearing experience. The median herd size was 2.5 TLUs (IQR = 1.3 – 7.0). More than 95% (333/350) of the farmers owned the livestock reared. Open field grazing, where the animals are released to feed on their own with little or no supervision by the farmers was the grazing method adopted by most (76%) of the farmers. To address animal health issues, 51% of farmers utilized informal providers, while 33% (116/350) used professional veterinary service providers.

About 45% (149/350) of the farmers reported experiencing outbreaks of either CBPP infection in cattle herds (46/87) and/or PPR infection in sheep and/ or goat herds (105/338) in the previous years (since they started rearing animals) prior to the study; while 47% (164/350) reported either PPR (155/338) and/or CBPP (43/87) outbreaks during the study year. The farmers scored an average (median) of 19 out of 25 (IQR = 17 – 21) on the perception scale, and 3 out of 5 (IQR = 2 – 3) on the knowledge scale.

Only 22% (76/350) of the farmers had good knowledge of vaccines (scored above 3 out 5). About 37% (128/350) of farmers perceived the risk of CBPP and/or PPR infections for their herds to be high (scored above 19 out of 25). About 18% (65/350) of farmers had ever vaccinated their herds against CBPP and/or PPR before the study year. In the study year (2021), 16% (56/350) of farmers had vaccinated their herds against the diseases. Farmers mainly used treatment of infected animals (64%) to prevent disease transmission within herds.

Table 11: Livestock husbandry characteristics of ruminant livestock farmers by study district

Characteristic	**KAPS**	**MION**	**PRU EAST**
	Median (IQR)	**Median (IQR)**	**Median (IQR)**
Livestock farming experience (years)	9 (5 – 16)	10 (6 – 17)	9 (5 – 15)
Knowledge of CBPP and/or PPR vaccine (out of 5)	3 (2 – 4)	3 (3 – 3)	3 (3 – 4)
Perception of CBPP and/or PPR risk (out of 25)	19 (17 – 21)	18 (17 – 20)	18 (16 – 21)
	% (n/N)	**% (n/N)**	**% (n/N)**
Herd size [Tropical Livestock Units (TLUs)]			
Small (0.3 – 1.6 TLUs)	42% (62/149)	43% (42/98)	23% (24/103)
Medium (1.7 – 4.2 TLUs)	31% (46/149)	24% (24/98)	35% (36/103)
Large (4.3 – 181.9 TLUs)	27% (41/149)	33% (32/98)	42% (43/103)
Livestock grazing practices ¥			
Open field grazing	78% (116/149)	49% (48/98)	99% (102/103)
Hired shepherd grazing of herd	15% (23/149)	22% (22/98)	18% (19/103)
Herd grazed on purchased feed	36% (53/149)	10% (10/98)	16% (16/103)
History of CBPP and/or PPR outbreak in herds [a]			
Previous history of CBPP and/or PPR outbreak	35% (52/149)	48% (47/98)	58% (60/103)
Present history of CBPP and/or PPR outbreak	31% (46/149)	41% (40/98)	76% (78/103)
Measures to address disease outbreaks in herds ¥			
Treatment of affected animals	69% (103/149)	71% (70/98)	51% (52/103)
Preventive treatment of unaffected animals	7% (10/149)	10% (10/98)	3% (3/103)
Vaccination of herd	4% (6/149)	14% (14/98)	35% (36/103)
Isolation of affected animals	10% (15/149)	0% (0/98)	5% (5/103)
Past herd vaccination against CBPP and/or PPR			
No	71% (106/149)	87% (85/98)	91% (94/103)
Yes	29% (43/149)	13% (13/98)	9% (9/103)
Main veterinary service providers utilized ¥			
Professional veterinary service providers	21% (32/149)	29% (28/98)	54% (56/103)
Informal veterinary service providers	60% (89/149)	60% (59/98)	28% (29/103)

Percentages (%) are the proportion of ruminant livestock farmers within each characteristic explored per study district sub-sample (N); ¥ depicts variables with multiple response categories, reference period being the study year (2021). Numbers (n) of households, falling into each sub-category of assessed characteristics within the districts; KAPS, MION and PRU EAST: denote Kwahu Afram Plains South, Mion and Pru East Districts respectively. For continuous variables, the median with corresponding lower and upper quartile values are reported in parentheses. CBPP denotes contagious bovine pleuropneumonia infection in cattle, and PPR denotes peste-des-petits-ruminants infection in sheep and/ or goats. [a] For the herd history of CBPP/PPR outbreak, non-experience of an outbreak in herd in the previous years (before 2021) and non-experience of an outbreak in the study year (2021) were the reference categories respectively.

Only 65% (228/350) of the farmers reported any livestock production-related expenditures during the farming year (2021). The median annual expenditure of the farmers was GHC 150 (IQR = 54 – 600). **Figure 12** shows the distribution of item-specific expenditures in terms of the total value of expenses made. Majority of the value of reported expenses (60%) were investments for new animals in the herds (median = GHC 785, IQR = GHC 338 – 3425), 20% were treatment-related expenses (median = GHC 83, IQR = GHC 35 – 220), 10% were expenses made on herdsmen support (median = GHC 200, IQR = GHC 100 – 300), 5% were expenses on vaccination (median = GHC 87, IQR = GHC 39 – 209) and 4% were other expenses including purchase of animal feeds, and transportation of livestock especially to markets for sale (median = GHC 70, IQR = GHC 38 – 160).

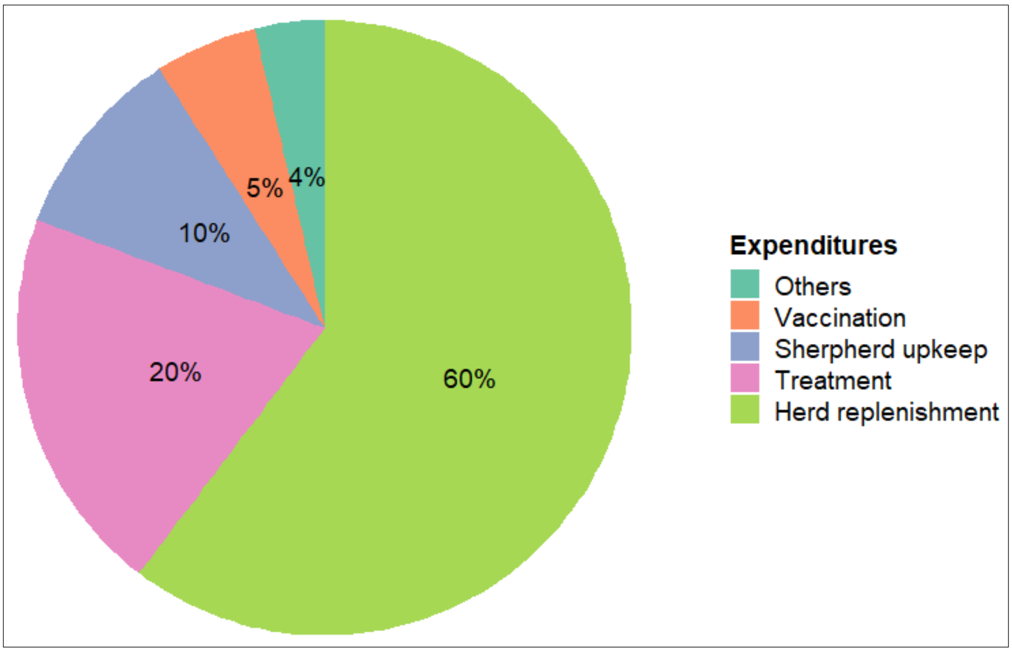

Figure 12: Main expenditure items of ruminant livestock farmers in Ghana.

The figure shows the items that contribute to the total share of livestock production related expenditures of farmers. The size of the pies show the proportion of the expenditures accounted for by each item, which are distinguished by the different colors.

Figure 13 shows further details on farming expenditures. About 72% (165/228) of households with livestock production-related expenditures spent the money on treatment costs; only 11% (24/228) spent money on herd replenishment. The distribution of households' share in expenses was similar across the study districts (**S3 Figure**).

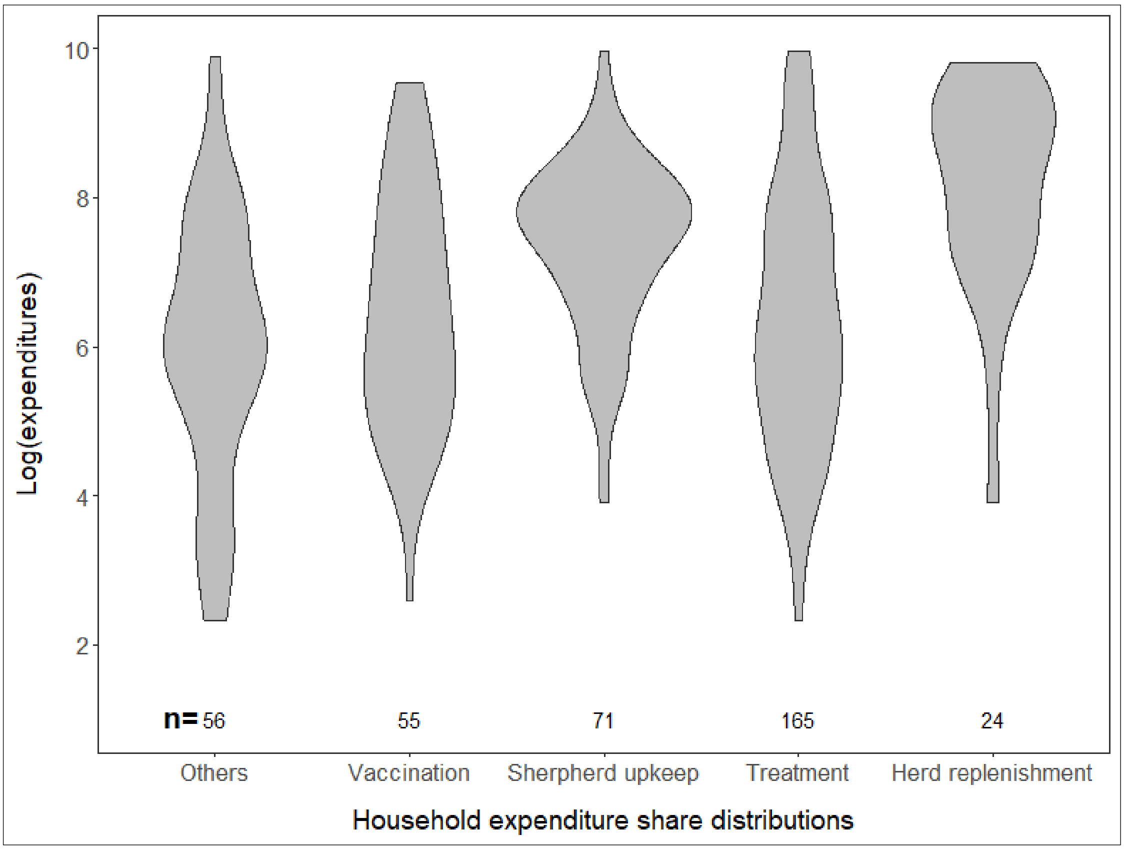

Figure 13: Ruminant livestock farming household expenditure share distributions in Ghana.

The figure presents a violin plot which shows a breakdown of the share of farmers making the specified expenditures. The height of the violins shows the distribution of the expenses in logarithms. GHC is Ghanaian Cedi; at the time of the study, 1 USD was approximately equal to GHC 6. The numbers (n) at the base of each violin represent the number of farmers who made the specified expenses during the study year (2021).

Farmers' valuation and willingness to pay for vaccination against priority diseases

Table 12 presents the distribution of WTP responses. The percentage of farmers willing to pay the initial bid price of GHC 6 for CBPP vaccination of one cattle, GHC 5 for PPR vaccination of one sheep, and GHC 5 for vaccination of one goat were 66% (57/87), 59% (98/165), and 54% (172/316) respectively. The percentage of farmers unwilling, and willing to pay for CBPP at the follow-up discount and increased bids for

CBPP vaccination were 8% (7/87) and 49% (43/87) respectively. In the case of sheep owners, the percentage of farmers unwilling, and willing to pay for PPR vaccination at the follow-up discount and increased bids were 8% (14/165) and 49% (81/165) respectively. While the percentage of farmers unwilling, and willing to pay for PPR vaccination of goats at the follow-up discount and increased bids were 7% (23/316) and 46% (144/316) respectively.

Table 12: Distribution of WTP responses in the double dichotomous contingent valuation experiment (N = 350)

WTP for CBPP Vaccination in Cattle (N = 87)			WTP for PPR Vaccination in Sheep (N = 165)			WTP for PPR Vaccination in Goats (N = 316)		
Bids	**Response**	**Frequency (%)**	**Bids**	**Response**	**Frequency (%)**	**Bids**	**Response**	**Frequency (%)**
INITIAL BIDS								
GHC 6.00	No	30 (34)	**GHC 5.00**	No	67 (41)	**GHC 5.00**	No	144 (46)
	Yes	57 (66)		Yes	98 (59)		Yes	172 (54)
FOLLOW UP BIDS								
GHC 1.50	No	0 (0)	**GHC 1.25**	No	2 (11)	**GHC 1.25**	No	4 (7)
	Yes	8 (100)		Yes	16 (89)		Yes	51 (93)
GHC 3.00	No	1 (14)	**GHC 2.50**	No	4 (15)	**GHC 2.50**	No	6 (15)
	Yes	6 (86)		Yes	23 (85)		Yes	33 (85)
GHC 4.50	No	6 (40)	**GHC 3.75**	No	8 (36)	**GHC 3.75**	No	13 (26)
	Yes	9 (60)		Yes	14 (64)		Yes	37 (74)
GHC 7.50	No	3 (14)	**GHC 6.25**	No	4 (11)	**GHC 6.25**	No	6 (9)
	Yes	18 (86)		Yes	33 (89)		Yes	62 (91)
GHC 9.00	No	5 (25)	**GHC 7.50**	No	9 (22)	**GHC 7.50**	No	8 (15)
	Yes	15 (75)		Yes	32 (78)		Yes	47 (85)
GHC 10.50	No	6 (38)	**GHC 8.75**	No	4 (20)	**GHC 8.75**	No	14 (29)
	Yes	10 (62)		Yes	16 (80)		Yes	35 (71)

GHC is Ghanaian Cedi: 1 USD = GHC 6 (2021); WTP is Willingness to pay; CBPP is Contagious Bovine Pleuropneumonia; PPR is Peste-des-Petits Ruminants. Initial bid prices utilized was the prevailing average price for vaccination per head of animal against the specific diseases in the study area in 2021. Follow-up bids were dependent on initial bid responses. Farmers willing to pay the initial bid were offered a follow-up premium bid (25%, 50%, or 75% higher than initial bid price). While farmers unwilling to pay the initial bid price were offered a follow-up discount bid (25%, 50%, or 75% lower than initial bid price). Follow-up offers were randomly drawn by farmers. Some farmers owned multiple species of livestock in their herd. The numbers (frequency) and percent (%) responding yes or no to each bid price are reported.

Cattle

The average estimated WTP for CBPP vaccination per cattle was GHC 8.63 (95% CI: GHC 7.08–GHC 10.19). **Table 13** presents the results of the censored regression models with explanatory variables that could influence farmers' willingness to pay for CBPP vaccination of cattle, adjusting for village-level clustering. After adjusting for all covariates, WTP was positively associated with resilience [Mean difference (MD) per unit: GHC 0.16, 95% CI: GHC 0.07–GHC 0.25], farmland size (MD per tertile: GHC 3.20, 95% CI: GHC 0.45–GHC 5.95), and limited knowledge about CBPP vaccines (MD: GHC 2.01, 95% CI: GHC 0.34–GHC 3.67).

Table 13: Determinants of ruminant livestock farmers' willingness to pay for vaccination against Contagious Bovine Pleuropneumonia (CBPP) infection in cattle (N = 87)

	Unadjusted model		**Adjusted model**	
Variables	**β (95% CI)**	**P-value**	**β (95% CI)**	**P-value**
Resilience level	0.17 (0.06, 0.28)	0.004	0.16 (0.07, 0.25)	0.001
Herd size (cattle)				
Small (1st tertile: 3 – 12 cattle)	ref		ref	
Medium (2nd tertile: 14 – 35 cattle)	-1.72 (-4.48, 1.04)	0.22	-1.72 (-4.37, 0.93)	0.20
Large (3rd tertile: 38 – 200 cattle)	-3.47 (-5.63, -1.31)	0.002	-2.35 (-4.82, 0.11)	0.06
Farmland size (acres)				
Small (1st tertile: 0 – 7 acres)	ref		ref	
Medium (2nd tertile: 8 – 15 acres)	1.92 (-0.01, 3.85)	0.05	1.30 (-0.47, 3.08)	0.15
Large (3rd tertile: 16 – 99 acres)	3.42 (1.17, 5.67)	0.003	3.20 (0.45, 5.95)	0.02
Sex				
Female	ref		ref	
Male	2.49 (0.11, 4.87)	0.04	0.91 (-1.20, 3.03)	0.39
Wealth status				
Poorest	ref		ref	
Below average	-0.52 (-3.15, 2.11)	0.69	-1.43 (-3.77, 0.92)	0.23
Average	-1.55 (-4.67, 1.57)	0.33	-1.56 (-4.08, 0.96)	0.22
Above average	-1.29 (-4.57, 1.98)	0.43	-1.01 (-3.72, 1.69)	0.46
Least poor	-1.99 (-4.91, 0.93)	0.18	-2.10 (-5.07, 0.86)	0.16
Herd history of CBPP prevention *				
Past history of CBPP outbreak in herd	-1.25 (-3.69, 1.19)	0.31	0.51 (-1.33, 2.36)	0.58
History of CBPP vaccination of herd	-1.54 (-3.80, 0.71)	0.18	0.96 (-1.70, 3.62)	0.48

Knowledge of CBPP vaccines				
Good	ref		ref	
Limited	3.26 (1.88, 4.63)	<0.001	2.01 (0.34, 3.67)	0.02
Perception of CBPP disease risk				
High	ref		ref	
Low	2.50 (0.44, 4.55)	0.02	2.24 (-0.06, 4.54)	0.06

Variables included as pre-specified predictors of farmers' willingness to pay for vaccination services against priority infectious diseases. The estimated coefficients (*β*) of predictors with 95% confidence intervals (95% CI) and associated *p*-values are from unadjusted and adjusted censored normal regression models, accounting for village-level clustering during sampling of respondents. 'ref' denotes the reference category. ***** For the herd history of CBPP prevention, non-experience of an outbreak in a household's herd in the past years (before 2021) and no vaccination experience of a herd were the reference categories respectively in each case.

Sheep

Average WTP for PPR vaccination per sheep was GHC 7.02 (95% CI: GHC 5.99–GHC 8.05). **Table 14** presents the results of the censored regression models with explanatory variables that could influence farmers' willingness to pay for PPR vaccination of sheep, adjusting for village-level clustering. After adjusting for all covariates, WTP was associated positively (at the 10% level) with resilience levels (MD per unit: GHC 0.08, 95% CI: GHC -0.01–GHC 0.16) and limited knowledge about PPR vaccines (MD: GHC 1.64, 95% CI: GHC -0.08–GHC 3.37).

Table 14: Determinants of ruminant livestock farmers' willingness to pay for vaccination against Peste-des-petits Ruminants (PPR) infection in sheep (N = 165)

	Unadjusted model		**Adjusted model**	
Variables	**β (95% CI)**	**P-value**	**β (95% CI)**	**P-value**
Resilience level	0.09 (0.01, 0.17)	0.04	0.08 (-0.01, 0.16)	0.07
Herd size (sheep)				
Small (1st tertile: 2 – 5 sheep)	ref		ref	
Medium (2nd tertile: 6 – 12 sheep)	-0.21 (-1.84, 1.42)	0.80	0.15 (-1.50, 1.80)	0.86
Large (3rd tertile: 13 – 60 sheep)	-0.27 (-2.03, 1.49)	0.76	0.15 (-1.66, 1.95)	0.87
Farmland size (acres)				
Small (1st tertile: 0 – 5 acres)	ref		ref	
Medium (2nd tertile: 6 – 13 acres)	1.73 (0.17, 3.29)	0.03	1.21 (-0.46, 2.89)	0.16
Large (3rd tertile: 14 – 99 acres)	1.16 (-0.43, 2.75)	0.15	1.21 (-0.76, 3.18)	0.23

Sex				
Female	ref		ref	
Male	0.89 (-0.83, 2.62)	0.31	0.60 (-1.39, 2.58)	0.55
Wealth status				
Poorest	ref		ref	
Below average	-0.03 (-2.65, 2.60	0.98	-0.19 (-2.79, 2.41)	0.88
Average	-0.14 (-2.03, 1.75)	0.88	-0.61 (-2.77, 1.55)	0.58
Above average	-0.11 (-1.83, 1.61)	0.90	-0.09 (-2.05, 1.87)	0.93
Least poor	-1.81 (-3.58, -0.04)	0.04	-1.43 (-3.49, 0.63)	0.17
Herd history of PPR prevention*				
Past history of PPR outbreak in herd	-2.10 (-3.96, -0.24)	0.03	-1.15 (-2.95, 1.64)	0.21
History of PPR vaccination of herd	-0.56 (-2.56, 1.45)	0.59	0.06 (-1.65, 1.77)	0.95
Knowledge of PPR vaccines				
Good	ref		ref	
Limited	2.49 (0.76, 4.21)	0.005	1.64 (-0.08, 3.37)	0.06
Perception of PPR disease risk				
High	ref		ref	
Low	1.60 (0.28, 2.93)	0.02	0.20 (-1.32, 1.72)	0.80

Variables included as pre-specified predictors of farmers' willingness to pay for vaccination services against priority infectious diseases. The estimated coefficients (β) of predictors with 95% confidence intervals (95% CI) and associated *p*-values are from unadjusted and adjusted censored normal regression models, accounting for village-level clustering during sampling of respondents. 'ref' denotes the reference category. ***** For the herd history of PPR prevention, non-experience of an outbreak in a household's herd in the past years (before 2021) and no vaccination experience of a herd were the reference categories respectively in each case.

Goats

Average WTP for PPR vaccination per goat was GHC 6.66, 95% CI: GHC 5.89–GHC 7.44. **Table 15** presents the results of the censored regression models with explanatory variables that could influence farmers' willingness to pay for PPR vaccination of goats, adjusting for village-level clustering. After adjusting for all covariates, WTP was positively associated with resilience levels (MD per unit: GHC 0.08, 95% CI: GHC 0.03–GHC 0.14) and male gender (MD: GHC 0.88, 95% CI: GHC 0.04–GHC 1.72).

Table 15: Determinants of ruminant livestock farmers' willingness to pay for vaccination against Peste-des-petits Ruminants (PPR) infection in goats (N = 316)

	Unadjusted model		Adjusted model	
Variables	**β (95% CI)**	**P-value**	**β (95% CI)**	**P-value**
Resilience level	0.09 (0.03, 0.15)	0.002	0.08 (0.03, 0.14)	0.003
Herd size (goats)				
Small (1st tertile: 2 – 7 goats)	ref		ref	
Medium (2nd tertile: 8 – 14 goats)	-0.21 (-1.34, 0.93)	0.72	-0.06 (-1.18, 1.06)	0.92
Large (3rd tertile: 15 – 65 goats)	0.38 (-0.82, 1.59)	0.53	0.80 (-0.49, 2.09)	0.22
Farmland size (acres)				
Small (1st tertile: 0 – 5 acres)	ref		ref	
Medium (2nd tertile: 6 – 12 acres)	0.78 (-0.41, 1.97)	0.20	0.40 (-0.81, 1.62)	0.51
Large (3rd tertile: 13 – 99 acres)	0.76 (-0.31, 1.83)	0.16	0.47 (-0.72, 1.66)	0.44
Sex				
Female	ref		ref	
Male	1.08 (0.32, 1.83)	0.01	0.88 (0.04, 1.72)	0.04
Wealth status				
Poorest	ref		ref	
Below average	-0.03 (-1.33, 1.27)	0.97	-1.41 (-1.71, 0.90)	0.54
Average	0.16 (-1.14, 1.45)	0.81	-1.18 (-1.77, 1.41)	0.83
Above average	0.43 (-1.18, 2.03)	0.60	0.24 (-1.49, 1.96)	0.79
Least poor	-1.17 (-2.47, 0.12)	0.08	-1.29 (-2.91, 0.33)	0.12
Herd history of PPR prevention*				
Past history of PPR outbreak in herd	-1.33 (-2.52, -0.15)	0.03	-1.01 (-2.34, 0.32)	0.14
History of PPR vaccination of herd	0.12 (-1.26, 1.50)	0.87	0.28 (-1.03, 1.59)	0.68
Knowledge of PPR vaccines				
Good	ref		ref	
Limited	1.06 (0.13, 2.00)	0.03	0.73 (-0.29, 1.74)	0.16
Perception of PPR disease risk				
High	ref		ref	
Low	0.81 (-0.15, 1.77)	0.10	0.48 (-0.60, 1.56)	0.39

Variables included as pre-specified predictors of farmers' willingness to pay for vaccination services against priority infectious diseases. The estimated coefficients (*β*) of predictors with 95% confidence intervals (95% CI) and associated *p*-values are from unadjusted and adjusted censored normal regression models, accounting for village-level clustering during sampling of respondents. 'ref' denotes the reference category. ***** For the herd history of PPR prevention, non-experience of an outbreak in a household's herd in the past years (before 2021) and no vaccination experience of a herd were the reference categories respectively in each case.

Figure 14 shows the demand curve for vaccination cost (price) and the proportion of farmers willing to pay to protect their herds against the specified diseases at different vaccination costs. To attain a 70% vaccination coverage target in Ghana, vaccination costs should not exceed GHC 5.30 (USD 0.88) per cattle head for CBPP vaccination, and GHC 3.89 (USD 0.65) and GHC 3.67 (USD 0.61) per sheep and goat head for PPR vaccination respectively. The amounts farmers are willing to pay however differ markedly especially for CBPP vaccines, by study districts; where costs at which 70% coverage is attainable are GHC 7.79 (USD 1.30), GHC 5.95 (USD 0.99), and GHC 4.5 (USD 0.75) for farmers in the Mion, Pru East and KAPS Districts respectively (**S4 Figure**), and according to the gender of the respondents; GHC 5.39 (USD 0.90) and GHC 4.03 (USD 0.67) for male and female farmers respectively (**S5 Figure**).

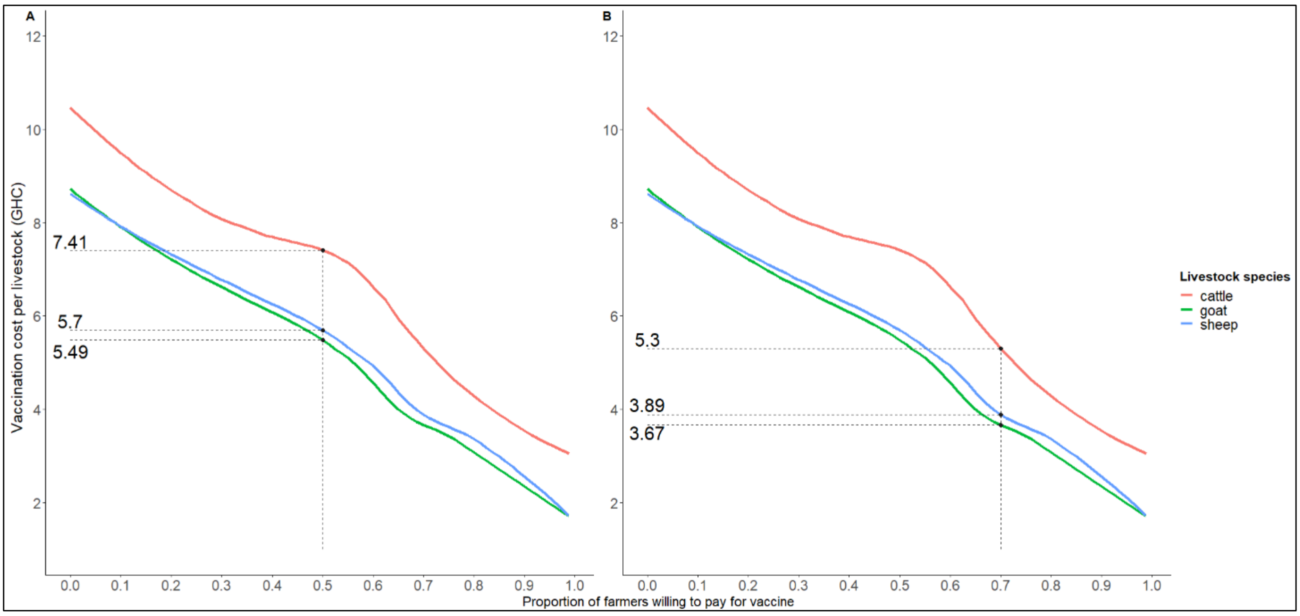

Figure 14: Proportion of livestock farmers willing to pay for vaccination to protect their herds against CBPP infection in cattle, and PPR infection in sheep and goats in Ghana.

The figure shows the cumulative proportion of the farmers willing to pay for Contagious Bovine Pleuropneumonia vaccines for cattle, and Peste-des-Petits Ruminants vaccines for sheep and goats at the specified prices. **Panel A** presents the potential prices at which the attainment of a 50% vaccination coverage target is plausible given farmers' current willingness to pay, while **Panel B** presents the potential prices at which the attainment of a 70% vaccination coverage target is plausible given farmers' current willingness to pay.

6.5 Discussion

In this study, we estimated ruminant livestock farmers' willingness to pay (WTP) for Contagious Bovine Pleuropneumonia (CBPP) and Pestes-des-Petits Ruminants (PPR) vaccines in a representative sample of Ghanaian livestock farmers. We implemented a stated preference survey in which we used dichotomous choice contingent valuation models to estimate the WTP. Based on the cumulative distribution of WTP, we also determined the prices at which national vaccination coverage targets were likely to be attained. Our results suggest that majority of the farmers are willing on average to pay higher than current prevailing vaccine costs of GHC 6 and GHC 5 per animal for CBPP and PPR vaccination, respectively (GHC is Ghanaian Cedi; at the time of the study, 1 USD was approximately equal to GHC 6). Relatively few farmers (less than 10% in all cases) were unwilling to pay for the vaccines at the current and the follow-up discounted prices. On average, farmers' WTP for vaccination against CBPP, and PPR were GHC 8.63 (USD 1.44) per cattle, GHC 7.02 (USD 1.17) per sheep, and GHC 5.89 (USD 0.98) per goat, respectively. We find that WTP for all the vaccines was significantly higher in our adjusted models for farmers with better resilience. Lacking vaccine knowledge, farmland size, and male sex were also positively associated with WTP.

These findings are consistent with previous studies evaluating WTP for ruminant livestock vaccines in Kenya, and Ethiopia, which showed that the average WTP of farmers for CBPP, Rift valley fever, and Foot-and-Mouth Disease vaccines were higher than the prices at which the vaccines were sold by veterinary authorities in the respective countries (Kairu-Wanyoike et al., 2014; Wanyoike et al., 2019; Jemberu et al., 2020a). In spite of the increasing research evidence of high WTP for livestock vaccines, the utilization of livestock vaccination remains low in many resource-limited countries in sub-Saharan Africa (SSA) including in Ghana (Donadeu et al., 2019; OIE, 2019a). A previous review has shown vaccination to be both effective and profitable in controlling most of the infectious ruminant livestock diseases in SSA (Nuvey et al., 2022a). Given that the maximum WTP is higher than the prevailing costs, the main barriers to the utilization of the vaccines could thus be attributed mainly to limited awareness levels of most farmers, and limitations in the organization of communities for vaccination exercises by veterinary service providers as reported previously in the study area (Nuvey et al., 2023a). This therefore underscores the need for innovative solutions to help improve the uptake of vaccination by farmers against these key infectious livestock diseases, which cause significant herd mortalities annually, with its attendant low productivity and food insecurity challenges for developing countries. Additionally, with the apparent positive relationship between farmer resilience and WTP, improving vaccines utilization has potential to confer improved wellbeing on livestock dependent populations. At the same time it is also important to highlight that a high mean WTP for vaccines does not mean that national vaccination targets can easily be reached. Our estimates suggest that 70% uptake of the two vaccines under investigation would likely only be achievable with price reductions or subsidies between 12 and 27 percent of the current market prices.

While it is surprising that the farmers with limited knowledge of vaccines had higher WTP for all the vaccines compared to the farmers with better knowledge, we believe the design of our experiment may at least partially explain this finding. Farmers' knowledge levels on vaccines were assessed prior to the presentation of detailed information on each vaccine during the creation of the hypothetical market scenarios. Thus, the awareness level on the vaccines could inherently be improved particularly for farmers with initial limited knowledge levels. Second, farmers who already had better knowledge of the vaccine would have also known the prevailing cost of the vaccines, and thus could be less likely to agree to pay more than they know the vaccines cost (not wanting to bid the price up against themselves). More so, we found in sensitivity analysis that the farmers were more likely to agree to pay the follow-up bids if they had limited knowledge of vaccines, than if they had better knowledge. We could have definitively assessed the extent of change in knowledge if we had reassessed the knowledge levels after the presentation of the hypothetical market scenarios. Future WTP studies should consider this possibility of a change in awareness distributions owing to the hypothetical market scenario presentation, and the influence of respondents' prior knowledge of the cost of the goods, especially for public goods already available in a study area. Nevertheless, given the previous evidence in the study area of low utilization of vaccination services (Nuvey et al., 2023a), awareness creation on these livestock vaccines in the population, could potentially improve WTP, and the utilization of vaccination.

There were apparent differences in the amounts that farmers were willing to pay based on the farmers' gender, districts in which farmers' rear their animals, and the size of farmland owned. We suspect that these differences might be related to farmers' satisfaction with the performance of the public veterinary services in the specific study districts, as well as the supplementary income derived from additional revenues generated by crop farming. In a previous study (Nuvey et al., 2023a), we had shown that the veterinary livestock units (VLUs), which measures the workload of each veterinary officer, was disproportionately high in the Kwahu Afram Plains South (KAPS) District (30000) compared to the Pru East (11500) and Mion (9000) Districts. Additionally, a higher proportion of farmers rate the performance of the public veterinary officers poorly in the KAPS District compared to the Pru East and Mion Districts (Nuvey et al., 2023c). Thus, addressing the inequitable distribution of public veterinary officers could potentially improve the satisfaction with veterinary services provided and the uptake of animal vaccines. Similar to our findings, the issue of gendered differences in the adoption of vaccinations have been reported in previous studies (Mutua et al., 2019; Omondi et al., 2022). Thus, policy makers could also consider gender-specific pricing policy for public goods such as vaccines. The approaches by which gender equity might be achieved in animal vaccine pricing and delivery could be the subject of future studies to fill this knowledge gap. Furthermore, the higher willingness of cattle owners with large farmland size is intuitive, as income generated from crop farming could bolster the disposable income of farmers, which can then be allocated towards annual herd vaccinations.

An assessment of the expenditure patterns of the livestock farmers in our study also revealed that most of the expenses incurred could be related to addressing the effect of diseases on herds; be it introduction of new animals, or the treatment of infected animals. It was also instructive to find that although herd replenishment constituted the majority expenditure share, only a few farmers could afford to spend resources on re-introducing new animals. This restricts this livelihood source for low income households who are unable to afford such replacement expenditures. Since most of the farmers' who made livestock production related expenses did so mainly on treatment of diseased animals, better community engagement and awareness raising could serve as tools that enable farmers to realign their treatment expenses towards preventing the diseases, which has been shown to be the more effective and profitable option. Evidence of improvements in vaccination adoption by smallholder farmers through awareness creation and empowerment, have previously been shown in poor and rural community settings in Ghana (Omondi et al., 2022).

Our study had limitations. We did not reassess knowledge level of the farmers after the presentation of the hypothetical market scenario, which could provide important information on the change in awareness on vaccines. Future studies implementing stated preference surveys, particularly for public goods which exist already, should consider this possibility and assess the potential effect on awareness on the survey subject. Furthermore, people's responses to follow-up valuation questions has been shown to depend on the specific value offered to them in the initial question (Hanley and Barbier, 2009). We tried to address this by offering an initial price which was the average prevailing vaccination costs. Also, the contingent valuation approach is prone to strategic bias where respondents could overstate their WTP, especially if they think their responses is less likely to influence the decision making process of pricing the vaccines. It is also possible that respondents could understate their WTP if they strategically hope to get access to cheaper vaccines later. Furthermore, our effort to streamline the overall estimated vaccination cost by considering scenarios involving ten animals (the average number of ruminant livestock holdings per household in Ghana) of each specific livestock species kept by the farmers could introduce potential bias in the results. Nevertheless, we believe it is reasonable to assume that farmers can extrapolate vaccination costs for larger or smaller herd sizes, in multiples or divisions of ten, just as they would if presented with a scenario of vaccinating each individual animal in their herds. Additionally, despite the efforts to obtain a representative sample of the different agro-ecological zones in Ghana, our study did not account for the two other distinct minority agro-ecological zones namely the Evergreen and Coastal Savannah zones. Although these zones are not typical areas for livestock production in Ghana, their inclusion would have improved the representativeness of our findings. In spite of this missing perspective, we do not expect the WTP to be markedly different in these zones.

6.6 Conclusion

Our study has shown that on average, farmers' valuation and willingness to pay for vaccines to protect herds against priority infectious diseases exceeds prevailing vaccination costs in Ghana. However, to attain the optimal vaccination coverage of

70%, discounts may need to be introduced, particularly also to reach female farmers as well as farmers in the poorest districts. Thus, new and innovative strategies should enable the improved uptake of livestock vaccines for effective control of infectious livestock diseases in Ghana.

6.7 Declarations

Ethics approval and consent to participate

The study was reviewed and approved by the Ghana Health Service Ethics Review Committee (approval number: GHS-ERC 006/09/20). In the study districts, permission was obtained from all the relevant authorities prior to data collection. The study participants provided written informed consent and the data generated are kept as confidential records. All methods were carried out in accordance with relevant guidelines and regulations (e.g. Helsinki Declaration).

Consent for publication

Not applicable.

Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Competing interests

The authors declare that they have no competing interests.

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Author contributions

Conceptualization, all authors; **methodology**, all authors; **validation**, N.H., K.S., D.T.H., J.H., G.I.M., K.K.A., B.B., J.Z. and G.F.; **formal analysis**, F.S.N.; **investigation**, F.S.N.; **resources**, D.T.H., J.H., B.B., J.Z., and G.F.; **data curation**, F.S.N.; **writing—original draft preparation**, F.S.N.; **writing—review and editing**, all

authors; **visualization**, F.S.N., D.T.H. and J.H.; **supervision**, N.H., D.T.H., J.H., K.K.A., G.I.M., B.B., J.Z., and G.F.; **project administration**, F.S.N. and B.B.; **funding acquisition**, K.K.A., B.B., and J.Z. All authors have read and agreed to the published version of the manuscript.

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6.8 Supplemental

Supplemental Appendix to

"Farmers' valuation and willingness to pay for vaccines to protect livestock resources against priority infectious diseases in Ghana"

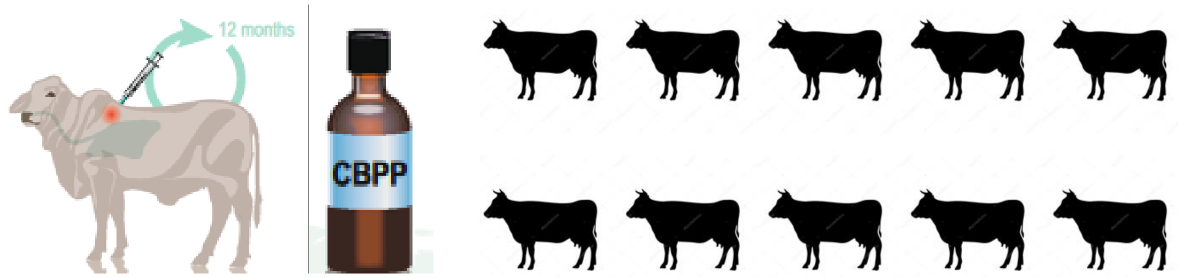
S1 File: WTP experiment tool, with background information and questions

WTP Experiment (For Cattle Owners)

CBPP is a disease that mainly affects cattle. The disease is spread through close contact between infected cattle and others that do not have protection against it. Common signs of the infection are fast, difficult or noisy breathing, discharges from the nose and/or mouth, painful cough and weight loss. The cattle may die if the disease is severe or after prolonged illness. The presence of CBPP in a cattle herd (kraal) results in direct losses due to its impact on cattle production, through increased mortalities, reduced milk yield, reduced weight gain, reduced fertility rate, and draught power and therefore it affects farmer income.

CBPP also causes indirect losses through additional cost of treatment, slaughter and sale of sick animals, affects cattle export and reduce investment in improved cattle breeds.

Vaccination is one of the key measures used to reduce the occurrence of CBPP in cattle. Vaccines are medicines given to offer protection for animals against specific diseases. The protection is most likely to be achieved if a sufficient proportion of animals in the area receive the vaccine [usually two-thirds of the cattle in an area (70% or 7 out of every 10 cattle)]. When done properly, about 70% of the cattle (70%) are protected against CBPP for one year after vaccination. Some of the cattle may experience some side effects after taking the vaccine. The vaccine needs to be taken at least once every year, for it to work.



Now we will like to ask you what you are willing to pay for CBPP vaccination. We are not selling or providing the vaccine, but trying to understand the need for vaccines in Ghana. Please ask any questions you have at this point. Now, we proceed:

A. Suppose that the CBPP vaccine will fully protect each vaccinated animal against CBPP for one year. For this example, assume you have ten cattle to vaccinate. Will you pay GHC 60 for this protection of the animals for one year against CBPP?

☐ Yes ☐ No

B. If the respondent says YES to the initial bid, present the second bid amount with the following statement using a 25%, 50% or 75% increment to the first bid amount depending on the randomly selected premium: Assume you have ten cattle to vaccinate, will you pay GHC (75, 90 or 105) for this protection of the animals for one year against CBPP?

☐ Yes ☐ No

C. If the respondent says NO to the initial bid, present the second bid amount with the following statement using a 25%, 50% or 75% discount to the first bid amount depending on the selected randomized discount: Assume you have ten cattle to vaccinate, will you pay GHC (45, 30 or 15) for this protection of the animals for one year against CBPP?

☐ Yes ☐ No

WTP Experiment (For Goat Owners)

PPR is a serious disease that mainly affects sheep and goats. The PPR virus is spread through close contact between goats or sheep infected and others that do not have protection against it. The protection is effectively provided through vaccination. PPR is highly infectious and kills between 30–70% of the goats or sheep it infects (about 5 out of every 10 goats/sheep infected). Common signs of the infection are high fever, eye and nose discharges, sore in the mouth, diarrhoea and difficulty breathing. The presence of PPR in a herd (pen) results in direct losses through increased deaths, reduced weight gain, and reduced fertility rate. Therefore it affects farmer income. It also causes indirect losses through the additional cost of treatment, slaughter and sale of sick animals.

PPR has been targeted to be eliminated in all countries in the world. Vaccination is the only strategy to achieve this goal. Vaccines are drugs given to offer protection for animals against specific diseases. The protection is most likely to be achieved if all goats in an area receive the vaccine (but at least 8 out of every 10 goats). When done properly, the vaccinated goats are protected against PPR for one year, but the protection may last for life if the disease is not re-introduced in the area. Some of the goats may experience some side effects after taking the vaccine. The vaccine needs to be taken by most of the eligible goats (from 3 months old) for it to work to ensure the elimination of the disease forever.

Now we will like to ask you what you are willing to pay for PPR vaccination. We are not selling or providing the vaccine, but trying to understand the need for vaccines in Ghana. Please ask any questions you have at this point. Now, we proceed:

A. Suppose that the PPR vaccine will fully protect each vaccinated animal against PPR for one year. For this example, assume you have ten goats to vaccinate, will you pay GHC 50 for this protection of the animals for one year against PPR?

☐ Yes ☐ No

B. If the respondent says YES to the initial bid, present the second bid amount with the following statement using a 25%, 50% or 75% increment to the first bid amount depending on the randomly selected premium: Assume you have ten goats to vaccinate, will you pay GHC (62.5, 75 or 87.5) for this protection of the animals for one year against PPR?

☐ Yes ☐ No

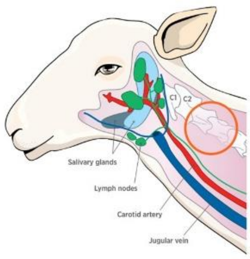
C. If the respondent says NO to the initial bid, present the second bid amount with the following statement using a 25%, 50% or 75% discount to the first bid amount depending on the randomly selected discount: Assume you have ten goats to vaccinate, will you pay GHC (37.5, 25 or 12.5) for this protection of the animals for one year against PPR?

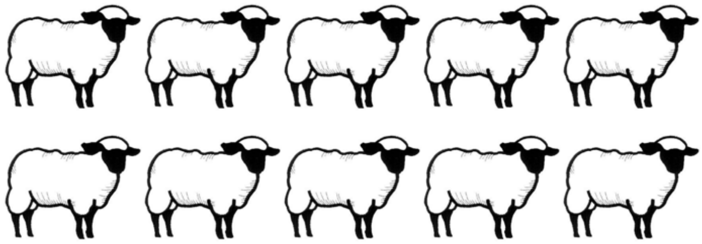
☐ Yes ☐ No

WTP Experiment (For Sheep)

PPR is a serious disease that mainly affects sheep and goats. The PPR virus is spread through close contact between goats or sheep infected and others that do not have protection against it. The protection is effectively provided through vaccination. PPR is highly infectious and kills between 30–70% of the goats or sheep it infects (about 5 out of every 10 goats/sheep infected). Common signs of the infection are high fever, eye and nose discharges, sore in the mouth, diarrhoea and difficulty breathing. The presence of PPR in a herd (pen) results in direct losses through increased deaths, reduced weight gain, and reduced fertility rate. Therefore it affects farmer income. It also causes indirect losses through the additional cost of treatment, slaughter and sale of sick animals.

PPR has been targeted to be eliminated in all countries in the world. Vaccination is the only strategy to achieve this goal. Vaccines are drugs given to offer protection for animals against specific diseases. The protection is most likely to be achieved if all sheep in an area receive the vaccine (but at least 8 out of every 10 sheep). When done properly, the vaccinated sheep are protected against PPR for one year, but the protection may last for life if the disease is not re-introduced in the area. Some of the sheep may experience some side effects after taking the vaccine. The vaccine needs to be taken by most of the eligible sheep (from 3 months old) for it to work to ensure the elimination of the disease forever.





Now we will like to ask you what you are willing to pay for PPR vaccination. We are not selling or providing the vaccine, but trying to understand the need for vaccines in Ghana. Please ask any questions you have at this point. Now, we proceed:

A. Suppose that the PPR vaccine will fully protect each vaccinated animal against PPR for one year. For this example, assume you have ten sheep to vaccinate, will you pay GHC 50 for this protection of the animals for one year against PPR?

☐ Yes ☐ No

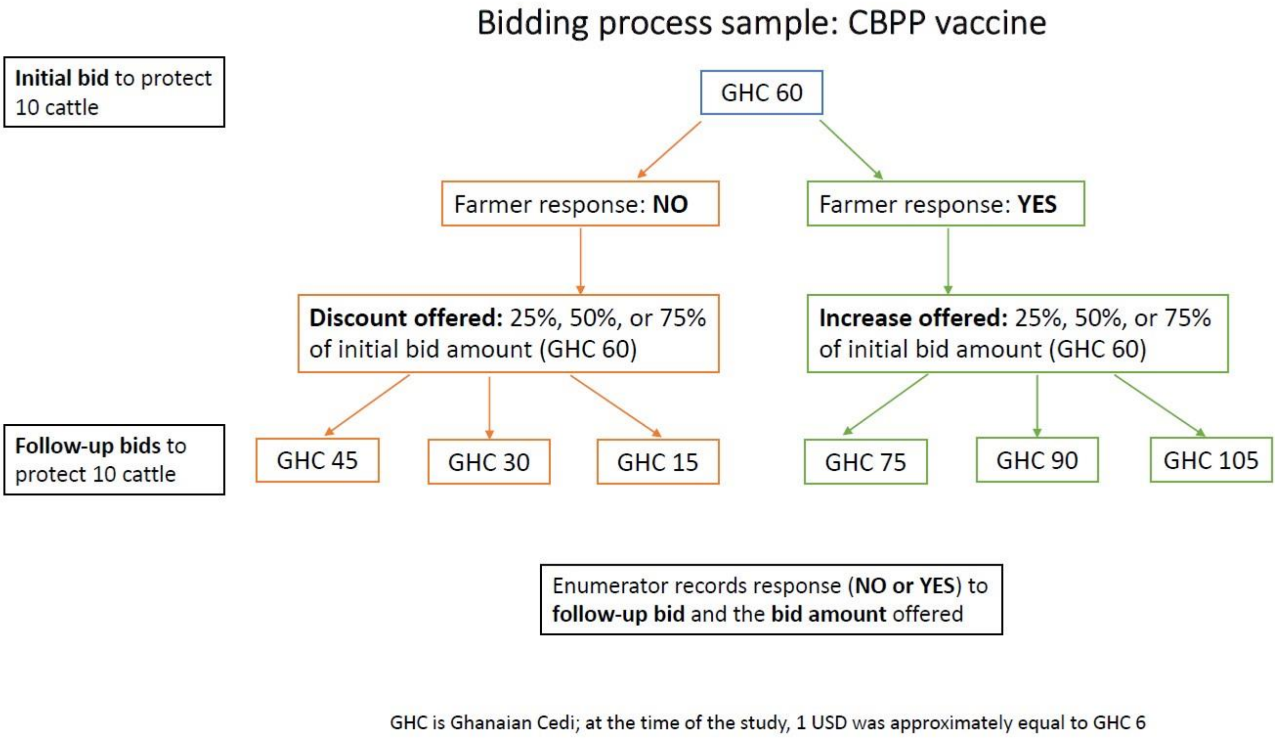
B. If the respondent says YES to the initial bid, present the second bid amount with the following statement using a 25%, 50% or 75% increment to the first bid amount depending on the randomly selected premium: Assume you have ten sheep to vaccinate, will you pay GHC (62.5, 75 or 87.5) for this protection of the animals for one year against PPR?

☐ Yes ☐ No

C. If the respondent says NO to the initial bid, present the second bid amount with the following statement using a 25%, 50% or 75% discount to the first bid amount depending on the randomly selected discount: Assume you have ten sheep to vaccinate, will you pay GHC (37.5, 25 or 12.5) for this protection of the animals for one year against PPR?

☐ Yes ☐ No

S2 File: Summary of bidding process in the double-bounded contingent valuation experiment

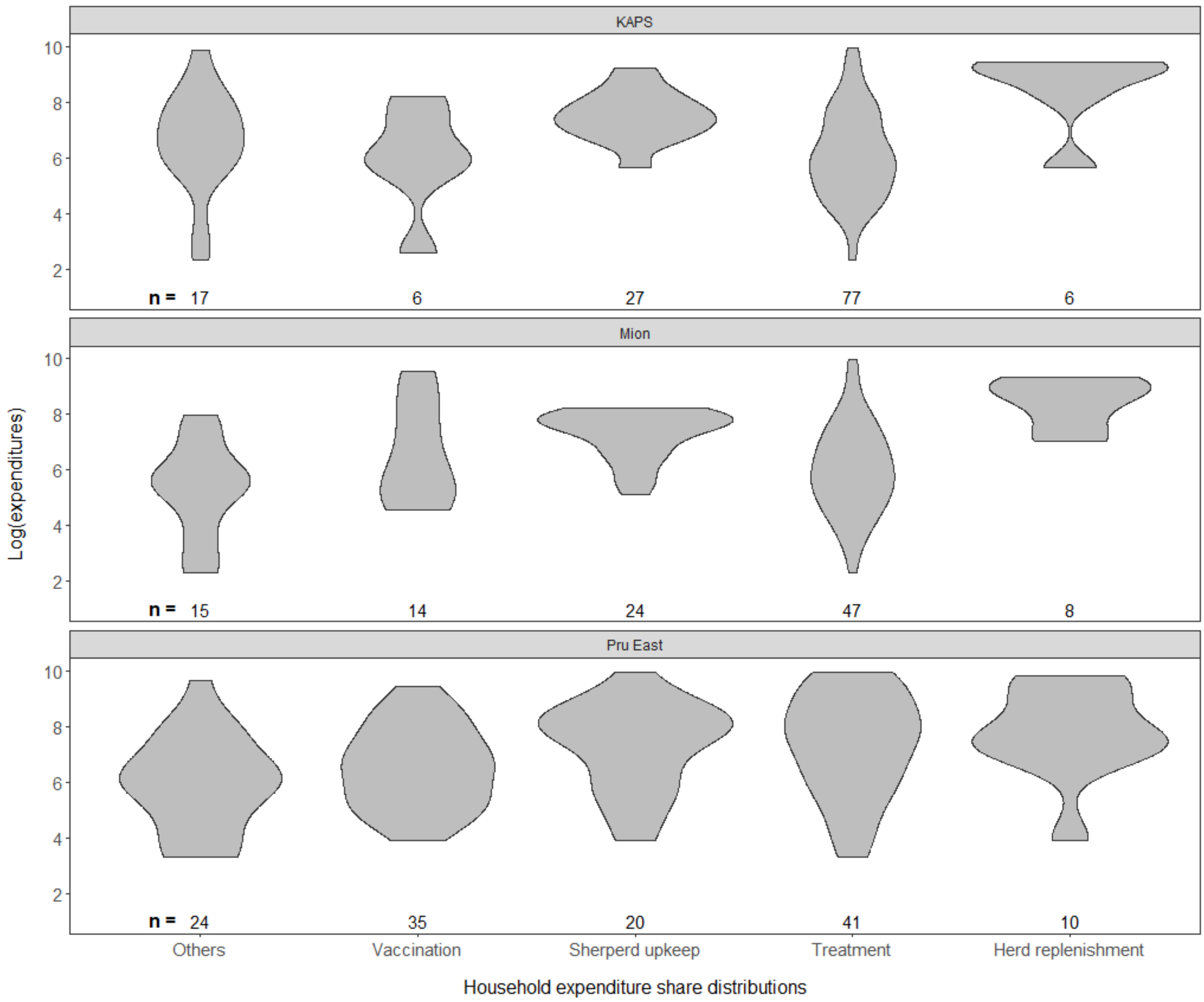


S3 Files 1 & 2: Survey Stata dataset and do file for WTP analysis

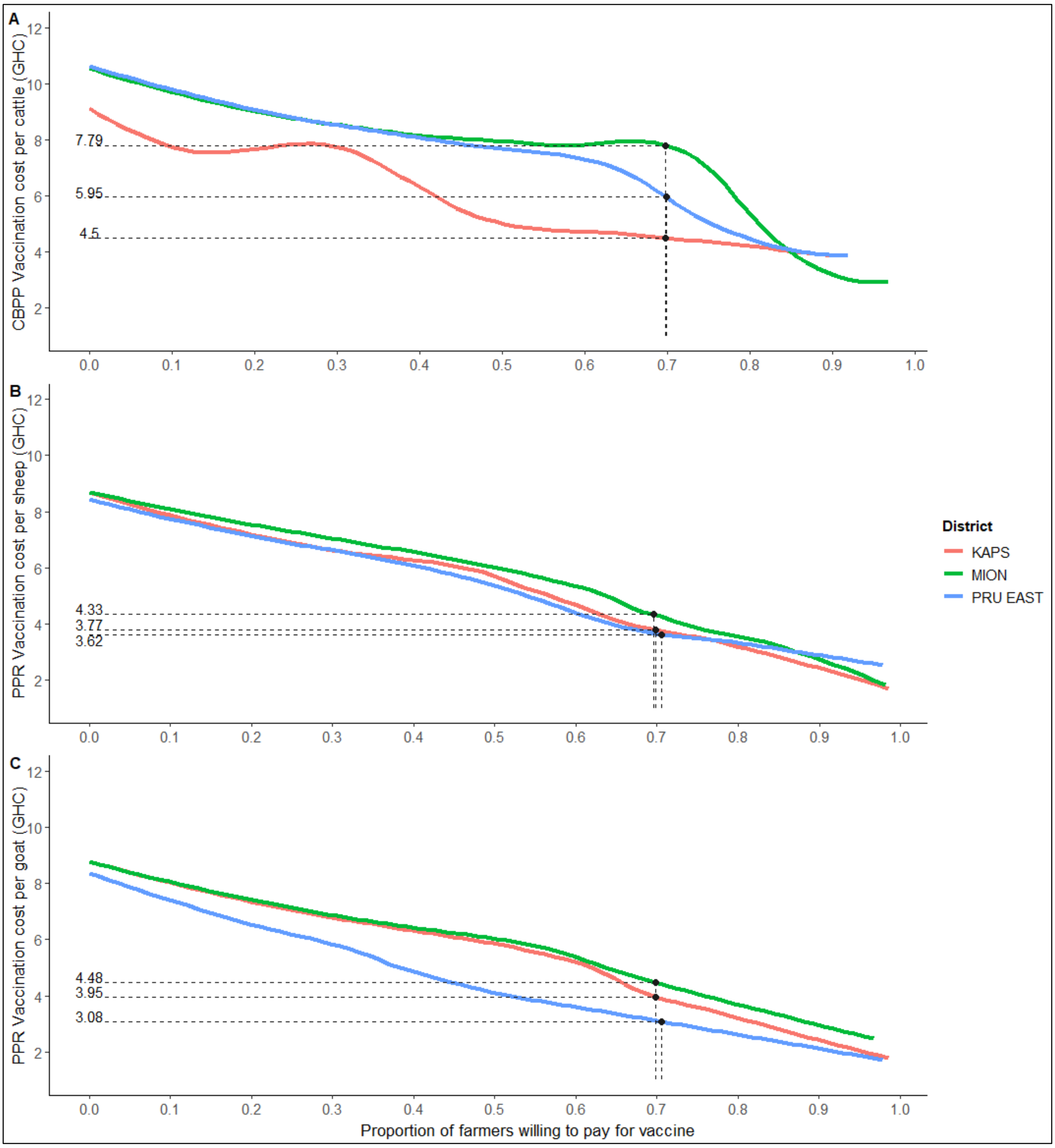
The Stata dataset and do file for the WTP analysis can be accessed via the following link:

http://dx.doi.org/ 10.1016/j.prevetmed.2023.106028

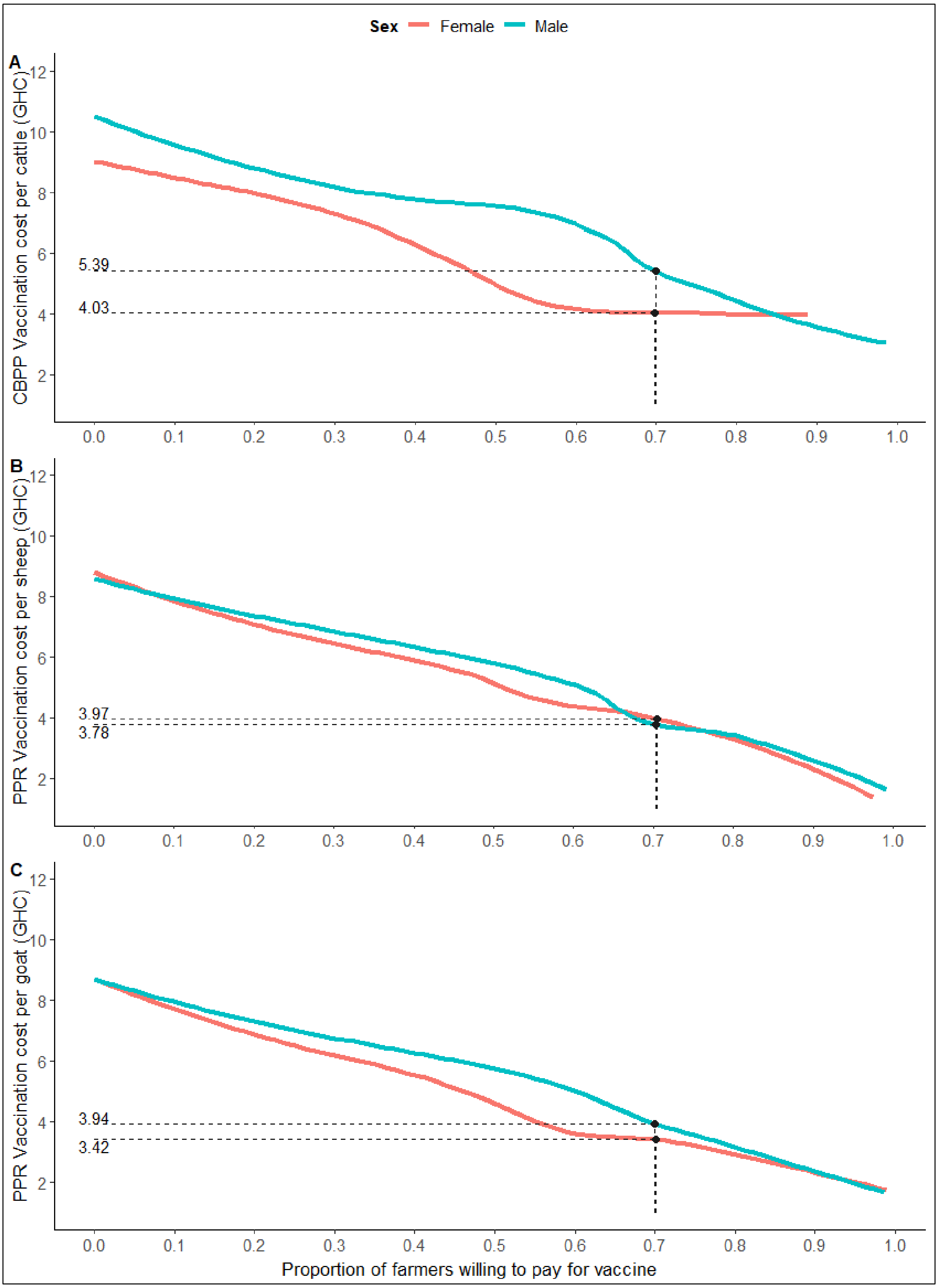
S4 Figure: Ruminant livestock farming households' expenditure share distributions by district



S5 Figure: Cumulative proportion of livestock farmers willing to pay for vaccination to protect their herds against CBPP infection in cattle, and PPR infection in sheep and goats by district



S6 Figure: Cumulative proportion of livestock farmers willing to pay for vaccination to protect their herds against CBPP infection in cattle, and PPR infection in sheep and goats by sex



Chapter 7 Relationship between animal health and livestock farmers' wellbeing in Ghana: beyond zoonoses

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7.1 Abstract

Introduction: Livestock production is a key livelihood source for many people in developing countries. Poor control of livestock diseases hamper livestock productivity, threatening farmers' wellbeing and food security. This study estimates the effect of livestock mortalities attributable to disease on the wellbeing of livestock farmers.

Methods: Overall, 350 ruminant livestock farmers were randomly selected from three districts located in the north, middle and southern belts of Ghana. Mixed-effect linear regression models were used to estimate the relationship between animal health and farmer wellbeing. Farmer wellbeing was assessed using the WHOQOL-BREF tool, as the mean quality-of-life in four domains (physical, psychological, social, and environmental). Animal health was assessed as annual livestock mortalities to diseases adjusted for herd size, and standardized in tropical livestock units to account for different ruminant livestock species. We adjusted for the potential confounding effect of farmers' age, sex, educational attainment, farmland size, socio-economic status, perception of disease risk to herd, satisfaction with health, previous experience of disease outbreaks in herds, and social support availability by including these as fixed effects, and community as random effects, in a pre-specified model.

Results: Our results showed that farmers had a median score of 65.5 out of 100 (IQR: 56.6 –73.2) on the wellbeing scale. The farmers' reported on average (median) 10% (IQR: 0 – 23) annual herd mortalities to diseases. There was a significantly negative relationship between increasing level of animal disease-induced mortality in herds and farmers' wellbeing. Specifically, our model predicted an expected difference in farmers' wellbeing score of 7.9 (95%CI 1.50 – 14.39) between a farmer without any herd mortalities to diseases compared to a (hypothetical) farmer with 100% of herd mortalities caused by diseases in a farming year. Thus, there is a reduction of approximately 0.8 wellbeing points of farmers, for the average of 10% disease-induced herd mortalities experienced.

Conclusions: Disease-induced livestock mortalities have a significant negative effect on farmers' wellbeing, particularly in the physical and psychological domains. This suggests that veterinary service policies addressing disease risks in livestock, could contribute to improving the wellbeing of livestock dependent populations, and public food security.

Keywords: Wellbeing, Quality of life, Livestock farmers, Livestock diseases, One Health.

7.2 Introduction

Livestock production remains a key source of livelihood for many people in developing countries, particularly for rural dwellers (Herrero et al., 2013). Livestock production contributes to public food security and revenues, as well as individual-level food resources, economic prosperity, and as an asset store against uncertainty (FAO et al., 2021; OECD and FAO, 2021). In spite of its value to society, livestock production is hampered by adverse events including climate variabilities, conflicts, and animal disease outbreaks. These adversities negatively affect the productivity of the livestock sector (FAO et al., 2021).

In many sub-Saharan African countries including Ghana, transboundary animal diseases are highly prevalent due to an inadequate adoption of disease prevention and control measures, causing significant herd mortalities (Grace et al., 2015). The lack of adequate prevention of diseases in animals predisposes humans, and the ecosystem to heightened risks of zoonotic disease, antimicrobial residue spread and related antimicrobial resistant pathogens (Kimera et al., 2020; Zinsstag et al., 2023a). Beyond these risks to human and ecosystem health, livestock mortalities could also affect the wellbeing of livestock dependent populations. Previous research has shown a negative effect of animal disease-related mortalities on livestock farmers' psychological wellbeing (Mort et al., 2005; Nuvey et al., 2020). Although other dimensions of the wellbeing of livestock farmers could be affected by poor animal health, there is a dearth of evidence on the extent of these effects in the literature.

Human wellbeing and productivity are closely interconnected. Research has shown a strong two-way link between productivity and wellbeing of people; better wellbeing has a strong and positive impact on productive performance in work, while the productivity gains from high performance also contribute to better wellbeing of people through higher incomes, life and job satisfaction (Sharpe and Fard, 2022). It is essential therefore, that challenges affecting the wellbeing of working people be addressed to foster better productivity. Wellbeing could be measured either objectively or subjectively. Objective measurements of wellbeing are often implemented as aggregate population level indexes of wellbeing using different indicators such as the human development index (United Nations Development Programme, 2019), while subjective wellbeing measures involve assessment of individual's own perception of their wellbeing (OECD, 2020). The WHO Quality of Life – BREF (WHOQOL – BREF) tool is often used to assess individual's perception of their own wellbeing including their satisfaction with the level of functioning (WHO, 1998).

A livestock herd's health is measured by the herd's productivity and ability to limit the incidence and effect of economically important diseases (Bowen, 2016). Although previous research has highlighted significant connections between human and animal health, the majority of existing literature has predominantly focused on areas such as the potential for zoonotic diseases, impact of antimicrobial usage on the development of pathogen resistance, and the effect of animal diseases on food security (Jones et al., 2008; Chitnis et al., 2015; Cunningham et al., 2017; Van Boeckel et al., 2017; Rohr et al., 2019; Azabo et al., 2022). It is worth noting that livestock farmers share strong bonds with their animals, with livestock fulfilling additional social roles, including serving as companion animals for farmers (Petitt, 2013; Hoffet, 2015). Hence, the impact of poor animal health on livestock farmers can potentially extend beyond livelihood loss, zoonotic infections, and food insecurity. Our goal in this study therefore was to evaluate the average impact on a livestock farmer's wellbeing that could be attributed to the health and mortality of animals in the farmer's herd.

7.3 Materials and methods

Description of study area

This study was conducted in the Mion, Pru East and Kwahu Afram Plains South (KAPS) Districts, which are representative of the northern, middle and southern farming belts of Ghana. The districts lie in the Guinea Savannah, Transition and Deciduous forest Vegetation zones, which are the main livestock production zones in Ghana (**Figure 5**) (GSS, 2014b, c, a). Agriculture contributed about one-fifth of the national gross domestic product of Ghana in 2019 with the livestock sector accounting for 14% of this production (GSS, 2020b). The selected districts are mainly rural and agrarian, with about one-third of the livestock holdings of households being ruminant species. The ruminant livestock species mainly reared by farmers include cattle, sheep, and goats. While the non-ruminant livestock species reared, include poultry, pigs, and rabbits (GSS, 2020a).

Study design

This study was a cross-sectional survey involving 350 ruminant livestock owners. The survey was conducted as a part of a larger project that employed a convergent parallel mixed-method design to assess the effectiveness of veterinary interventions in Ghana. The full details of the project design is provided in an earlier paper (Nuvey et al., 2023c). In summary, the wellbeing of the ruminant livestock farmers in the study was assessed using the WHO Quality of life – BREF tool, and herd health was assessed as the proportion of annual herd mortalities attributable to diseases. We evaluate in this paper, the sensitivity of farmer's wellbeing to the level of disease-induced animal mortalities in the farmer's herd, adjusting for other pre-specified covariates.

Study population

The study population included all ruminant livestock farmers' in the study area. We first obtained district maps and created a sampling frame of villages within the study area. Based on the population and housing census data available prior to the study (2010 Population and Housing Census), there was about 80,880, 54,694, and 47,230 tropical livestock units (TLUs) of ruminant livestock species in the KAPS, Mion and Pru East Districts respectively, with an average of about 10 holdings per household. We randomly drew from the sampling frame, 15 villages in the KAPS District, and 10 villages each in the Pru East and Mion Districts, proportional to the number of livestock farming households per district (GSS, 2014b, c, a). A household refers to a person or group of persons who normally live together and are catered for as one unit; members may or may not be related. Any member of the household who takes responsibility for the upkeep of the household's livestock was eligible to participate in the study.

Sample size and sampling technique

The sample size determination and sampling procedure for the survey is described in detail in an earlier paper (Nuvey et al., 2023c). In summary, 350 livestock farmers were recruited from 38 villages in the three study districts, proportional to the size of ruminant livestock owning households using segmentation; where selected villages are divided into smaller equal units called segments depending on size, and all eligible households recruited in one randomly selected segment (Himelein et al., 2016). In selected segments of the study villages, all households who keep ruminant livestock were eligible to be selected and the households providing consent were recruited to participate in the survey. For villages where sufficient households were not attained due to low number of livestock-owning households, the adjoining village was selected in an attempt to reach the desired sample size. Overall, the median number of farmers recruited per village was 10 farmers [interquartile range (IQR) = 7 to 11].

Data collection and data management

The enumeration team visited the households keeping ruminant livestock to administer the questionnaires between November 2021 and January 2022. The survey questionnaire was administered to the respondents' face-to-face using tablets with Open Data Kit (ODK) application (Hartung et al., 2010). The data collected included social support availability to farmers, farmers' perception of disease risk to herd, farmers' wellbeing and satisfaction with health, and other socio-demographic characteristics. The livestock farmers' wellbeing was assessed using the WHO Quality of life – BREF (WHOQOL-BREF) tool (WHOQOL Group, 1996). The WHOQOL-BREF is a 26-item 5-point Likert scale, with scores ranging from 1 to 5; higher scores on the scale denote better wellbeing. Two of the items on the scale assess the study subject's own perception of quality of life or wellbeing and overall satisfaction with health status, and are excluded in the analysis for wellbeing. The 24 questions assess individual's perception of their wellbeing on the physical, psychological, social, and environmental domains. Farmers' perception of disease risk to herds was assessed on a five-item Likert scale with responses ranging from 1 to 5; higher scores indicate higher risk perception of the diseases to a herd. The social support level available to farmers was assessed on a 5-point Likert scale of the level of support, the farmers received from different facets of society including family, friends, law enforcement, credit institutions, community leaders and religious leaders, to aid them in livestock farming. We measured animal health using reported annual disease-induced mortalities of livestock relative to a herd size, and standardized in tropical livestock units (Farrell and Davies, 2019). The data was downloaded in Microsoft Excel format from ODK and imported into R version 4.1 (RStudio Team, 2022) for analyses.

Data analyses

We performed descriptive analyses of the survey data, comparing the distribution of responses by study district. The farmers' herd sizes were converted to tropical livestock units (TLU) to standardize livestock holdings as follows: 1 TLU corresponds to 0.75 cattle and 0.1 small ruminants (sheep and goats) (Rothman-Ostrow et al., 2020). The number of animal mortalities were also converted to TLUs. The relative wealth of households was determined using an index of household's ownership of selected assets, such as televisions, refrigerators and bicycles (ICF, 2019). We determined the severity of losses suffered as the proportion of a herd lost to different factors in TLUs. The social support available to a farmer was the sum of the reported support level received from the different sources. We derived the disease risk to herd perception score as the sum of the Likert scale scores. One item score on the perception scale (Q4) is reversed to achieve a similar direction of the perception score. For the wellbeing score, firstly three negatively framed items (Q3, Q4, and Q26) were reversed to achieve a similar direction of wellbeing scores. To obtain the scores for each wellbeing domain, the mean of all items included within each wellbeing domain is calculated, and multiplied by a factor of four and then transformed to a scale from 0 to 100, according to the tool's guidelines (WHOQOL Group, 1996). We derived the overall wellbeing score as the average of the four wellbeing dimension scores (Feder et al., 2015).

We performed univariable analyses, using linear regression models to compare the relationship between farmers' wellbeing and the level of mortalities in their herds [categorized in three quantiles (tertiles): low, moderate and severe] to all causes, and specifically to diseases. We present the results using boxplots, comparing the average wellbeing scores between the levels of herd mortalities. In a pre-specified linear regression model, we evaluated the hypothesis that the level of animal disease-induced mortality in herds (herd health) is associated with farmers' overall wellbeing, accounting for the potential confounding effects of other covariates in a linear mixed effects model. The level of disease-induced herd mortality is derived as the number of animals lost to diseases relative to each farmers' herd size (both in TLUs). The covariates included in the model were farmers' age, sex, educational attainment, farmland size, wealth status, perception of disease risk to herds, overall satisfaction with health, and level of social support received as fixed effects, and village-level clusters as random effects in a linear mixed effect regression model. Values of $p<0.05$ were considered statistically significant. We performed sensitivity analysis to assess the robustness of the findings, and examined model residuals to determine if key assumptions of model fit were met.

7.4 Results

Socio-demographic characteristics of study respondents

Table 16 presents the socio-demographic characteristics of all study respondents (N = 350) stratified by district. The median age of the farmers completing the survey was 45 years (IQR = 35 to 54 years). The median household size was 8 persons (IQR = 6 to 11 persons), with each household keeping on average (median) 2.5 TLUs of ruminant livestock per herd (IQR = 1.3 to 7.0 TLUs). More than 95% (333/350) of the respondents own the livestock themselves. The farmers also cultivated on average 7 acres of farmland (IQR = 3 to 15 acres) in addition to rearing livestock. More than two-thirds (71%) of the respondents were male, and about half of farmers had received no formal education (51%). The wealth index analysis of households showed that in the Mion District, 67% of households were in the poorest two wealth quintiles, while the same was true only for 42% of households in KAPS and for 16% of households in the Pru East Districts. On average, farmers ranked the social support received in the study year at 6 out of 30 (IQR = 6 to 8). The social support was received mainly from family and friend sources (**Figure 15**). Farmers scored on average, 19 out of 25 (IQR = 17 to 21) on the disease risk perception scale.

Table 16: Socio-demographic characteristics of the study respondents by study district

Characteristic	KAPS	MION	PRU EAST
	Median (IQR)	**Median (IQR)**	**Median (IQR)**
Age (years)	46 (36, 56)	41 (34, 51)	46 (34, 57)
Household size (persons)	7 (5, 10)	10 (7, 15)	8 (6, 13)
Health satisfaction score	75 (50, 75)	75 (50, 75)	75 (50, 75)
	% (n/N)	**% (n/N)**	**% (n/N)**
Sex			
Female	38% (57/149)	16% (16/98)	28% (29/103)
Male	62% (92/149)	84% (82/98)	72% (74/103)
Educational attainment			
No formal education	28% (41/149)	87% (85/98)	51% (52/103)
Up to 12 years education	48% (72/149)	6% (6/98)	28% (29/103)
Higher education	24% (36/149)	7% (7/98)	21% (22/103)
Wealth status			
Poorest	14% (21/149)	42% (41/98)	8% (8/103)

Below average	28% (41/149)	26% (25/98)	8% (8/103)
Average	24% (36/149)	14% (14/98)	15% (16/103)
Above average	25% (37/149)	10% (10/98)	22% (23/103)
Least poor	9% (14/149)	8% (8/98)	47% (48/103)
Farm size (acres)			
Small (1st tertile: 0 – 5 acres)	63% (94/149)	16% (16/98)	28% (29/103)
Medium (2nd tertile: 6 – 11 acres)	21% (31/149)	43% (42/98)	21% (22/103)
Large (3rd tertile: 12 – 99 acres)	16% (24/149)	41% (40/98)	51% (52/103)
Herd size (TLU)			
Small (1st tertile: 0.3 – 1.6 TLUs)	42% (62/149)	43% (42/98)	23% (24/103)
Medium (2nd tertile: 1.7 – 4.2 TLUs)	31% (46/149)	24% (24/98)	35% (36/103)
Large (3rd tertile: 4.3 – 181.9 TLUs)	27% (41/149)	33% (32/98)	42% (43/103)

For continuous variables, the median value with corresponding lower and upper quartile values (IQR) are presented in parentheses. Percentages (%) are the proportions of ruminant livestock farmers within each characteristic explored per study district sub-sample (N). Numbers (n) of farmers, falling into each sub-category of characteristics within the study districts; Kwahu Afram Plains South (KAPS), Mion and Pru East Districts.

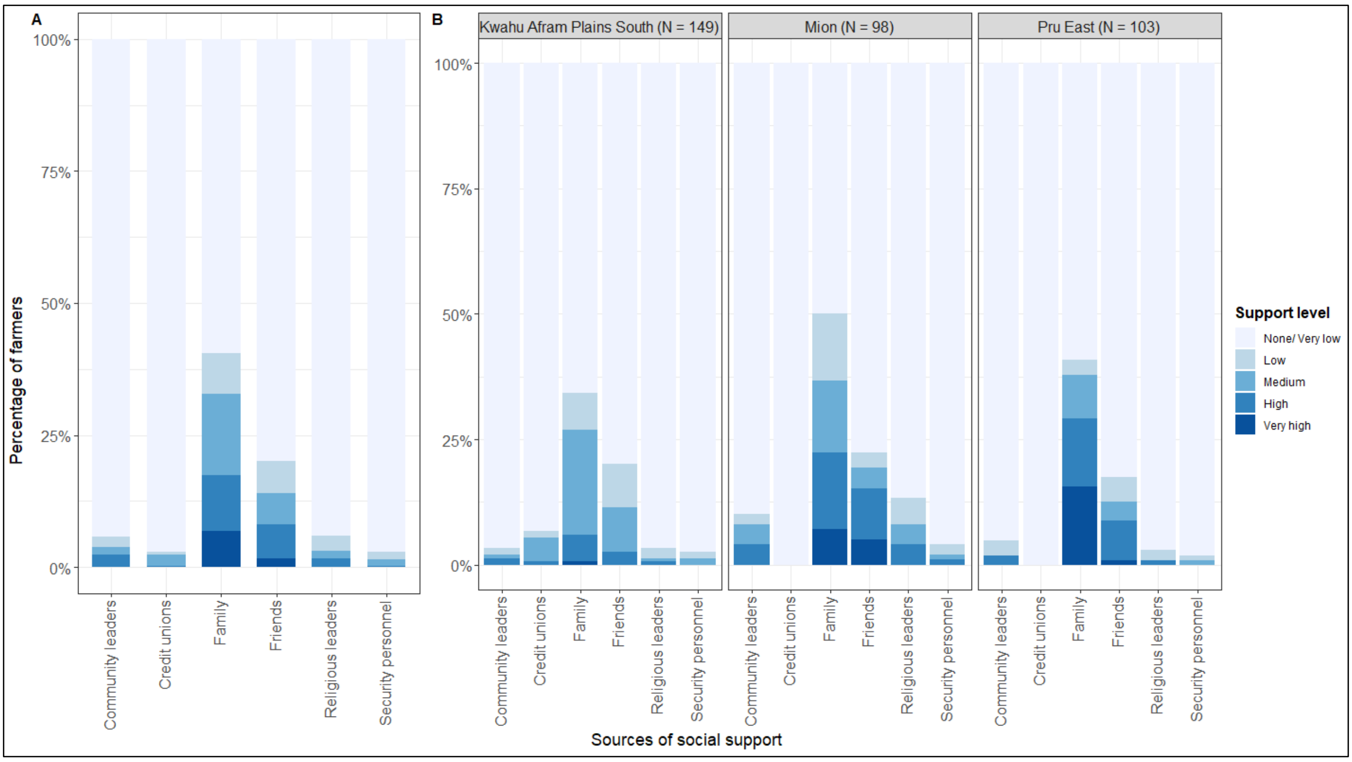

Figure 15: Sources and level of social support available to livestock farmers in Ghana.

Panel A presents the un-stratified distribution of support availability to farmers from the listed sources, while **Panel B** presents the stratified distribution of support received by study district. The height and gradient of the color shows the proportion of farmers and the level of support received from each source respectively. For the gradient of the coloration, light coloration depicts no or very low support level from a source and deep coloration depicts very high support level. The y-axis shows the proportion of the farmers receiving support from a source.

Effect of livestock mortality on livestock farmers' wellbeing

The farmers reported a median of 0.5 TLUs (IQR = 0.1 to 1.4 TLUs) of ruminant livestock mortalities per herd in the study year (2021), corresponding to an average (median) of 19% mortality per herd (IQR = 6% to 37%). Livestock diseases accounted for the majority of reported herd mortalities. The farmers reported a median disease-induced mortalities of 10% of the herds (IQR = 0% to 23%) (**Figure 16**). About 45% (159/350) of farmers had past history of disease outbreaks in their herds, while 47% (164/350) of them reported a disease outbreak in the study year (2021).

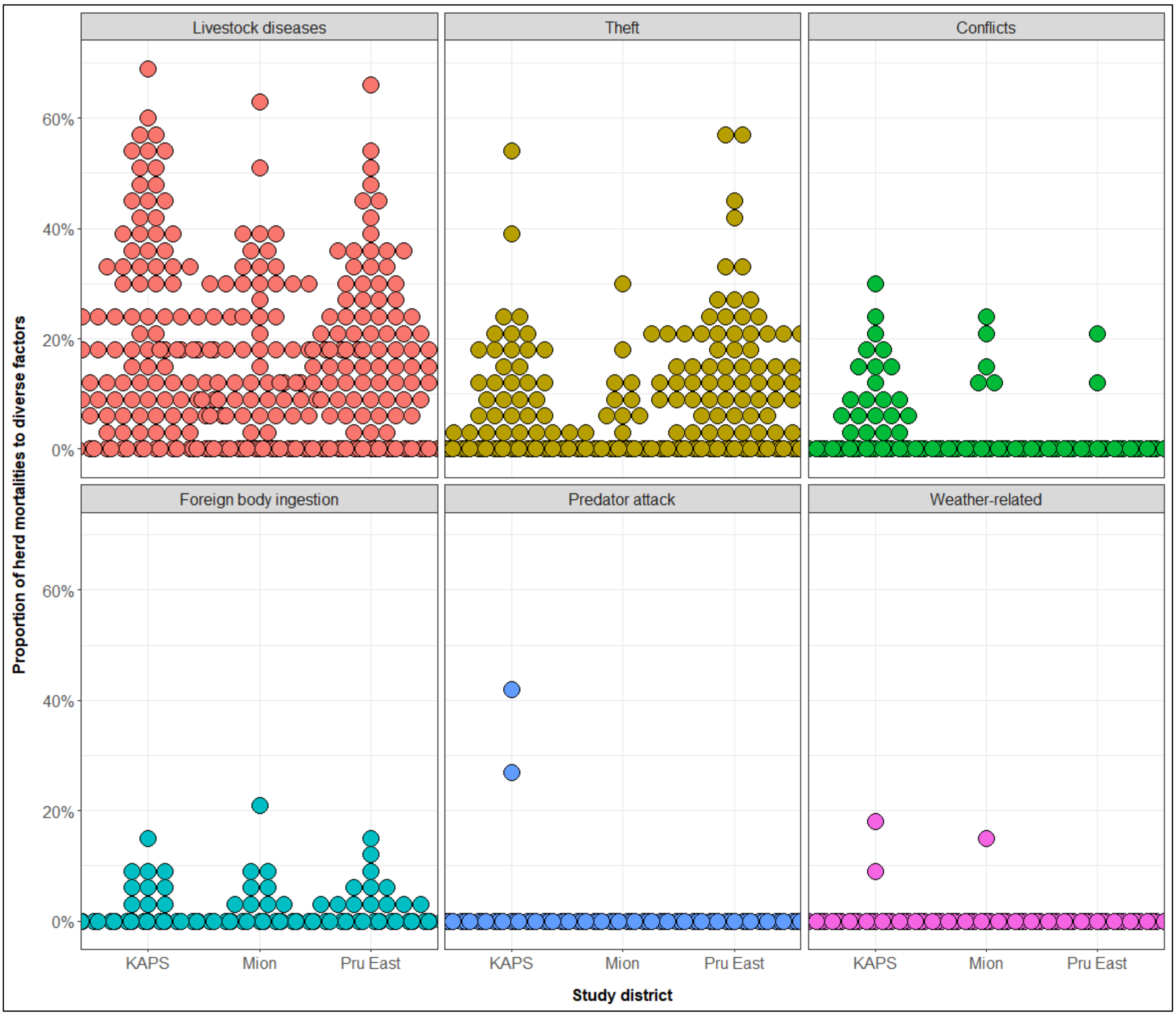

Figure 16: Factors causing animal mortality in ruminant livestock herds in Ghana.
The y-axis shows the proportion of herd mortalities for each specified factor depicted by different colors for a livestock farmer and stratified by study district. The position of each dot on the y-axis denotes each individual farmer's level of reported losses to a factor.

Table 17 presents the farmers' scores on the physical, psychological, social and environmental domains of wellbeing, as well as a pooled overall wellbeing score. The farmers scored on average (median) 71.4 out of 100 (IQR = 57.1 to 85.7) on the physical, 70.8 out of 100 (IQR = 58.3 to 79.2) on the psychological, 66.7 out of 100 (IQR = 50.0 to 75.0) on the social and 56.3 out of 100 (IQR = 43.8 to 65.6) on the environmental domains of wellbeing. The median overall wellbeing score was 65.5 out of 100 (IQR = 56.6 to 73.2). The farmers ranked their overall satisfaction with health at 75 out of 100 on average (IQR = 50 to 75).

Table 17: Summary of overall wellbeing and wellbeing domain scores by study district

Domain	Number of items	KAPS	MION	PRU EAST
		Median (IQR)	**Median (IQR)**	**Median (IQR)**
Overall wellbeing	**24**	**65.1 (55.8, 72.5)**	**67.0 (60.3, 76.3)**	**64.8 (55.4, 72.2)**
Physical	7	71.4 (53.6, 82.1)	82.1 (67.9, 89.3)	67.9 (53.6, 78.6)
Psychological	6	66.7 (58.3, 79.2)	75.0 (62.5, 83.3)	66.7 (58.3, 75.0)
Social	3	66.7 (58.3, 75.0)	66.7 (58.3, 83.3)	58.3 (50.0, 75.0)
Environment	8	53.1 (43.8, 62.5)	50.0 (40.6, 62.5)	59.4 (50.0, 68.8)

Wellbeing domains include physical, psychological, social and environmental quality of life of farmers assessed using the WHO Quality of life – BREF tool; a 24-item 5-point Likert scale. Overall wellbeing is the average of scores in all the domains of wellbeing. Median wellbeing scores with corresponding interquartile ranges (IQR) stratified by study district are presented.

We assessed the relationship between the level of mortality in herds and overall farmer wellbeing. The levels of herd mortality to all causes and specifically to diseases, was categorized into tertiles (three quantiles); low, moderate and severe, based on the distribution of proportions of herd mortalities. **Figure 17** presents the relationship between farmers' wellbeing in all domains and the three levels of herd mortalities (low, moderate and severe) to all causes. Farmers with severe herd mortalities (more than 31% of herd mortality) had significantly lower levels of overall (mean score of 60.5 versus 66.5, $p < 0.001$), physical (64.1 vs 73.4, $p < 0.001$), psychological (64.6 vs 69.2, $p = 0.04$), and social (60.2 vs 68.2, $p < 0.001$) wellbeing, compared to farmers with low level of loss (less than 1% of herd mortality).

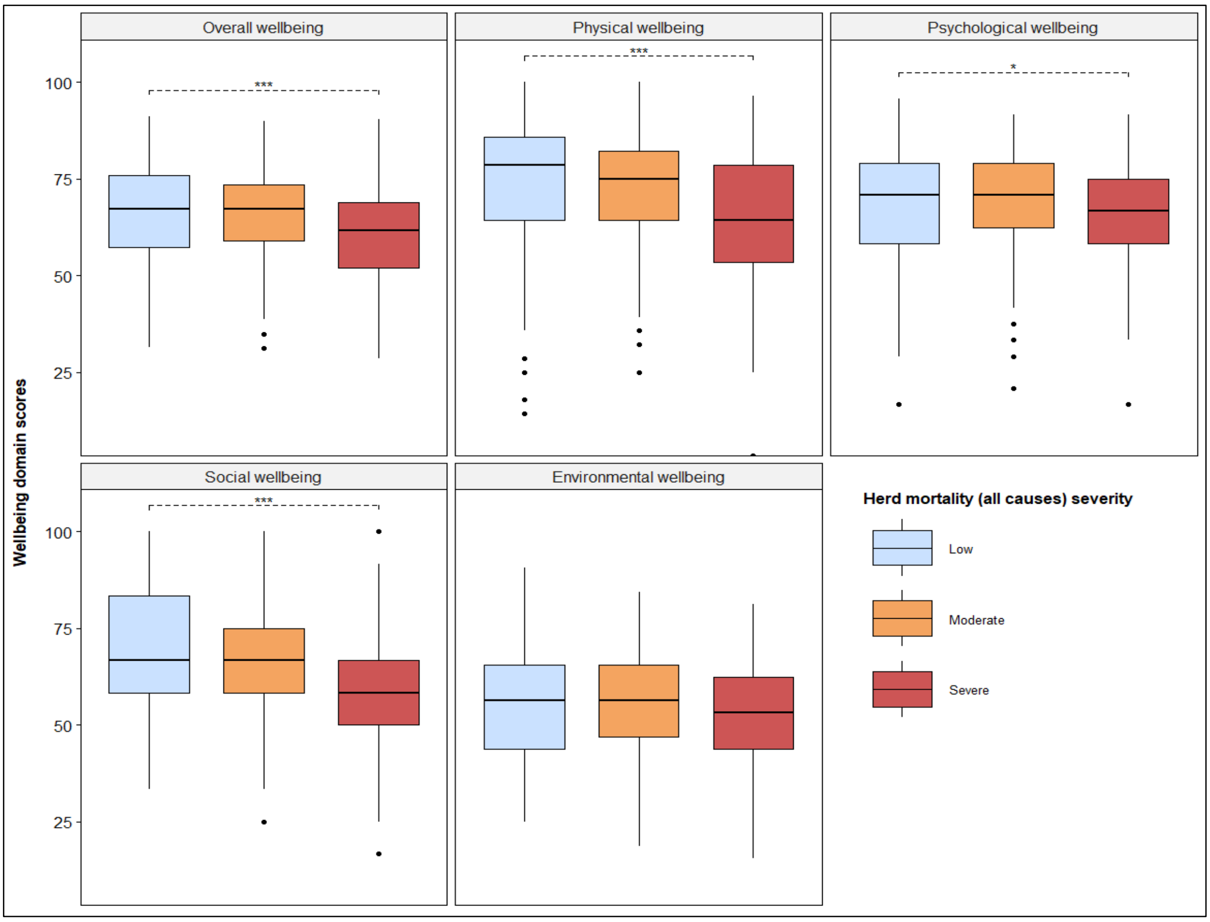

Figure 17: Relationship between the severity of herd mortality and farmers' wellbeing.

The figure shows the relationship between the level of herd mortality to all causes and farmers' wellbeing in all domains. The overall wellbeing is the average of wellbeing scores in the physical, psychological, social and environmental domains. The level of herd mortalities are reported animal deaths on farms due to all causes relative to a farmer's herd size in the study year. The level of herd mortality is categorized into tertiles (three quantiles) of severity: low (less than 1% of herd mortality), moderate (1 to 30% of herd mortality) and severe (more than 31% of herd mortality). The box plots show the average wellbeing scores with corresponding interquartile ranges for farmers within each level of herd mortality, with the levels of herd mortalities distinguished by colors. The dashed lines show significant results of hypothesis testing of the relationship between farmers' wellbeing and higher levels of herd mortalities compared to low loss levels using a linear regression model. *, ***, denote 5%, and 0.1% significance levels respectively.

The relationship between levels of herd mortalities specific to diseases and farmers' wellbeing is presented in **Figure 18**. The level of disease-induced herd mortalities was significantly associated with farmers' overall, physical, and psychological wellbeing. The farmers with severe herd losses (more than 18% of herd mortality to diseases), had significantly lower overall (mean score of 61.7 versus 66.9, p = 0.002), physical (65.1 vs 74.6, p < 0.001), and psychological (65.7 vs 70.6, p = 02) wellbeing scores, compared to the farmers with low level of losses (less than 1% of herd mortality to diseases). The farmers with moderate herd losses (between 1% and 18% of herd mortality) also had significantly lower physical (69.4 vs 74.6, *p* = 0.02) and psychological (66.7 vs 70.6, *p* = 0.04) wellbeing scores compared to the farmers with low level of loss.

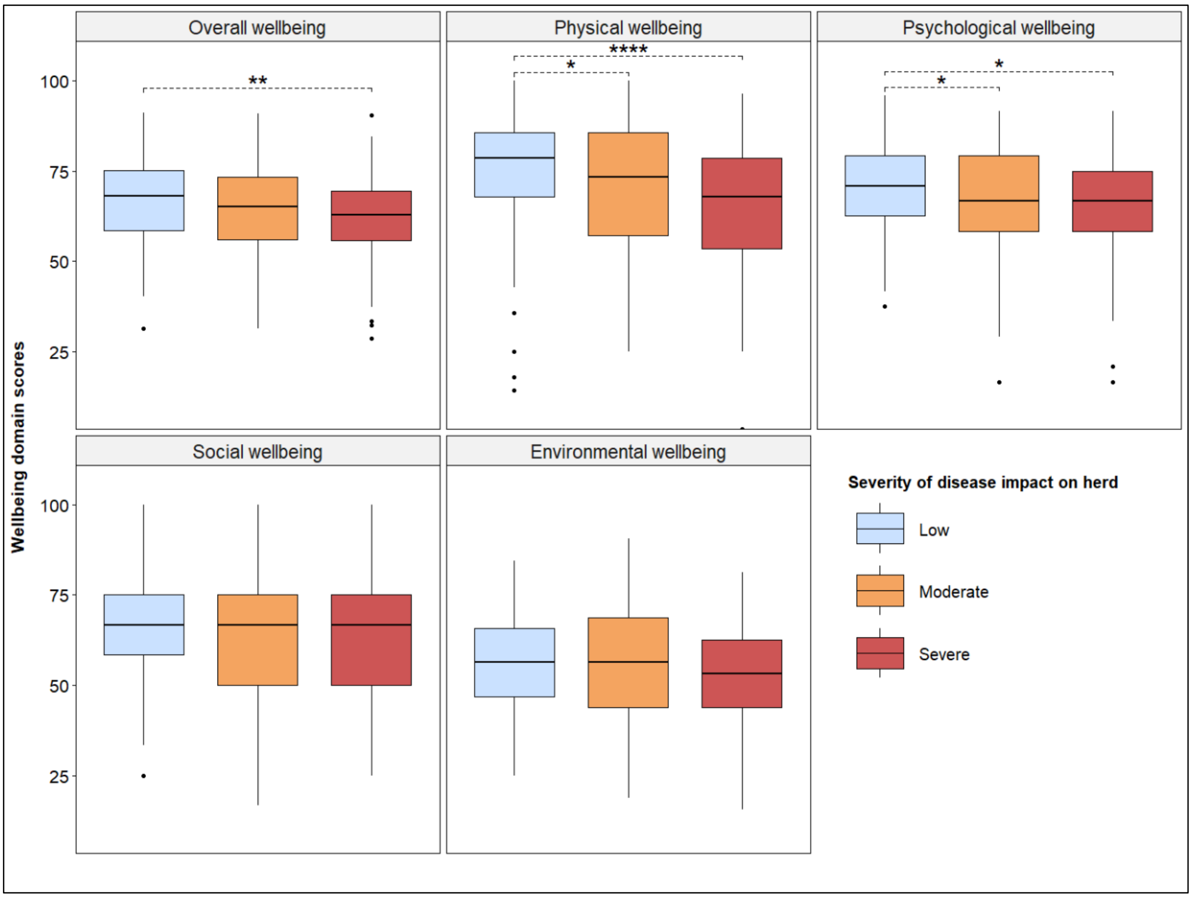

Figure 18: Relationship between the severity of herd mortality to diseases and farmers' wellbeing.

The figure shows the relationship between the level of herd mortality specifically to only diseases and farmers' wellbeing in all domains. The overall wellbeing is the average score of wellbeing scores in the physical, psychological, social and environmental domains. The level of herd mortalities are reported disease-induced animal deaths on farms relative to a farmer's herd size in the study year. The level of herd mortality is categorized into tertiles (three quantiles) of severity: low (less than 1% of herd mortality), moderate (1 to 18% of herd mortality) and severe (more than 18% of herd mortality). The box plots show the average wellbeing scores with corresponding interquartile ranges for farmers within each level of herd mortality, with the levels of disease-induced herd mortalities distinguished by colors. The dashed lines show significant results of hypothesis testing of the relationship between farmers' wellbeing and higher levels of herd mortalities to diseases compared to low loss levels using a linear regression model. *, **, ***, denote 5%, 1%, and 0.1% significance levels respectively.

Table 18 presents the results of the linear mixed effect regression model, with fixed effects for disease-related herd mortalities relative to the herd sizes (all in TLUs), farmers' age, sex, educational attainment, farmland size, wealth index, social support level received, overall satisfaction with health, and perception of disease risk to herd and village-level clusters as random effects. There was a significantly negative relationship between increasing levels of disease-induced herd mortalities and farmers' overall wellbeing. Specifically, our model predicted an expected difference in farmers' wellbeing score of 7.9 (95%CI 1.50 to 14.39) between a farmer without any animal mortalities compared to a hypothetical farmer with 100% of animal mortalities to diseases. Thus, there is a reduction of approximately 0.8 wellbeing points of farmers, for the average of 10% disease-induced herd mortalities experienced (**Figure 19**). A likelihood-ratio test showed that the model including disease-induced herd mortalities provided a better fit for the data than a model without it, $\mathcal{X}^2(1) = 6.13$, $p = 0.01$. Excluding livestock farmers who did not own animals in their herds did not change the results and conclusions (**Additional file 1**). In addition, including the other causes of animal mortalities relative to the herd size did not change significantly the effect size (**Additional file 2**).

Table 18: Mixed effects model predicting the effect of level of herd mortalities to diseases on farmer wellbeing scores adjusting for other covariates

Parameter	Estimate	95% CI	*p*-value
Fixed effects			
Proportion of herd mortality *	-7.94	-14.39 – -1.50	0.02
Satisfaction with health	0.27	0.23 – 0.32	<0.001
Social support received	0.84	0.47 – 1.22	<0.001
Perception of disease risk to herd	0.41	0.01 – 0.80	0.04
Age (years)	-0.10	-0.17 – -0.02	0.01
Farm size (acres)	0.06	-0.02 – 0.14	0.17
Sex [ref = female]			
Male	1.50	-0.72 – 3.71	0.19
Education level [ref = no formal education]			
Up to 12 years	0.01	-2.36 – 2.37	0.99
Higher education	2.27	-0.53 – 5.07	0.11
Wealth index [ref = poorest]			

Below average	0.08	-2.93 – 3.10	0.96
Average	2.80	-0.36 – 5.95	0.08
Above average	2.92	-0.38 – 6.23	0.08
Least poor	2.92	-0.53 – 6.38	0.09
History of disease outbreak [ref = No]			
Yes	-0.01	-2.21 – 2.20	0.99
Random effects			
Within cluster standard deviation	8.78	8.02 – 9.56	…
Between cluster standard deviation	2.08	0.00 – 3.44	…
Marginal R^2 / Conditional R^2	0.47 / 0.50		

* Proportion of herd mortality refers to livestock mortalities to diseases relative to herd size standardized in tropical livestock units. Estimates are the mean changes in overall wellbeing scores of ruminant livestock farmers attributable to changes in parameters, with their corresponding 95% confidence intervals (95% CI) and p-values. Overall wellbeing is the average of scores in all the wellbeing domains including physical, psychological, social and environmental wellbeing assessed using the WHO Quality of life – BREF tool. "ref" denotes the reference level for categorical variables in the model. Marginal and conditional R^2 are the model variance explained by the fixed effect, and both fixed and random effects respectively.

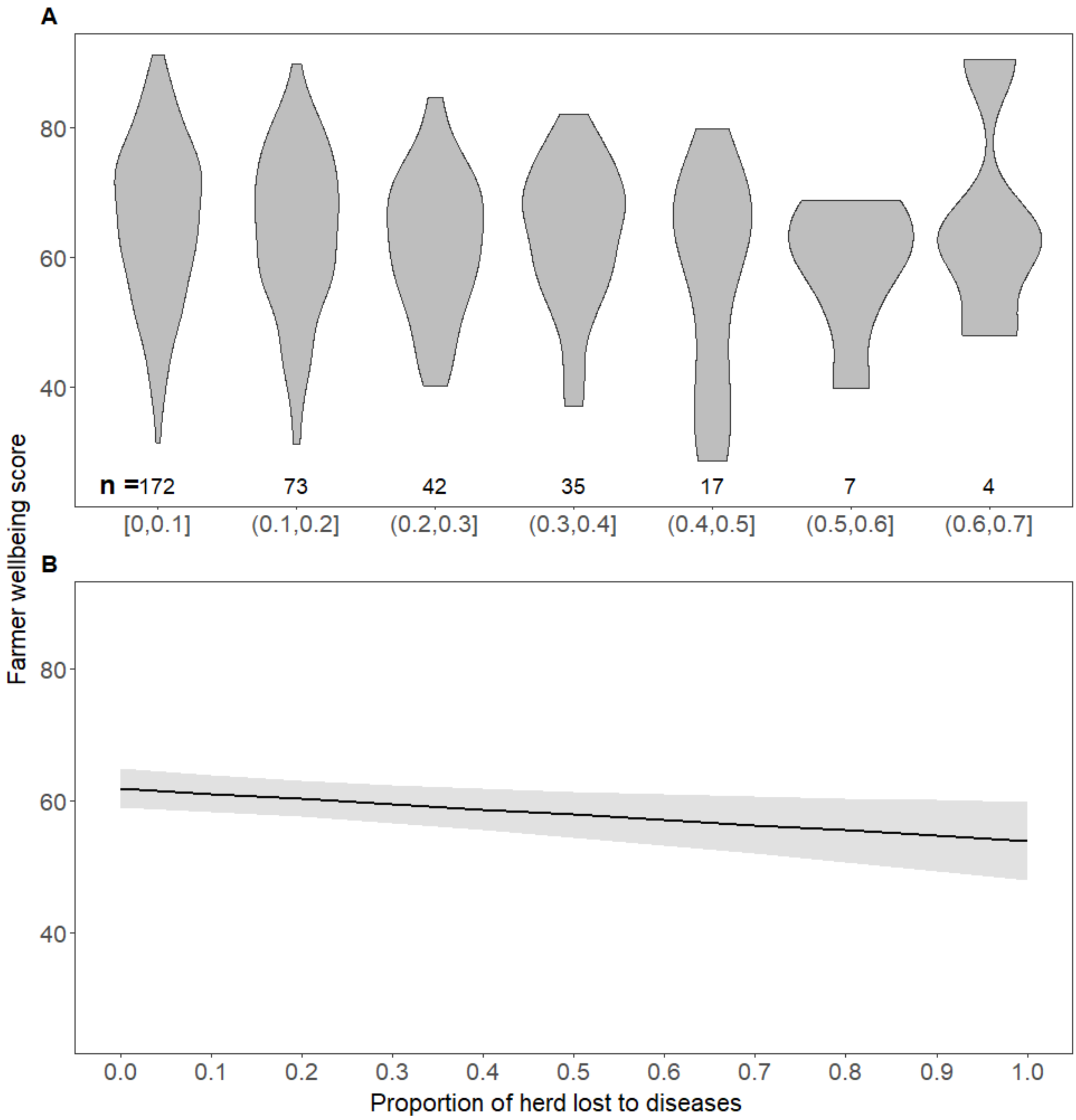

Figure 19: Effect of herd mortalities to diseases on farmers' wellbeing.

The figure shows the actual and predicted relationship between the severity of disease-induced animal mortalities and farmers' overall wellbeing. The overall wellbeing is the average score of wellbeing scores in the physical, psychological, social, and environmental domains. **Panel A** shows the relationship between 10 percentage increments in relative herd mortalities to diseases and farmers overall wellbeing without accounting for the potential confounding effect of other covariates. **Panel B** shows the estimated marginal effect at different levels of disease-induced livestock mortalities, conditional on the other co-variates in the pre-specified linear mixed effect linear regression model. The slope of the marginal effect line with confidence intervals around the point estimates shows the extent and direction of the relationship between the levels of disease-induced herd mortalities and livestock farmers' overall wellbeing.

7.5 Discussion

In this study, we aimed to estimate the average effect on the wellbeing of a livestock farmer that can be attributed to disease-induced mortalities in the farmer's herd. To achieve this goal, we adopted a cross-sectional survey design, in which we measured farmers' wellbeing and annual herd mortalities and evaluated this association, accounting for specified covariates, using linear mixed effect models. Our results suggest that the level of animal disease-induced herd mortalities have a large and negative effect on farmers' wellbeing significantly different from zero, particularly in the physical and psychological domains of wellbeing. The effect size did not change significantly after the inclusion of other causes of livestock mortality including theft, conflict, accidents and weather-related herd mortalities and control variables in the model.

These results underscore the need to consider the interdependencies between human, animal and ecosystem health, beyond zoonosis spread in health research. There exists substantial evidence supporting the impact on global health security, of pathogen spread between the animal, human, and environmental interfaces, in the absence of adequate control measures (Zinsstag et al., 2023a). These health impact evaluations usually have a biomedical physical health focus. Thus, the observed impact could be even larger when the multidimensionality of health is fully considered. We have demonstrated in this study that the impact of poor animal health on farmers' overall wellbeing is large and significant. Few studies have highlighted the strong link between poor animal health and the psychological wellbeing of livestock dependent populations (Hood and Seedsman, 2004; Mort et al., 2005; Goffin, 2014; Nuvey et al., 2020).

The effect of the severity of herd mortalities to diseases was more pronounced on the physical and psychological domains of health compared to the other wellbeing domains (i.e. social and environmental wellbeing). This finding is intuitive given the extensive nature of farming in the study area (GSS, 2020a) and the relative emotional and security attachment between farmers and their livestock (Vittersø et al., 1998; Hoffet, 2015; Nuvey et al., 2020). Other sources of herd mortality including livestock theft, conflict, and weather-related losses would affect more the social and environmental domains of wellbeing, compared to disease-induced losses as shown in our results. The extent of these associations could be assessed in future studies. In-depth studies from an ecosystem perspective, of the relationship between ecosystem challenges, and human and animal wellbeing, are needed.

Disease-induced livestock mortalities remain a significant barrier to the productivity and trade in the livestock sector in many African countries including Ghana (Grace et al., 2015). Similar to our results, previous research in other countries identified animal diseases as a significant source of livestock herd mortalities for households (Admassu et al., 2005; Fadiga et al., 2013b; Catley et al., 2014; Gizaw et al., 2020). Based on this impact of diseases on herds, studies have emphasized the effectiveness and profitability of applying preventive measures particularly vaccination to sustainably address disease-induced livestock mortalities (Domenech and Vallat, 2012; Zhang et al., 2018; Campbell et al., 2021; Nuvey et al., 2022a). Our findings in the earlier studies of the larger project showed that the main diseases causing livestock mortalities are Contagious Bovine Pleuropneumonia and Food and Mouth Disease in cattle, and Peste des Petits Ruminants in small ruminants (sheep and goats) (Nuvey et al., 2023c). Vaccination utilization by farmers to protect herds against these diseases was also very low (Nuvey et al., 2023a) although observed as the key intervention that reduces the mortalities (Nuvey et al., 2022a). There is thus the need for transdisciplinary strategies that improve high quality vaccine adoption, given the availability of effective vaccines to control these diseases (Donadeu et al., 2019). The evidence from our work suggests that, addressing animal health challenges through veterinary service policies could contribute to improving the wellbeing of livestock dependent populations. However, it should be noted that disease control policies should be adequate to the farming systems. For example the mass culling of livestock during the Foot and Mouth Disease epidemic in the United Kingdom led to larger mental health and suicide problems (Zinsstag and Weiss, 2001). In this particular instance, a ring vaccination and quarantine policy might have been more appropriate.

Our study had some limitations. The nature of the design does not enable us to determine the temporal relationship between poor animal health (disease-induced mortalities) and farmer wellbeing. Furthermore, in our attempt to measure reliably the impact of diseases on farmers' herds, we relied on only disease-induced herd mortalities. Thus, the impact of diseases resulting in only morbidity without the death of the infected animals was not accounted for in our measurements. We argue however that, the observed impact on farmers' wellbeing is likely to be larger, if disease-induced morbidities should be considered. Future studies implementing interventions to reduce disease incidence using randomized controlled trials could evaluate the extent of this relationship more definitively, as well as assess the pathways of the impact. Our study focused on ruminant livestock farmers, however, based on our engagements with the farmers in our study who also own other species such as poultry and pigs, we understand that they experience similar challenges with diseases among these other species. Thus, future studies could further explore this missing perspective in our study. Additionally, despite efforts to obtain a representative sample of the different agro-ecological zones in Ghana, our study did not account for the two other minority agro-ecological zones namely the Evergreen and Coastal Savannah zones. Even though these zones are not typical areas for livestock production in Ghana, their inclusion would have improved the representativeness of our findings with diversification and the crop production as adaptations options. In spite of this missing perspective, we do not expect the parameters evaluated to be markedly different in these agro-ecological zones. Our study thus, has provided valuable information on the relationship between poor animal health and the wellbeing of livestock dependent populations, making a strong case for improvements in performance of veterinary services, for better animal health.

7.6 Conclusion

Our study has shown that diseases are the main cause of animal mortalities for ruminant livestock farmers in Ghana. The poor health of the livestock herds has a significant influence on the wellbeing of the livestock farmers. Given that, the main diseases accounting for these mortalities have effective vaccines for their control, and vaccination utilization is low among the farmers, our findings suggest that improvements in veterinary policies and service delivery, which address disease risks in livestock, would contribute to better wellbeing of livestock dependent populations. This study exemplifies the benefits of integrated human and animal health studies through a One Health approach, which cannot be achieved if human and animal health are studied in separation.

7.7 Declarations

Ethics approval and consent to participate

The study was reviewed and approved by the Ghana Health Service Ethics Review Committee (approval number: GHS-ERC 006/09/20). In the study districts, permission was obtained from all the relevant authorities prior to data collection. The study participants provided written informed consent and the data generated are kept as confidential records. All the methods were carried out in accordance with relevant guidelines and regulations (Such as Declaration of Helsinki).

Availability of data and materials

All data generated or analyzed during this study are included in this published article [and its supplementary information files].

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author contributions

Conceptualization, all authors; **methodology**, all authors; **validation**, D.T.H., J.H., K.K.A., G.I.M., G.F., J.Z., and B.B.; **formal analysis**, F.S.N.; **investigation**, F.S.N.; **resources**, D.T.H., J.H., J.Z., G.F. and B.B.; **data curation**, F.S.N.; **writing—original draft preparation**, F.S.N.; **writing—review and editing**, all authors; **visualization**, F.S.N. and J.H.; **supervision**, D.T.H., J.H., K.K.A., G.I.M., G.F., J.Z., and B.B.;

project administration, F.S.N. and B.B.; **funding acquisition**, K.K.A. and B.B. All authors have read and agreed to the published version of the manuscript.

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7.8 Supplemental

Supplemental Appendix to

"Relationship between animal health and livestock farmers' wellbeing in Ghana: beyond zoonoses"

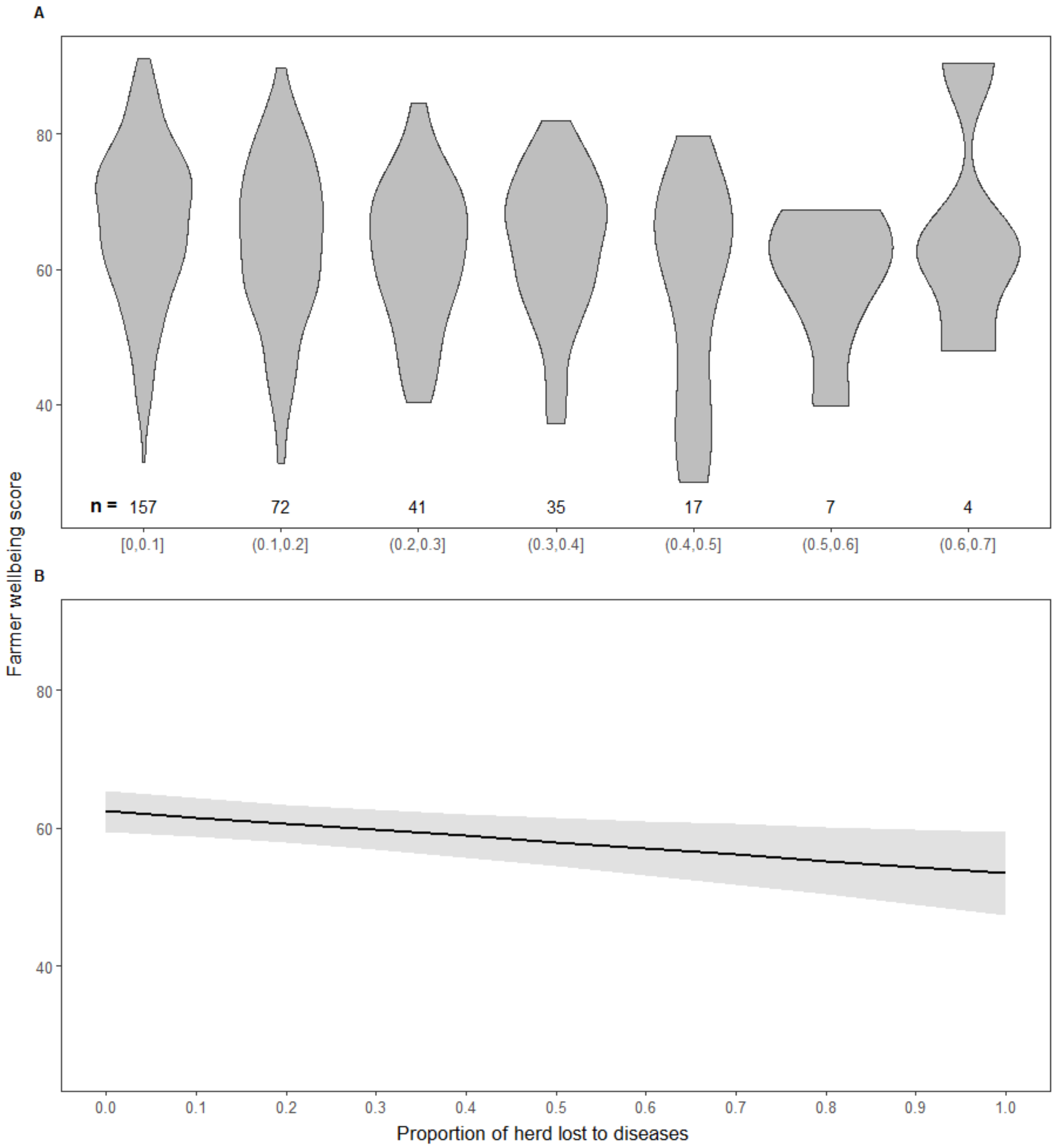
Table S1: Mixed effects model predicting the effect of level of herd mortalities to diseases on farmer wellbeing adjusting for other covariates (N = 333)

Parameter	**Estimate**	**95% CI**	***p*-value**
Fixed effects			
Proportion of herd mortality *	-9.02	-15.51 – -2.53	0.01
Satisfaction with health	0.26	0.22 – 0.31	<0.001
Social support received	0.93	0.55 – 1.31	<0.001
Perception of disease risk to herd	0.38	-0.03 – 0.79	0.07
Age (years)	-0.08	-0.16 – -0.01	0.03
Farm size (acres)	0.05	-0.03 – 0.13	0.22
Sex [ref = female]			
Male	1.33	-0.91 – 3.57	0.24
Education level [ref = no formal education]			
Up to 12 years	0.09	-2.34 – 2.52	0.94
Higher education	2.32	-0.50 – 5.13	0.11
Wealth index [ref = poorest]			
Below average	0.32	-2.75 – 3.38	0.84
Average	3.00	-0.14 – 6.13	0.06
Above average	3.35	0.06 – 6.65	0.04
Least poor	2.79	-0.67 – 6.24	0.11

History of disease outbreak [ref = No]			
Yes	0.11	-2.14 – 2.36	0.92
Random effects			
Within cluster standard deviation	8.68	7.98 – 9.41	…
Between cluster standard deviation	2.08	0.00 – 3.58	…
Marginal R^2 / Conditional R^2	0.46 / 0.49		

* Proportion of herd mortality refers to livestock mortalities to diseases relative to herd size, standardized in tropical livestock units. Estimates are the changes in overall wellbeing scores of ruminant livestock farmers attributable to changes in parameters, with their corresponding 95% confidence intervals (95% CI) and p-values. Overall wellbeing is the average of scores in all the wellbeing dimensions including physical, psychological, social and environmental wellbeing assessed using the WHO Quality of life – BREF tool. The farmers included in the analysis are only those who own the animals in the herds (N = 333). "ref" denotes the reference level for categorical variables in the model. Marginal and conditional R^2 are the model variance explained by the fixed effect, and both fixed and random effects respectively.

S1 Figure: Effect of the level of herd mortalities to diseases on farmers' wellbeing (N = 333)



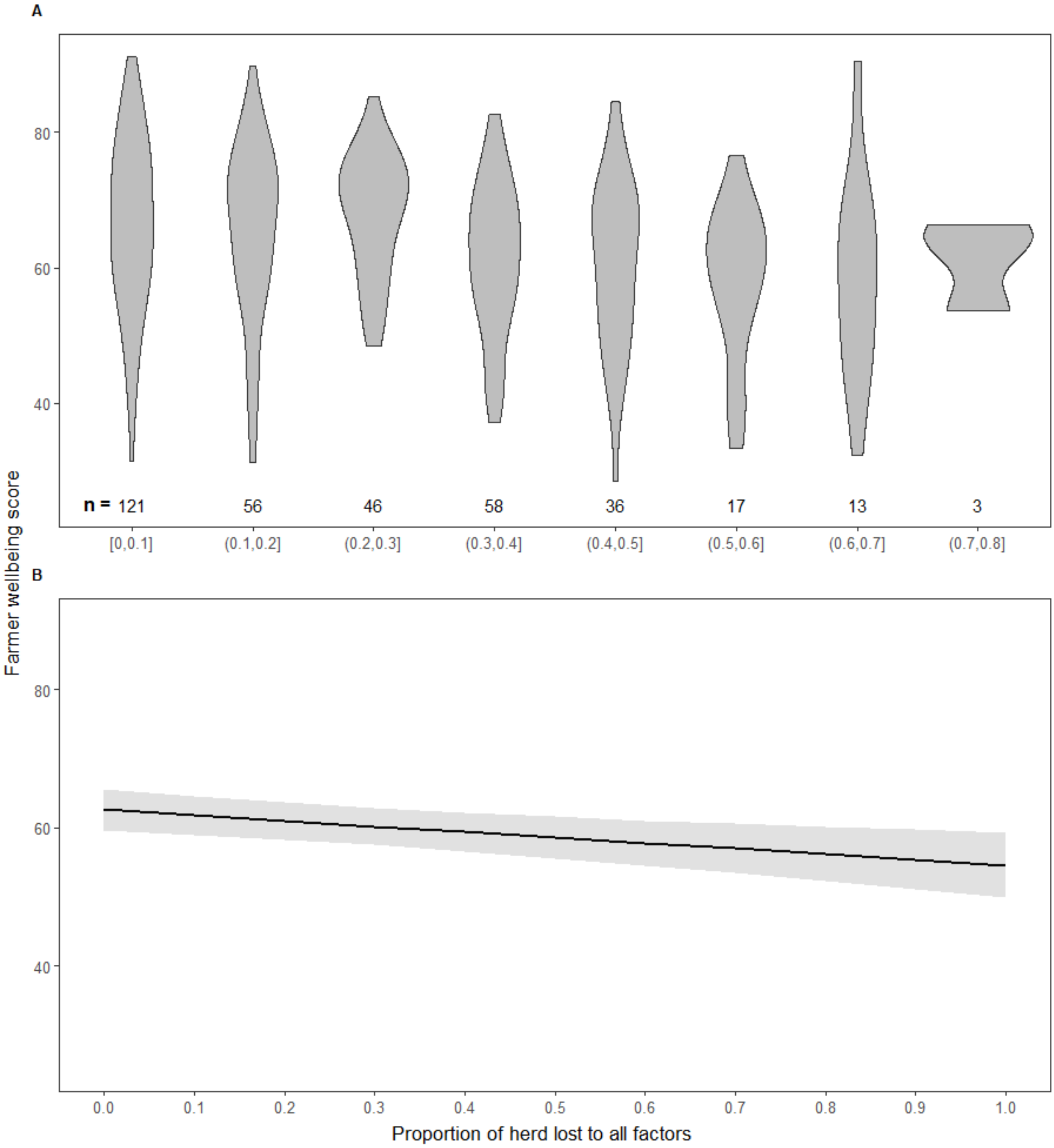
The figure shows the actual and predicted relationship between the level of animal mortalities to diseases and farmers' overall wellbeing. The overall wellbeing is the average score of wellbeing scores in physical, psychological, social, and environmental domains. **Panel A** shows the relationship between 10 percentage increments in relative herd mortalities to diseases and farmers overall wellbeing without accounting for the potential confounding effect of other covariates. **Panel B** presents the estimated marginal effect at different levels of disease-induced livestock mortalities, conditional on the other co-variates in the pre-specified linear mixed effect model. The slope of the marginal effect line with confidence intervals around the point estimates shows the extent and direction of the relationship between the levels of disease-induced herd mortalities and livestock farmers' overall wellbeing.

Table S2: Mixed effects model predicting the effect of level of herd mortalities to all causes on farmer wellbeing adjusting for other covariates

Parameter	Estimate	95% CI	*p*-value
Fixed effects			
Proportion of herd mortality *	-8.05	-13.29 – -2.80	0.003
Satisfaction with health	0.28	0.23 – 0.32	<0.001
Social support received	0.82	0.44 – 1.19	<0.001
Perception of disease risk to herd	0.40	0.01 – 0.79	0.04
Age (years)	-0.09	-0.17 – -0.01	0.02
Farm size (acres)	0.05	-0.03 – 0.13	0.23
Sex [ref = female]			
Male	1.39	-0.81 – 3.60	0.21
Education level [ref = no formal education]			
Up to 12 years	0.00	-2.35 – 2.34	0.99
Higher education	2.00	-0.79 – 4.78	0.16
Wealth index [ref = poorest]			
Below average	0.05	-2.95 – 3.06	0.97
Average	2.77	-0.37 – 5.90	0.08
Above average	3.25	-0.03 – 6.52	0.05
Least poor	3.31	-0.09 – 6.71	0.06
History of disease outbreak [ref = No]			
Yes	0.01	-2.18 – 2.20	0.99
Random effects			
Within cluster standard deviation	8.79	8.08 – 9.50	…
Between cluster standard deviation	1.76	0.00 – 3.07	…
Marginal R^2 / Conditional R^2	0.48 / 0.50		

* Proportion of herd mortality refers to total livestock mortalities relative to herd size, standardized in tropical livestock units. Estimates are the changes in overall wellbeing scores of ruminant livestock farmers attributable to changes in parameters, with their corresponding 95% confidence intervals (95% CI) and p-values. Overall wellbeing is the average of scores in all the wellbeing dimensions including physical, psychological, social and environmental wellbeing assessed using the WHO Quality of life – BREF tool. "ref" denotes the reference level for categorical variables in the model. Marginal and conditional R^2 are the model variance explained by the fixed effect, and both fixed and random effects respectively.

S2 Figure: Effect of the level of herd mortalities suffered on farmers' wellbeing



The figure shows the actual and predicted relationship between the severity of animal mortalities to all causes and farmers' overall wellbeing. The overall wellbeing is the average score of wellbeing scores in physical, psychological, social, and environmental domains. **Panel A** shows the relationship between 10 percentage increments in relative herd mortalities to all causes and farmers overall wellbeing without accounting for the potential confounding effect of other covariates. **Panel B** presents the estimated marginal effect at different levels of livestock mortalities experienced, conditional on the other co-variates in the pre-specified linear mixed effect model. The slope of the marginal effect line with confidence intervals around the point estimates shows the extent and direction of the relationship between the levels of herd mortalities to all causes and livestock farmers' overall wellbeing.

Chapter 8 Discussion and Conclusions

8.1 Summary of findings

This thesis has highlighted the main challenges associated with livestock disease management in Ghana, and the mechanisms through which effective disease control could be attained. The research evidence prior to this thesis had emphasized the negative impact of infectious livestock diseases on animal health and productivity, on human health and livelihood mainly via zoonoses, and on ecosystem health through infection-induced greenhouse gas emissions in livestock (Pradère, 2014; Wiethoelter et al., 2015; Ezenwa et al., 2020). A recent survey of veterinary authorities in 34 countries in sub-Saharan Africa (SSA) identified transboundary animal diseases including foot-and-mouth disease (FMD), peste-des-petits ruminants (PPR) and contagious bovine pleuropneumonia (CBPP), as top priority diseases requiring intervention strategies to reduce their burden and impact on the population (Grace et al., 2015). In principle, disease prevention measures offer a viable option to effectively control the emergence, transmission, and impact of infectious livestock diseases (Sekiguchi et al., 2021). Although different strategies including disease surveillance, vaccination, and culling have been reported to provide effective control of diseases, their utilization levels remain low in many countries in SSA including Ghana (OIE, 2019a). Few studies have attempted to synthesize the existing evidence on the relative effectiveness and profitability of these different preventive veterinary interventions, as well as identify the main bottlenecks to their utilization, and the end-user valuation and willingness to invest resources on them, to inform policy decisions.

The goal of the research presented in this thesis was therefore to provide evidence on effective and cost-effective preventive veterinary interventions, to assess the barriers to their utilization, and to determine the willingness of livestock farmers to pay for the interventions to protect livestock assets, and wellbeing, using a One Health approach.

In Chapter 3, we found that overall, vaccination was the most widely used preventive intervention against infectious diseases in livestock in SSA. It is also the most effective and cost-effective intervention, providing high returns on investment, for controlling most of the infectious livestock diseases compared to the other strategies. The other strategies including antimicrobial treatment, parasite control, culling, surveillance, and feed supplementation, were seldom implemented exclusively, but were typically implemented in combination with vaccination to attain enhanced outcomes. These findings confirm the existing evidence in the literature of the importance of vaccination in controlling infectious livestock diseases (Morens et al., 2011; Conrady et al., 2021).

In the subsequent chapters, I examined the different strategies used by livestock farmers and veterinary officers to tackle the infectious diseases affecting their herds, the performance of veterinary services in meeting the animal health needs, the barriers to accessing vaccination, the farmers' willingness to pay for vaccination to protect their livestock assets against the diseases, and the effect of poor health of animals on farmers' wellbeing. Chapter 4 assessed the priority diseases affecting livestock in Ghana, the management strategies applied to deal with diseases and the performance of veterinary services in meeting animal health needs using a participatory approach. The results in Chapter 4 show clearly that transboundary animal diseases (i.e. CBPP, FMD, and PPR) are highly prevalent in herds causing significant livelihood losses to households. From the perspective of both farmers and veterinary officers, it was evident that the veterinary system had considerable weaknesses, specifically relating to shortfalls in the veterinary workforce and the material resources required to deliver effective animal health services. As a result, farmers were mainly utilizing the services of informal providers - who are not regulated by the veterinary system - or managing the livestock diseases on their own. In most of the cases, the medicines applied by the farmers were not useful for the conditions being treated. Additionally, the farmers who have accessed professional veterinary service providers tend to rate them highly on most performance attributes including the availability and quality of their medicines, effectiveness of treatment, quality of advisory services, affordability of the services rendered, and their competence in delivering animal health care, compared to the informal veterinary service providers. Only in the case of proximity and popularity of their use within the communities that farmers ranked informal veterinary service providers higher than the professional veterinary officers.

The findings in Chapter 5 highlight a significantly low utilization of vaccination services by livestock farmers, which was attributed to a combination of factors on both demand and supply sides. On the demand side, barriers primarily stem from farmers' limited awareness and sometimes misconceptions about the benefits of vaccines, as well as the financial burden associated with vaccine affordability. Particularly, the requirement for farmers to bear the full cost of vaccine vials, even if they do not have a sufficient number of animals to utilize an entire vial. Additionally, competing expenditure needs exert an influence on farmers' decision-making process to utilize vaccination services. The supply-side barriers are mainly due to the limited number of professional veterinary officers accessible to farmers, and inadequate veterinary health infrastructure, which restricts the availability and accessibility of veterinary services when required. To overcome these significant barriers to vaccination uptake, the farmers suggested several measures, including the establishment of localized community networks. This proposed approach involves harnessing the strength of a collective group of farmers to coordinate vaccination visits with veterinary officers, thereby improving access to veterinary services and enhancing vaccination rates.

In Chapter 6, we examined the valuation and willingness of households to pay for vaccination against two of the priority infectious diseases identified in the study area with existing approved vaccines (i.e. PPR and CBPP). When sensitized on the benefits of vaccines for enhancing livestock productivity, many farmers demonstrate a willingness to pay for vaccination exceeding the prevailing prices. This indicates a strong commitment by farmers to protecting and preserving their valuable livestock assets. Furthermore, our findings revealed that by leveraging community sensitization and engagement, it is feasible to achieve the intermediate national vaccination target of 50% at the existing vaccination costs. However, to attain the desirable target of 70% coverage for the priority diseases identified in the study area, it would be necessary to introduce subsidies to ensure broader inclusivity and participation in vaccination programs, especially for female farmers and farmers residing in the poorest districts.

In Chapter 7, we showed the relationship between the severity of diseases impact on herds, and the wellbeing of livestock farmers. After accounting for potential confounding factors in our model, our analysis revealed a significant and negative effect of increasing disease-induced livestock mortalities on the overall wellbeing of livestock farmers. Specifically, we observed significant negative impacts on the psychological and physical dimensions of the farmers’ wellbeing.

8.2 Implications for policy and recommendations

Based on the summary of the evidence presented above, our study findings strongly indicate that the implementation of integrated community-centered approaches, alongside enhancements in veterinary policies and service delivery, would be pivotal in achieving improved control of infectious diseases in livestock in Ghana. Such measures are crucial for mitigating the detrimental impact of livestock diseases on the population, and fostering better wellbeing among livestock-dependent communities. These findings raise important policy and research issues that are summarized below.

Enhancing veterinary workforce and infrastructure for better service delivery

The findings in this thesis suggest serious deficiencies in the veterinary workforce and infrastructure required for efficient service provision. While professional veterinary services remain largely inaccessible to the majority of farmers in need, those who have utilized the services express high satisfaction with their performance. Thus, substantial investments in the human and material resources are critical to strengthen the capacity of veterinary services to be able to play its role in improving the health of animals, humans, and their shared environment. This is particularly vital for low- and middle-income countries (LMICs) facing resource limitations (Gebreyes et al., 2014). For example, data from the World Organization for Animal Health (WOAH, founded as OIE) reveal that the average global veterinary workforce per animal was approximately 2611 veterinary livestock units (VLUs) in 2019. Comparatively, Africa had an average of one veterinary officer per 3530 VLUs, while Europe had 612 VLUs, the Middle East had 1365 VLUs, and the Americas had 2974 VLUs. Only the Asia Pacific region had a lower workforce per animal ratio of 3883 VLUs (WOAH, 2022). Based on the most recent Performance of Veterinary Services (PVS) Gap Analysis conducted in 2011 in Ghana, the data clearly showed that the ratio of veterinary workforce to animals is substantially lower, more than tenfold less than the African average (Diop et al., 2011). There is therefore a need for innovative strategies to bolster the veterinary workforce in Ghana. Continuous professional development opportunities, and welfare incentives such as better remuneration, and elaborate career pathways, are some measures, with potential to enhance the capacity of the veterinary workforce to effectively address the current and emerging challenges (Elton and Borges, 2018; Wieland et al., 2021).

In addition to strengthening the veterinary workforce, there is a crucial requirement for veterinary infrastructure and tools to support the veterinary personnel. A previous study in Ghana reported a lack of adequate veterinary health infrastructure such as veterinary clinics and slaughter facilities, particularly in rural farming areas. Consequently, farmers often resort to self-treating animal diseases, and engaging in the sale of sick or deceased animals to mitigate their losses in cases where treatments were unsuccessful (Nuvey et al., 2020). Research findings have also documented the presence of medicine residues in raw meat and milk samples sampled from various livestock markets in Ghana (Addo et al., 2011; Addo et al., 2014; Darko et al., 2017; Mensah et al., 2019). The PVS Gap analysis also highlighted that animal slaughtering predominantly takes place in areas without professional veterinary supervision, coupled with the absence of a residue testing program in the country (Diop et al., 2011). The lack of sufficient veterinary infrastructure for addressing animal health issues, and conducting inspections of livestock products before they enter the food chain poses a significant risk to public food safety, necessitating immediate action.

The effective provision of veterinary services should be considered as a public good as it is critical for enhancing food safety and food security, protecting the livelihoods and wellbeing of livestock dependent populations, and also protecting public health through effective control of infectious disease especially transboundary animal diseases (Schneider, 2011; Eloit, 2012; Narayan et al., 2023). To enhance the sustainability of animal health service delivery, relying solely on the public sector and donor funding schemes for veterinary services delivery would be inadequate, particularly in LMICs. Studies have advocated for the reinforcement of public-private partnerships in veterinary service delivery, incorporation of culturally appropriate practices in veterinary interventions, and enhanced veterinary services governance through establishment of effective collaborative frameworks between public and private veterinary service providers, livestock owners, and food processors, as crucial towards achieving sustainability of veterinary initiatives, especially in disease prevention and control (Schneider, 2011; Gizaw and Berhanu, 2019; MacPhillamy et al., 2023). In LMICs, Community-based animal health workers (CAHWs), are increasingly being empowered as private actors to complement professional veterinarians in addressing animal health service needs mainly in rural settings (Leyland and Catley, 2002). Some studies have assessed their performance and documented positive overall effects on the delivery of animal health services in the settings where CHAWs had been deployed (Mugunieri et al., 2004; Allport et al., 2005; Bugeza et al., 2017). We propose therefore that the Veterinary Services Directorate (VSD) considers the training and formalization of CAHWs for the provision of some animal health services in Ghana. This is particularly important considering the presence of informal providers whose activities currently fall outside their purview.

Need for enhanced antimicrobial stewardship strategies

The improper use of antimicrobials in animal production has been shown to contribute to the persistence of medicine residues in livestock products, particularly when the treated animals are slaughtered prior to the recommended withdrawal period, and accelerates the emergence of antimicrobial resistant pathogens (Van Boeckel et al., 2015; Van Boeckel et al., 2017; Van Hao et al., 2020; Mshana et al., 2021; Omwenga et al., 2021; Azabo et al., 2022). These pathogens may be zoonotic, and undermine the efficacy of antimicrobials used in human medicine, with serious consequences for public health, such as an increase in the occurrence and severity of infections, treatment failures, increased healthcare costs, and in certain cases fatalities (Angulo et al., 2006; Szmolka and Nagy, 2013). The World Health Organization (WHO) in conjunction with the WOAH and the Food and Agriculture Organization of the United Nations (FAO) developed and maintains a classification framework for antimicrobials based on their importance for human medicine, enabling policy makers to establish regulations and guidelines for the judicious use of antimicrobials, especially in the agricultural sector. The primary objective is to safeguard the effectiveness of these antimicrobial agents (Collignon et al., 2016; WHO, 2017a).

In light of the research findings presented here, it is imperative to urgently develop novel approaches aimed at improving antimicrobial stewardship in Ghana to mitigate the adverse consequences for public health. Various strategies have been previously employed to promote responsible use of antimicrobials, especially within human medicine. Some of these strategies are now being increasingly adapted for implementation in antimicrobial stewardship programs within animal medicine. Recent studies reveal that interventions focused on behavior change, such as provision of guidance on antimicrobial use and stewardship, participatory engagement between farmers, veterinarians and policy makers, imposition of restrictions on medicine prescriptions, awareness and sensitization programs, and implementation of infection prevention and control measures, are largely effective in reducing antimicrobial use in animal health (Postma et al., 2017; van Dijk et al., 2017; Craig et al., 2023), and the development of antimicrobial resistant pathogens in animals and humans (Tang et al., 2017). Nevertheless, it should be noted that the majority of these studies were carried out in developed countries. Thus, it is crucial to develop and assess context-specific antimicrobial stewardship programs tailored to LMICs to determine their effectiveness and feasibility. In LMICs, the application of transdisciplinary approaches involving extensive engagement of various stakeholders, including laypersons, policymakers, and scientists in antimicrobial stewardship programs, has demonstrated potential in improving prudent antimicrobial use within human and animal medicine (Eagar and Naidoo, 2017; Musoke et al., 2020). This exemplifies the advantages of integrated transdisciplinary collaboration within a One Health framework, which additionally fosters a sense of ownership among stakeholders of the public health initiatives, and ensuring long-term sustainability.

Moreover, ensuring the success of antimicrobial stewardship programs would require an effective monitoring of antimicrobial usage patterns and the emerging resistant pathogens. This is often achieved through close collaboration and integration between human and animal health surveillance systems (WHO, 2017b; Bennani et al., 2021; Fajt et al., 2022; Otto et al., 2022). Hence, we recommend that the Ministries of Health, Fisheries and Aquaculture Development, Environment, Science, Technology and Innovation, and Food and Agriculture in Ghana, through their respective agencies, actively explore possibilities for integrating the health surveillance systems nationwide, with the aim of providing a holistic understanding of health hazards to the population to inform appropriate and timely responses. A recent systematic review of integrated health surveillance systems demonstrated substantial enhancements in the sensitivity, data quality, and timeliness of the surveillance systems in addressing infectious diseases and health hazards (George et al., 2020). Additionally, it is essential to include the surveillance of veterinary medicine sales and use, as well as the monitoring of emerging antimicrobial resistant pathogens over time, within an integrated health surveillance system. There is also a need for behavior change strategies employing targeted engagement and sensitization of livestock farmers on the benefits of responsible antimicrobial use in animal health, and the need for strict adherence to withdrawal periods for treatments administered (McKernan et al., 2021; Regan et al., 2023). This will greatly enhance the attainment of the objectives set forth in the "Ghana National Action Plan for Antimicrobial Use and Resistance" (MOH et al., 2017), thereby reinforcing the government's commitment to tackling antimicrobial resistance.

Improving vaccination services access and use, for effective disease control

Even though effective control of infectious animal diseases can be achieved in principle using rapid diagnostic tools for pathogen surveillance, and vaccination strategies, neither strategy is currently used adequately in practice in many LMICs (Donadeu et al., 2019; OIE, 2019a; Torres-Velez et al., 2019). Empirical research studies are therefore needed to generate evidence on the effectiveness of different approaches aimed at improving vaccination uptake among farming households. Additionally, urgent policy actions are necessary to address both the demand and supply side barriers that impede access to vaccination. Of particular concern is the existing "cash and carry" system for vaccine delivery in Ghana, which restricts the ability of individual veterinary officers to personally finance the costs associated with acquiring required vaccines and consumables from central supply for use in their respective operational areas. Collaborative efforts between field veterinary officers and veterinary policymakers are crucial to establishing mutually beneficial and cost-effective strategies that alleviates the financial burden on field veterinary officers, while enhancing the accessibility of vaccines at the district level. The significance of vaccine availability as a crucial factor influencing the effectiveness of animal vaccination have been previously documented in SSA (Mosimann et al., 2017), and in this doctoral project. Furthermore, the VSD needs to address the lack of cold chain refrigeration equipment, particularly at the district level, in order to ensure the potency and efficacy of available vaccines. Maintaining the potency of available vaccines is critical to enhancing the benefits of vaccination at both herd and community levels, as well as acceptability of vaccines to farmers (Robinson et al., 2016; Nampanya et al., 2018).

Although farmers seem motivated to prevent livestock diseases in their herds, the reduction in the occurrence of infectious diseases among animals generates positive externalities for farmers, the government, and the population as a whole. For example, research has shown significant cost-savings and health benefits to the human population if brucellosis transmission is interrupted in animals through vaccination (Roth et al., 2003). Thus, for the prevention and control of transboundary animal diseases, which can be viewed as a public good, the funding mechanism for vaccination could be jointly supported by the government and livestock owners, taking into account their capacities to contribute (Hennessy, 2007; National Research Council (US) Committee on Achieving Sustainable Global Capacity for Surveillance and Response to Emerging Diseases of Zoonotic Origin, 2009). Our study showed that when farmers are well informed about the benefits of vaccines, a considerable number of them are willing to pay the full costs for vaccinating their herds. However, it is essential to address the challenges related to the existing mechanisms for vaccination delivery, particularly for small herds, where individual farmers are burdened with paying the full cost of entire vaccine vials to vaccinate their animals even when they do not own sufficient animals in their herds to use the vials. Furthermore, additional subsidies are required to enhance access for the most vulnerable farmer groups, if the desirable 70% vaccination coverage target for CBPP and PPR control, is to be attained. It is worth noting though, that a regional approach to implementing infectious disease control strategies would be essential for achieving disease elimination (Domenech et al., 2006; Albina et al., 2013; Fakri et al., 2016).

While public and private investments are needed to enhance the uptake of vaccination, it is equally important to conduct evaluations of existing vaccines to identify potential areas for improvement in the technologies employed. Most of the current animal vaccines rely on technologies that were developed by renowned epidemiologists such as Edward Jenner and Louis Pasteur several years ago. Thus, evaluating and updating these technologies is crucial to ensure advancements in vaccine efficacy and overall disease prevention and control (Adams et al., 2009). The recent progress in human vaccine development, incorporating innovative genomic, proteomic, bio- and nano-technological approaches, presents promising opportunities for enhancing animal vaccines as well (Aida et al., 2021; Tripp, 2021). These novel strategies would be essential to improving the longevity of immunity conferred on vaccinated animals and optimizing the effectiveness of animal vaccines and therapeutics (Charlier et al., 2022). Regional organizations such as the Pan-African Veterinary Vaccine Center (PANVAC) remain crucial to the advancement of vaccine development and delivery in Africa. Additionally, strategies that enhance the effectiveness of vaccines especially under field conditions, are needed, as our research indicates some reductions in the protection rates compared to controlled on-station trials. There is also a need for an evaluation of vaccine formulations and delivery methods to identify potential areas for enhancement, while also mitigating the post-vaccination adverse events associated with certain vaccines (Adams et al., 2009; Shoulah et al., 2022). These measures will contribute to the wider adoption of vaccination among livestock owners. Furthermore, reliable diagnostic tools capable of differentiating between infected and vaccinated animals are needed for improved infectious disease control (Charlier et al., 2022).

Health services to support the wellbeing of livestock dependent populations

Although we observed a significant impact of animal diseases on the wellbeing of farmers, particularly on the physical and psychological domains, clinical evaluations of affected farmers are required to assess, and address their specific healthcare needs. In many rural communities in LMICs where farming predominantly occurs, primary healthcare (PHC) facilities such as Community-based Health Planning and Services (CHPS) facilities, outreach clinics, and health centers are the main sources of health services for the population. These facilities primarily offer services related to maternal and child health, chronic disease management, and treatment for prevalent diseases such as malaria, tuberculosis, and HIV/AIDS (Woldie et al., 2018). The provision of health services is primarily carried out by community or lay health workers (CLHWs), who often possess limited healthcare expertise to address complex health issues. The CLHWs are mainly recruited based on individual motivation to provide healthcare services rather than formal healthcare qualifications (Vouking et al., 2013; de Vries and Pool, 2017; Shipton et al., 2017). Efforts should therefore be made to empower and equip CLHWs with simplified tools for assessing and addressing complex patient issues, including mental illness and other social health problems facing rural dwellers (Rathod et al., 2017). Previous reviews have shown the potential effectiveness of CLHWs in improving the psychosocial wellbeing of persons with mental, neurological and substance use disorders in LMICs (Mutamba et al., 2013; van Ginneken et al., 2013). Collaborative efforts between the Ministries of Health, Food and Agriculture, and Fisheries and Aquaculture Development in Ghana are necessary to identify communities with high infectious livestock disease burden, to evaluate the feasibility of implementing the relevant healthcare interventions for these livestock dependent populations.

Despite PHC facilities being the main providers of healthcare services in rural areas in LMICs, the services provided usually do not reach mobile populations such as pastoralists, who are frequently overlooked by public services and health campaigns (Cohen, 2005; Wild et al., 2020). Pastoralists are livestock farmers who predominantly engage in animal husbandry and depend on regular seasonal movements across borders, along with their livestock, to access sufficient grazing and water resources (Majok et al., 1996; Gibson, 2020). Studies have shown that ensuring equity in the delivery of health services enhances the effectiveness and sustainability of implemented health interventions (Zinsstag et al., 2011; Thomson et al., 2013). Thus, adapting healthcare interventions to local contexts and implementing targeted strategies within rural settings are crucial to enhance access to essential health services, particularly for vulnerable groups (Segall, 2003). While recognizing the importance of healthcare for rural communities, it is crucial to actively involve various stakeholders in the provision of the health services to enhance uptake. Transdisciplinary approaches based on the One Health principles, offers valuable prospects for fostering extensive stakeholder participation in decision-making processes, thus promoting inclusivity and effectiveness in healthcare delivery (Smith, 2007; Hemmerling et al., 2023). The success of health interventions in LMIC settings, has been closely associated with a comprehensive and iterative engagement processes involving key stakeholders such as communities, healthcare providers, and authorities in designing and implementing healthcare strategies (Schelling et al., 2008; Gaihre et al., 2019; Nguyen-Viet et al., 2021; Zinsstag et al., 2023b).

Addressing sustainability issues in livestock production

While the effective control of infectious animal diseases is crucial to improve livestock productivity, enhance food security, and promote the wellbeing of farmers and the population, it is important to acknowledge and address the sustainability challenges associated with livestock production before concluding this thesis. Available evidence indicates that livestock production significantly contributes to global greenhouse gas (GHG) emissions, notably methane, nitrous oxide, and carbon dioxide, thereby exacerbating the climate crisis (Poore and Nemecek, 2018; United Nations Environment Programme, 2022). The primary sources of emissions are attributed to enteric fermentation, manure losses, and the energy use associated with animal feed production (Gerber et al., 2011). Hence, it is essential to maintain a balance between improvements in animal welfare and health, while ensuring environmental sustainability of livestock production in intervention strategies (Llonch et al., 2017).

Existing strategies for mitigating GHG emissions from livestock primarily focus on reducing total emissions and emission intensities within the value chain. These strategies entail enhancing feed efficiency and animal health, as well as implementing measures to improve manure management, land use, and on-farm energy use (Bellarby et al., 2013; Hristov et al., 2013; Rivera and Chará, 2021). Although the effectiveness of these mitigation strategies has predominantly been evaluated in developed countries, policy makers in LMICs including Ghana need to assess the feasibility and effectiveness of these strategies within their specific contexts. This is especially important considering that LMICs often rely on extensive farming systems, which generally have lower GHG emission impacts compared to the more intensive farming systems commonly found in developed countries (Thornton and Herrero, 2010; Rust, 2019). Nevertheless, the success of feed management interventions in enhancing livestock productivity is contingent upon the effective control of infectious diseases within herds (Graham et al., 2008; Espinosa et al., 2020). Additionally, achieving improvements in production efficiency towards GHG emissions mitigation necessitates finding a balance between the number of animals, and the availability of feeding and waste management resources within livestock production systems (March et al., 2021; Rivera and Chará, 2021). While farmers may seem motivated to prevent livestock diseases and enhance herd productivity, designing a successful intervention aimed at maintaining optimal herd sizes and promoting investment in feed resources would require a holistic understanding of the private incentives and strategic interactions of farmers, as well as extensive engagement. It is important to note that by demonstrating a commitment to safeguarding farmers' livelihoods through disease prevention strategies, we have a greater likelihood of gaining their support and cooperation in maintaining optimal herd sizes and making investments in animal feeds.

To summarize, based on the findings highlighted in this doctoral project, the main recommendations for veterinary and public health policy makers in Ghana include the following:

1. Explore avenues to strengthen the veterinary workforce in Ghana, potentially by offering incentives to attract and retain young talents in the veterinary services, and formalizing certain roles for CAHWs to augment veterinary service delivery especially in rural areas.
2. Need for increased funding allocation towards improving the veterinary infrastructure, including establishing animal health clinics, slaughter facilities, and providing the necessary tools for the effective implementation of an integrated

health surveillance system nationwide. The health surveillance system, in addition to disease surveillance, should also monitor antimicrobials sale and use, and the safety of animal products in the food chain, to detect early any potential hazards.

3. Establish antimicrobial stewardship programs, using transdisciplinary approaches, to enhance prudent antimicrobial use for animal health, and safeguard the efficacy of existing medicines.
4. Conduct a thorough review of vaccine delivery and pricing policies with the goal of enhancing access for farmers. Additionally, there is the need to address challenges in the cold chain system for vaccination delivery at the district and community levels, enhance community-level sensitization efforts on the benefits of vaccination, and establish surveillance mechanisms for circulating pathogens and adverse events following vaccination to monitor vaccines effectiveness and safety.
5. Conduct an evaluation of the psychosocial and physical health needs of farmers to inform suitable health interventions for livestock dependent populations.

For livestock farmers, the following are the main recommendations:

1. Prioritize preventive strategies especially vaccination in order to reduce the occurrence of diseases and take advantage of cost-saving opportunities offered by vaccination.
2. Actively engage in collective community efforts to exchange valuable insights regarding animal health practices and enhance access to existing veterinary services.
3. Need to participate in activities to improve awareness of prudent antimicrobial use for animal health.
4. In case of adversities related to livestock farming, it is important to seek assistance from nearby health facilities to obtain the necessary psychosocial support.

8.3 Implications for research and recommendations

Pathways for antimicrobial resistance pathogen development, and transmission

The increase in multidrug antimicrobial resistance poses a significant threat to public health worldwide, negatively affecting the efficacy of treatments for infectious diseases in both humans and animals, and leading to elevated rates of morbidity and mortality

(O'Neill J. (chair), 2016; Dhingra et al., 2020; Mestrovic et al., 2022). Scientific research has shown a direct connection between the specific types of antimicrobials utilized in various environments and the increased likelihood of the development of pathogen resistance to commonly used antimicrobials by individuals residing in those settings (Bell et al., 2014). Although theoretical evidence indicates the connection between the misuse of antimicrobials and the emergence of resistant pathogens, it is crucial to obtain empirical real-world research evidence elucidating the physical and genetic mechanisms involved in the transfer of antimicrobial resistance between animals and humans within their shared environments. Such evidence is essential for informing effective intervention strategies. In-vitro model studies have provided insights by demonstrating that microbial populations can transfer resistance genes through vertical and horizontal mechanisms. Vertical gene transfer occurs within lineages of the same species, from parents to offspring, whereas horizontal gene transfer occurs between different species (Stevenson et al., 2017; Li et al., 2019). The balance between vertical and horizontal gene transfers over time significantly influences the extent of pathogen resistance (Tao et al., 2022).

The implementation of antimicrobial stewardship programs provides a dependable strategy to addressing the issue of antimicrobial resistance resulting from animal health-related antimicrobial use (Weese et al., 2013; Lloyd and Page, 2018). Hence, it is crucial to assess the effectiveness of intervention strategies aimed at improving antimicrobial stewardship in livestock production. These strategies are essential for preserving the efficacy of current drugs and enhancing the longevity of newly developed molecules. Some studies have proposed a 5Rs framework - encompassing responsibility, reduction, replacement, refinement, and review - as fundamental components to be integrated into antimicrobial stewardship programs. This framework aims to foster leadership, commitment, action, and behavioral changes among relevant stakeholders, fostering the judicious use of antimicrobials in animal health (Weese et al., 2013; Page et al., 2014). Therefore, it is essential to conduct studies that evaluate the knowledge, attitudes, and practices of farmers and veterinary service providers regarding the use of veterinary medicines, and particularly the adherence to withdrawal periods after administering such medicines. Understanding these aspects within the context of LMICs would significantly contribute to the effectiveness of any antimicrobial stewardship interventions developed. The insights gained from these research studies would play a crucial role in achieving the principal goals outlined in the global action plan on antimicrobial resistance (WHO et al., 2016)

As part of antimicrobial stewardship strategies, the adoption of alternatives (replacement) for antimicrobials in animal health is often recommended. Various alternatives have been employed for this purpose, including the use of organic acids, probiotics, bacteriophages, and teat sealants (EMA committee for medicinal products for veterinary use (CVMP) and EFSA panel on biological hazards (BIOHAZ), 2017). Furthermore, aligning with the increasing interest in organic food production, herbal or plant-based remedies have emerged as potential alternatives to conventional biochemical therapeutics for enhancing animal health (McGaw and Eloff, 2008; Mayer et al., 2014). Herbal remedies are an integral part of ethnoveterinary medicine, a discipline that draws upon folk or traditional beliefs, practices, knowledge, and skills to manage animal diseases (Van der Merwe et al., 2001). Previous research on herbal remedies for livestock diseases have primarily concentrated on documenting the various plant species utilized in animal health, and elucidating their pharmacological properties (Abdalla and McGaw, 2020; Iwaka et al., 2022). As a result, only a limited number of herbal remedies are formally registered for the treatment of livestock. This can be attributed to the scarcity of clinical data that establishes the efficacy and effectiveness of these remedies under controlled and field conditions (Mayer et al., 2014). Therefore, there is a need for studies conducting clinical and field trials to assess the efficacy of herbal preparations against established pathogens. These trials are necessary to assess the efficacy of these preparations under controlled conditions, and their effectiveness in real-world field settings. Furthermore, determining the safety profiles of these herbal remedies is crucial to enhance their compliance with regulatory requirements for registration as therapeutic products (Wynn and Fougère, 2007).

One of the primary obstacles faced in ethnoveterinary practice pertains to concerns about the protection of intellectual property associated with the indigenous medical knowledge held by herbal medicine practitioners. These concerns have implications for the complete disclosure of active ingredients in herbal remedies, as well as the standardization of the processes involved in the preparation of these products (Timmermans, 2003; Kasilo et al., 2019; Jambwa and Nyahangare, 2020). Another concern relates to the sustainability of harvesting procedures for herbal products, necessitating further research to guide the cultivation and harvesting practices of medicinal plants in a sustainable manner (Chen et al., 2016; van Wyk and Prinsloo, 2018). Nonetheless, policymakers in animal health can gain valuable insights from the experiences and lessons learned in the introduction of alternative (herbal) medicine within human healthcare. These insights can aid them in overcoming some of the challenges associated with the standardization and regulation of herbal practitioners.

Strategies to improve community ownership and uptake of vaccination services

The importance of cooperation between different actors including scientists, policy makers and communities in addressing health problems in a sustainable manner have been well documented (Schelling and Zinsstag, 2015; Zinsstag et al., 2023b). To foster greater community ownership and acceptance of vaccination interventions in LMICs, it is imperative to develop context-specific strategies through broad stakeholder engagement. These strategies should entail an evaluation of existing barriers hindering vaccination uptake and the formulation of community-level proposals to address the primary challenges identified (Donadeu et al., 2019). Animal vaccines offer numerous advantages compared to antimicrobials, including the absence of residues in livestock products, reduced frequency of administration, cost-effectiveness, and prevention of the emergence of antimicrobial-resistant pathogens in food animals that can be transmitted through the food chain to humans (Scheerlinck and Greenwood, 2006; Charlier et al., 2022).

Within the scope of this doctoral project, farmers have put forth various proposals that require empirical studies to assess their effectiveness in enhancing vaccination uptake and the potential for scaling them up. Evaluating the feasibility and impact of these proposals is crucial to enhancing vaccination utilization. One proposal of particular interest is the formation of localized farmer networks that leverage the collective strength of the group in coordinating and participating in vaccination campaigns. This approach aims to overcome a major hindrance to vaccination uptake, wherein individual farmers opting to vaccinate their animals were burdened with the cost of entire vaccine vials, even if they did not own sufficient animals to use the entire vaccine vial (Nuvey et al., 2023a). It is crucial to conduct empirical studies to assess the potential of this intervention in enhancing vaccine uptake for the identified priority diseases in Ghana. These studies could also examine the intervention impact on the frequency and quantity of antimicrobials used in livestock production, as well as on the occurrence of disease-induced animal mortalities in herds, and the overall wellbeing of farmers. Additionally, the studies should evaluate the acceptability of the intervention among the key stakeholders, examine the costs associated with its implementation, and determine the feasibility of scaling up the strategy to other regions in Ghana. Moreover, since FMD is one of the priority diseases identified in the study area, and considering the lack of approved vaccines for it currently in Ghana, it is imperative to conduct studies evaluating the circulating FMD strains, and farmers' willingness to pay for FMD vaccination of their livestock to inform the introduction of FMD vaccines. The evidence generated from these studies will play a pivotal role in informing policy actions aimed at controlling infectious animal diseases in the country.

Furthermore, enhancing the veterinary workforce is vital to ensure the effective delivery of vaccination services when the demand for such services increases (Mazeri et al., 2021). Therefore, studies exploring the potential strategies that can foster interest in veterinary medicine among young talents and promote their retention in the profession would be valuable for policymakers. Evaluating measures aimed at enhancing the willingness of professional veterinary officers to serve in rural areas, where their services are in high demand, is also essential (Jackson and Armitage-Chan, 2017). In addition, it is essential to address the roles of informal veterinary service providers who currently operate outside the purview of veterinary authorities. Thus, future research need to assess the acceptability of informal veterinary service providers to policy makers, and the potential mechanisms of engagement between professional veterinary officers and the informal veterinary service providers. This will provide insights for shaping policies that delineate specific roles that can be delegated to the informal veterinary service providers to augment veterinary service delivery. Studies should also consider the perspectives of informal veterinary service providers as stakeholders within the animal health sector. Assessing their capabilities to deliver the required services effectively, and identifying training requirements to enhance their capacity for delivering quality veterinary services are important considerations for effective policy formulation (Catley et al., 2004; Wieland et al., 2021). Moreover, exploring the potential mechanisms for regulating their practice would be valuable in maintaining veterinary service quality and standards in the country.

Additionally, although households on average demonstrated a willingness to pay for vaccines that exceeded the prevailing vaccination prices, there exists affordability constraints faced by vulnerable groups, including women and farmers residing in the poorest districts. It would be valuable to investigate the proportion of households' annual incomes dedicated to animal health expenses, including vaccination costs, in order to gain a better understanding of the socioeconomic factors influencing farmers' decisions regarding herd vaccination. Future studies could also assess the impact of subsidy provision on vaccination uptake, and determine the necessary subsidy levels to achieve optimal vaccination rates. It is worth noting that the provision of subsidies to crop farmers as part of the Ghana Planting for Food and Jobs (PFJ) initiative has been reported to improve the adoption of improved seeds and fertilizers, as well as increased yields per cultivated hectare over time (Pauw, 2022; Taylor, 2022). Thus, there is a potential opportunity to stimulate increased livestock vaccination uptake by implementing subsidies in Ghana. Moreover, ruminant livestock farmers in a previous study in Ghana have expressed a certain level of discontent, and a perception of unequal treatment from policymakers in comparison to crop and poultry farmers. The ruminant livestock farmers feel that the support they receive to enhance their productivity is comparatively inferior, leading to a sense of frustration (Nuvey, 2019).

While studies are needed to evaluate various strategies that promote the uptake of livestock vaccines among farmers, there is also a need for research studies that assess the circulating pathogen strains in the country. Such studies would serve to validate the effectiveness of existing vaccines and provide insights for the introduction of alternative vaccine formulations, if necessary (Adams et al., 2009; Dimitrov et al., 2017). Moreover, scientific research has demonstrated that imperfect vaccination potentially increases the transmission of more virulent pathogen forms (Read et al., 2015; Bull and Antia, 2022). Additionally, it is imperative to investigate and monitor any adverse events that may occur following the vaccination of animals, similar to the practices in public health. This would enable the identification of necessary remedial actions or potential adjustments in vaccine formulations. Improving vaccination uptake would be an exercise in futility if farmers do not reap the full benefits of the vaccines they invest their resources in. Research shows that without significant benefits from vaccination to incentivize farmers to vaccinate their herds, even the most diligent efforts would fall short of achieving the necessary coverage (Chambers et al., 2016). Thus, instances of vaccine failures are anticipated to have a negative effect on future participation of farmers in vaccination initiatives. There is also a need for studies focused on enhancing the effectiveness of vaccines in real-world field conditions, as existing evidence indicates a potential decrease in effectiveness when compared to controlled on-station trials (Nuvey et al., 2022a). Furthermore, it would be beneficial to explore simplified vaccine delivery mechanisms (Charlier et al., 2022), especially if informal providers are considered to participate in vaccination programs to augment the efforts of professional veterinary personnel. The existing methods for administering animal vaccines primarily relies on intramuscular or intravenous routes (Sharma and Hinds, 2012). However, some studies have highlighted the potential of intranasal and intraocular routes as alternative modes of vaccine delivery to ease the administration of animal vaccines (Grosenbaugh et al., 2006; Meeusen et al., 2007; Sharma et al., 2009).

Empirical studies determining the impact of disease control on farmer wellbeing

The available research evidence indicates that infectious diseases in animals have adverse effects on the overall wellbeing of farmers, particularly in the psychological, social, and physical domains (Peck et al., 2002; Mort et al., 2005; Nuvey et al., 2020; Nuvey et al., 2023b). Nevertheless, there remains a dearth of evidence concerning the influence of animal diseases on the dependants of farmers, as well as the coping mechanisms and adaptive strategies employed by these dependants to mitigate the impact of animal diseases on the households. Previous research has shown that certain coping and adaptive strategies implemented by livestock farmers to address the impacts of infectious animal diseases can inadvertently introduce unsafe livestock products into the food chain (Bett et al., 2009; Chengula et al., 2013; Nuvey et al., 2021). Therefore, new research studies evaluating the effects of animal diseases on the dependants of livestock owners, along with the coping mechanisms and adaptive strategies employed to address these challenges, would provide valuable insights for policy makers. This is particularly relevant for children, whose development and functionality throughout the course of life is significantly influenced by the early life experiences (Richter et al., 2019; Daines et al., 2021). Therefore, future studies could investigate the effects of animal diseases on various aspects of child development, including biological, social, emotional, and cognitive outcomes, as well as the impacts on women, to provide further insights into the overall impact of animal diseases on livestock dependent populations.

Furthermore, conducting empirical randomized controlled studies would offer more conclusive evidence regarding the impact of effective control of infectious animal diseases on the wellbeing of livestock farmers and their dependants. These studies could evaluate various interventions for disease control and provide a comprehensive overview of the most effective approaches for addressing the wellbeing challenges faced by farmers and their dependants. Additionally, it would be valuable to investigate the extension of the benefits of effective disease control to the development and wellbeing of dependants of livestock owners, including children and women. These studies would enhance the applicability of a One Health framework in addressing health issues that interplay in the human, animal and environment interface, and the added value of inter-sectoral collaboration in addressing these complex challenges.

8.4 Study limitations to guide future inquiries

Over the past five years, my research has focused on identifying sustainable solutions to address the challenges faced by farmers, particularly those involved in livestock production. The ultimate goal of my research focus is to contribute to improving the productivity of farmers' herds and enhance their overall wellbeing and public food security and health. I acknowledge that my clinical and epidemiological background may have influenced my attention towards the health and wellbeing-related outcomes associated with these challenges. However, it is important to acknowledge that the impacts of these livestock farming-related adverse events extend beyond the realms of health and wellbeing alone. They have the potential to affect various aspects of individuals' lives, including but not limited to social, economic, and cultural dimensions, for both livestock-dependent populations and the general public. Exploring these broader impacts in future research studies would be valuable. It would be very informative, to observe how researchers without a health-focused lens perceive the associated impacts of farming-related adversities, particularly the impact of animal diseases, on both livestock-dependent populations and the public as a whole.

Additionally, incorporating a policy analysis component into this doctoral project would have enhanced our understanding of the existing strategies related to the training, deployment, and retention of veterinary personnel within the veterinary services sector in Ghana. Such insights would have provided valuable policy-oriented perspectives on the primary challenges encountered in maintaining an adequate veterinary workforce, thereby informing our recommendations for policy actions more effectively. Furthermore, although the scope of this doctoral project did not allow for the inclusion of informal veterinary service providers, examining their perspectives regarding their roles in veterinary service delivery, the knowledge base that underpins their practice, and the potential for their inclusion within the formal veterinary system for oversight is crucial. In future studies, it is important to consider this missing perspective in evaluating the performance of veterinary service delivery, particularly in rural areas. Additionally, future studies should also explore acceptable modes of engagement that can satisfy the requirements and preferences of the key stakeholders involved.

Overall, I consider this doctoral project to be an important initial step in addressing a complex problem faced by the population, laying the foundation for future research studies. The implementation of evidence-informed policy actions is crucial for all countries, particularly those with limited resources. Evidence-driven policies serve to guide policymakers in making decisions that yield maximum benefits for the population. It is crucial to note however that sustainable solutions to the challenges presented in this thesis, require long-term approaches that encourage the active participation of various stakeholders in identifying the problems, formulating potential intervention strategies, and evaluating the interventions effectiveness. Without the involvement and commitment of the key stakeholders including community members and policymakers throughout the process, the anticipated benefits of health interventions are likely to be short-lived and may not be fully realized.

8.5 Conclusion

The objective of this doctoral project was to consolidate the existing evidence on effective and cost-effective preventive veterinary interventions, to evaluate the barriers hindering their utilization, and to assess livestock farmers' willingness to invest resources in these interventions for the protection of their livestock assets and overall wellbeing. This research affirms vaccination as the most effective and cost-effective approach for controlling a wide range of infectious animal diseases. In spite of the availability of effective vaccines for the diseases prioritized by livestock owners i.e. CBPP, and PPR, the study findings reveal that a significant proportion of livestock owners do not regularly vaccinate their herds. The main obstacles to vaccination uptake include farmers' limited awareness on the value of vaccines, financial constraints arising from the requirement of farmers to purchase entire vaccine vials regardless of herd size, and inadequate availability and accessibility of professional veterinary officers when animal health services are required. Upon sensitizing farmers about the benefits of vaccines, the results demonstrate that, on average, they are willing to pay vaccination costs exceeding the prevailing prices. Nonetheless, in order to attain desirable national animal vaccination coverage targets for the priority diseases identified, subsidies need to be extended to reach vulnerable farmers, including women and farmers residing in the poorest districts. Thus, to achieve effective animal disease control, strategies aimed at improving vaccination uptake need to inculcate extensive community engagement, alongside reforms in the vaccination policies within the veterinary services.

An assessment of the disease management approaches employed by farmers, and the performance of veterinary services in addressing animal diseases revealed that farmers predominantly relied on treatment services rendered by informal veterinary service providers operating outside the purview of the veterinary authorities, or farmers administered treatments themselves. Furthermore, the veterinary system exhibited a limited capacity to regulate the sale and usage of veterinary medicines, and essential infrastructure such as slaughter facilities were lacking in rural areas, resulting in challenges in observing proper slaughtering practices and ensuring adherence to safety standards. Additionally, the treatments applied by farmers in most cases were not useful for the targeted conditions. These practices pose significant risks to public health and food safety. Thus, the design and implementation of context-specific antimicrobial stewardship programs would be valuable to promote the responsible and prudent use of antimicrobials in animal production, to mitigate the adverse impacts on the population.

The study also revealed significant impacts of diseases on herd productivity through high levels of disease-induced livestock mortalities among herds, leading to economic losses for farming households. The results also show that the increasing severity of disease-induced herd mortalities is associated with deteriorating wellbeing among the affected farmers. Therefore, interventions aimed at reducing or preventing the occurrence of diseases in livestock herds can mitigate their adverse effects on livestock productivity, thereby safeguarding farmers' livelihood, and enhancing public food security and the overall wellbeing of livestock dependent populations.

Chapter 9 Policy brief: Improving vaccination utilization for better food security, public health, and farmer wellbeing in Ghana

Policy message: Preventive veterinary interventions such as vaccination offer a reliable, effective and profitable means for controlling most infectious diseases in livestock. However, less than 20% of livestock farmers frequently vaccinate their herds in Ghana. Both demand and supply side barriers, mainly related to the acceptability, affordability, accessibility, and availability of vaccination, limit the uptake. Consequently, infectious diseases including contagious bovine pleuropneumonia, foot and mouth disease, and pestes-des-petits ruminants, are highly prevalent, causing high animal mortalities, and negatively affecting farmers' wellbeing. Also, to minimize the impact of the diseases, farmers frequently use antimicrobials without professional veterinary advice, with the risk of persistence of medicine residues in livestock products entering the food chain, as well as the development of related resistant pathogens. Thus, new community-centered initiatives for improving vaccination uptake are needed, alongside reforms in the vaccination policies to mitigate the impacts of the diseases on the population.

Main text

Contributions of livestock production in Ghana

The livestock sector contributes immensely to the lives of many people in low- and middle-income countries including Ghana, where it supports households' livelihoods, contributes to public food security and provides the nutritional needs in the human diet for better health and wellbeing. The livestock sector contributes about 15% of the overall agriculture output in monetary terms in Ghana. Poultry, cattle, sheep, and goats are the main livestock species reared by farmers. Our research revealed that farmers rear multiple species of livestock as well as grow food crops. Open field grazing is the main mode by which feeding resources are provided for the livestock reared.

Effectiveness, utilization and valuation of preventive veterinary interventions by livestock farmers

Our research revealed vaccination as the most effective and profitable intervention for controlling most infectious diseases in livestock. In spite of its value, less than 20% of livestock frequently vaccinate their herds. Both demand and supply constraints limit vaccination utilization in Ghana. Demand-side barriers include farmers' limited awareness of the value of vaccines, and unaffordability issues, especially when farmers must cover the entire cost of vaccine vials, even if they do not have enough animals to use an entire vial. Supply-side barriers are mainly due to a limited number of professional veterinary officers (VOs), and lack of adequate veterinary health infrastructure, which limit accessibility to VOs' services when needed. However, when farmers were sensitized on the benefits of vaccines, majority demonstrate a willingness to pay vaccination costs that exceed the prevailing market prices.

Strategies to address the livestock disease burden and impact on the population

Infectious diseases including contagious bovine pleuropneumonia, foot-and-mouth disease, and pestes-des-petits ruminants are highly prevalent in Ghana. Overall, farmers lose on average 10% of their herds to diseases annually. To minimize the impact of diseases, farmers primarily favored disease treatment over disease prevention. Informal veterinary service providers, operating outside the purview of the veterinary system or farmers themselves mainly rendered treatment services. In addition, the medicines applied were not useful for the target diseases. Thus, these existing challenges with the livestock sector in Ghana, poses significant threat to the livelihoods and wellbeing of livestock farmers, food security and public health thereby necessitating urgent strategies to address the problems.

Mitigating food insecurity through comprehensive strategies

Livestock vaccination offers numerous advantages compared to antimicrobials, including the absence of residues in livestock products, reduced frequency of administration, cost-effectiveness, and prevention of the emergence of antimicrobial-resistant pathogens in food animals that can be transmitted through the food chain to humans. However, there are significant bottlenecks mainly affecting acceptability, affordability, accessibility and availability of vaccination services to farmers in Ghana. The farmers thus proposed among other strategies, that the formation of localized farmer networks could mitigate most of their challenges with vaccination utilization. Such a context-specific strategy generated through broad stakeholder engagement could potentially improve livestock disease control in a sustainable manner while fostering community ownership and acceptance of vaccination interventions.

Policy implications

To address the main challenges identified, there is the need for significant investment by the relevant government agencies in the veterinary services directorate in order to bolster the veterinary workforce and infrastructure. Additionally, better regulation of veterinary medicine marketing and use, as well as antimicrobial stewardship programs are needed to foster prudent veterinary medicine use and to safeguard the efficacy of existing medicines.

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Curriculum vitae

Francis Sena Kwaku Nuvey

PROFILE

Francis is a Senior Epidemiologist with expertise in emergency preparedness, and response to unusual public health events particularly infectious diseases. He has experience in field epidemiology, clinical nursing, as well as the design, implementation, and evaluation of empirical scientific research. He has finalized his doctoral studies in the Human and Animal Health Unit, Department of Epidemiology and Public Health at the Swiss Tropical and Public Health Institute, an associated institute of the University of Basel in Switzerland. Francis is leading research projects that focus on strengthening health and food systems to address priority health issues affecting human, animal, and ecosystem health. Francis has a substantial experience in risk assessment, emergency preparedness, capacity building, health policy, strategic planning, and research to improve public health and wellbeing, particularly in resource-limited settings. He also provides mentorship to Field Epidemiology Training Programme (FETP) residents and trainee nurses to support them to develop the relevant competencies.

ACADEMIC QUALIFICATIONS

09. 2020 – 09. 2023

PhD (Epidemiology/ Public Health), Swiss Tropical and Public Health Institute, University of Basel, Switzerland

Title of Thesis: Effectiveness of veterinary service interventions in improving the wellbeing of livestock dependent populations in Ghana.

08. 2017 – 07. 2019

Master of Philosophy (Applied Epidemiology and Disease Control), School of Public Health, University of Ghana, Ghana

Title of Thesis: Factors leading to livestock losses and its influence on the psychosocial wellbeing of livestock farmers in two districts in Ghana.

08. 2010 – 06. 2014

Bachelor of Science (Nursing), School of Nursing and Midwifery, University of Ghana, Ghana

Title of Thesis: Sex education and adolescent reproductive health: University of Ghana nursing students' perspectives.

WORK EXPERIENCE

09. 2020 – present

PhD Fellow in Epidemiology and Public Health at Swiss Tropical and Public Health Institute (Swiss TPH), Switzerland and Centre Suisse de Recherches Scientifiques (CSRS), Côte d'Ivoire

- Design epidemiological studies using a One Health approach on preventive veterinary services effectiveness, profitability, and utilization for planning and implementation in Ghana.
- Design and deploy questionnaires on ODK for primary data collection.
- Conduct field surveys and facilitate focus group discussions.
- Implement data analysis on primary and secondary data using Stata, R Programming and NVivo software.
- Write manuscripts, policy briefs, and reports for the project.
- Prepare and actively participate in national and international workshops to engage key stakeholders to influence policy and informed decision making.
- Conduct systematic literature reviews and disseminate research findings using diverse channels: journals, conferences, and workshops.

04. 2017 – 08. 2020 **Nursing Officer at Korle Bu Teaching Hospital - Infectious Diseases Unit, Ghana**

- Design and direct a rotational system for managing patient care in the unit.
- Coordinate workforce management to ensure that quality care was delivered to patients and ensure all patients information is handled confidentially.
- Train and supervise student nurses in developing and achieving professional expertise in nursing and infectious diseases management and prevention.
- Obtain primary and secondary data for the hospital, partner institutions, and National AIDS Control Programme initiated research studies.
- Provide specialized nursing care for patients mainly with HIV, tuberculosis, rabies, COVID-19, tetanus, and other chronic non-communicable diseases.
- Provide health education and counselling for patients and families presenting with infectious diseases especially HIV/AIDS, tuberculosis, and cancer.
- Carry out weekly review of patient's medical records and submit the reports in line disease surveillance protocols (IDSR) to the Public Health Directorate.
- Delegate on the Infection Prevention and Control (IPC) Team of the Hospital, providing training to all staff cadres on IPC practice and PPE use in seminars.

04. 2017 – 11. 2019 **MSc Fellow in Epidemiology at Centre Suisse de Recherches Scientifiques (CSRS), Côte d'Ivoire, and Ghana Field Epidemiology and Laboratory Training Programme (GFELTP), Ghana**

- Work in close collaboration with the principal investigator to design, plan and implement epidemiological studies using a One Health approach.
- Conduct field surveys and key informant in-depth interviews to collect primary research data for the project.
- Develop data management and analysis plan and analyze the study data using appropriate statistical tools e.g., Stata and NVivo software.
- Interpret the study results and disseminate the findings to stakeholders in workshops, policy briefs and in scientific publications.
- Co-lead active disease outbreak investigations including seasonal influenza, avian flu, yellow fever, and COVID-19, by developing disease prevention, emergency preparedness, and response strategies in line with IHR (2005).
- Evaluate disease surveillance system performance and analyze population-level surveillance system data using appropriate tools e.g., Stata, and QGIS.

10. 2016 – 03. 2017 **Registered Nurse – Nursing Unit Head at Sanford World Clinics, Ghana**

- Assist research and health informatics unit with surveillance data collection.
- Develop and implement a rotational system for scheduling and assignment for nursing staff as unit head to ensure effective care of patients.
- Interpret, and explain healthcare options to patients and their families while supporting them to make informed decisions about their health problems.
- Organize relevant training for clinic staff e.g., on infection prevention and control (IPC) protocols, and manage unit healthcare delivery resources.

- Administer healthcare interventions including laboratory sample collection, treatment administration and care evaluation to out- and-inpatients under care including children, pregnant women, and the aged.
- Present Unit performance in staff, facility, and designated regional meetings.

11. 2014 – 08. 2016 **Teaching Assistant at the School of Nursing and Midwifery, University of Ghana, Ghana**

- Assist with the development of a nursing and midwifery curriculum, and its implementation on an online platform in a newly introduced distance learning programme for practicing nurses and midwives in Ghana.
- Train nursing and midwifery students on primary data collection and the use of clinical patient information.
- Deliver tutorials to nursing students, explaining, and clarifying key concepts.
- Conduct systematic literature reviews and prepare teaching materials for nursing students' use. Provide students' mentoring to enhance performance.
- Deliver revision sessions and implement student evaluations of the taught lessons. Provide feedback on examination performance.

TECHNICAL SKILLS

Epidemiology skills: Proficient in disease surveillance, emergency preparedness, outbreak investigation and response, disease surveillance system evaluation, epidemiological study designs, and Randomized Controlled Trials (GCP, ICH, SPIRIT, CONSORT).

Research skills: Skilled in designing and implementing Quantitative, Qualitative and Mixed-methods studies, and systematic literature reviews. Proficient in developing and deploying surveys on Open Data Kit (ODK) and Epi Info. Proven record in field data collection (survey, interviews and FGDs), management of large datasets, data analytics, and data visualization. Skills in disseminating research findings to diverse audiences (scientists, policy makers and lay people), and written (publications, and reports).

Project Management: Proven record in effectively managing project resources (time, personnel, and logistics), and fostering collaboration among project stakeholders (academia, lay communities, and government institutions) for successful project delivery.

Computer skills: Skills in Microsoft Office Suite (Word, PowerPoint, Excel, and Access), Microsoft Windows and Apple macOS, and Data Management in Endnote, Mendeley, and Health Information Systems; Quantitative (R and Stata), Qualitative (NVivo), Spatial (QGIS) data analysis.

Managerial skills: Strong leadership, organization, teamwork, communication, problem-solving skills.

Language skills: English (Native, C2); Ewe (Native, C2); French (Basic, A1).

PUBLICATIONS: for full list, please visit https://www.researchgate.net/profile/Francis-Nuvey

Nuvey, F.S., Hanley, N., Simpson, K., Haydon, D.T. et al. (2023). Farmers' Valuation and Willingness to Pay for Vaccines to Protect Livestock Resources Against Priority Infectious Diseases in Ghana. Preventive Veterinary Medicine 219.

Nuvey, F.S., Haydon, DT., Hattendorf, J., Addo KK. et al. (2023). Relationship between animal health and livestock farmers' wellbeing in Ghana: beyond zoonoses. BMC Public Health 23, 1353.

Nuvey F.S., Fink G., Hattendorf J., Mensah G.I., Addo, K.K. et al. (2023). Access to Vaccination Services for Priority Ruminant Livestock Diseases in Ghana: Barriers and Determinants of Service Utilization by Farmers. Preventive Veterinary Medicine 215.

Nuvey, F.S., Mensah, G.I., Zinsstag, J., Hattendorf, J., Fink G. et al. (2023). Management of diseases in a ruminant livestock production system: a participatory appraisal of the performance of veterinary services delivery, and utilization in Ghana

Nuvey, F.S., Arkoazi, J., Hattendorf, J., Crump, L., Addo, K.K., et al. (2022). Effectiveness and profitability of preventive veterinary interventions in controlling infectious diseases of ruminant livestock in sub-Saharan Africa: a scoping review. BMC Vet Res 18, 332.

Nuvey, F.S., Nortey, P.A., Addo, K.K., Addo-Lartey, A., Kreppel, K. et al. (2022). Farm-related determinants of food insecurity among livestock dependent households in two agrarian districts with varying rainfall patterns in Ghana. Frontiers in Sustainable Food Systems. 6. 743600.

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Ameme, D.K., Odikro, M.A., Baidoo, A., Dsane-Aidoo, P., **Nuvey, F.S.**, et al. (2021) Hand hygiene and face mask wearing practices for COVID-19 prevention: a non-intrusive observation of patrons of community convenience shops in Accra, Ghana. PAMJ. 1;40:195.

Nuvey, F.S., Addo-Lartey, A., Nortey, P.A., Addo, K.K., Bonfoh, B. (2021). Coping with Adversity: Resilience Dynamics of Livestock Farmers in Two Agroecological Zones of Ghana. Int. J. Environ. Res. Public Health, 18, 9008.

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