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

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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.

1. 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,

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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., 2023b). 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, 2019). 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., 2023). 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., 2022). However, neither strategy is currently used adequately in practice in many LMICs (Donadeu et al., 2019; OIE, 2019).

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 1 ml per cattle, administered subcutaneously. Vaccination is advised annually for cattle aged at least 6 months (OIE, 2018a, 2018b; 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 1 ml, 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, 2018a, 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., 2023b). 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., 2020). 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.

2. Materials and methods

2.1. 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 (Fig. 1) (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).

2.2. 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).

2.3. Study population

The target population included all ruminant livestock farmers in the study area. We obtained district maps from the District Directorates of

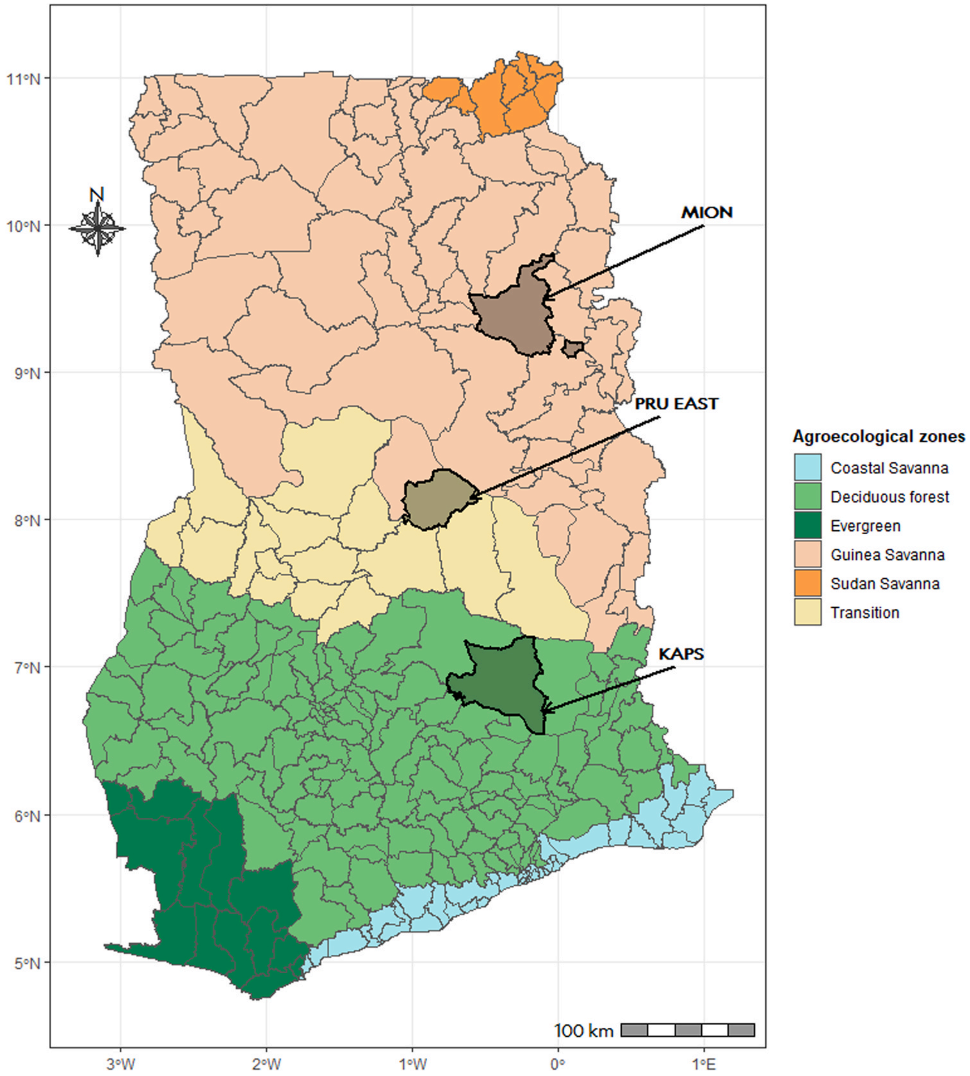

Fig. 1. Administrative map of Ghana showing the agro-ecological zones and study districts.[1]

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.

2.4. 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.

2.5. 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

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[1] Fig. 1: The figure shows the district-level administrative and ago-ecological map of Ghana. It 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.

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.

2.6. 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.

2.7. 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, where 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 *i*th farmer (WTP_i) rearing livestock in the *j*th community is unobserved, and could be expressed as shown in Eq. 1; 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.

$$WTP_i = x_{ij}\beta + \varepsilon_{ij} \tag{1}$$

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.

3. Results

3.1. Socio-demographic and livestock husbandry characteristics of study respondents

Table 1 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

Table 1
Socio-demographic characteristics of ruminant livestock farmers by study district.

Characteristic	KAPS (N = 149) Median (IQR)	MION (N = 98) Median (IQR)	PRU EAST (N = 103) 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)
	Frequency (%)	**Frequency (%)**	**Frequency (%)**
Sex			
Female	57 (38%)	16 (16%)	29 (28%)
Male	92 (62%)	82 (84%)	74 (72%)
Wealth status quintiles			
Lowest	21 (14%)	41 (42%)	8 (8%)
Second	41 (28%)	25 (26%)	8 (8%)
Middle	36 (24%)	14 (14%)	16 (15%)
Fourth	37 (25%)	10 (10%)	23 (22%)
Highest	14 (9%)	8 (8%)	48 (47%)
Educational attainment			
No formal education	41 (28%)	85 (87%)	52 (51%)
Up to high school education	72 (48%)	6 (6%)	29 (28%)
Tertiary education	36 (24%)	7 (7%)	22 (21%)
Main source of employment			
Farming (livestock, crop and fish farming)	115 (77%)	93 (95%)	70 (68%)
Business	18 (12%)	1 (1%)	14 (13%)
Artisanal worker	8 (5%)	2 (2%)	5 (5%)
Formal sector employed	7 (5%)	1 (1%)	11 (11%)
Student	1 (1%)	1 (1%)	3 (3%)
Farmland size (acres)			
Small (0 – 5 acres)	94 (63%)	16 (16%)	29 (28%)
Medium (6 – 11 acres)	31 (21%)	42 (43%)	22 (21%)
Large (12 – 99 acres)	24 (16%)	40 (41%)	52 (51%)
Annual livestock farming-related income			
Less than GHC 1500	88 (59%)	92 (94%)	80 (78%)
GHC 1500 or more	12 (8%)	1 (1%)	10 (10%)
Don't know/ refused to disclose earnings	49 (33%)	5 (5%)	13 (12%)

Percentages (%) are the proportions of ruminant livestock farmers within each characteristic explored per study district sub-sample (N). Frequency is the number of farmers falling into each sub-category of characteristics in the 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 2
Livestock husbandry characteristics of ruminant livestock farmers by study district.

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

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). Frequency is the number of farmers, falling into each sub-category of assessed characteristics in the districts; Kwahu Afram Plains South (KAPS), Mion and Pru East Districts. 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.

Fig. 2. Ruminant livestock farming household expenditure share distributions in Ghana.[2]

Table 3
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 Pestes-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.

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 2 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

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[2] Figure 2: Fig. 2 presents a violin plot show a breakdown of the share of farmers making the specified expenditures. The height of the violins show 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).

Table 4
Determinants of ruminant livestock farmers' willingness to pay for vaccination against Contagious Bovine Pleuropneumonia (CBPP) infection in cattle (N = 87).

Variables	Unadjusted model		Adjusted model	
	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				
Lowest	ref		ref	
Second	-0.52 (−3.15, 2.11)	0.69	-1.43 (−3.77, 0.92)	0.23
Middle	-1.55 (−4.67, 1.57)	0.33	-1.56 (−4.08, 0.96)	0.22
Fourth	-1.29 (−4.57, 1.98)	0.43	-1.01 (−3.72, 1.69)	0.46
Highest	-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.

Table 5
Determinants of ruminant livestock farmers' willingness to pay for vaccination against Pestes de Petits Ruminants (PPR) infection in sheep (N = 165).

Variables	Unadjusted model		Adjusted model	
	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				
Lowest	ref		ref	
Second	-0.03 (−2.65, 2.60	0.98	-0.19 (−2.79, 2.41)	0.88
Middle	-0.14 (−2.03, 1.75)	0.88	-0.61 (−2.77, 1.55)	0.58
Fourth	-0.11 (−1.83, 1.61)	0.90	-0.09 (−2.05, 1.87)	0.93
Highest	-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.

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.

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). 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

Table 6
Determinants of ruminant livestock farmers' willingness to pay for vaccination against Pestes de Petits Ruminants (PPR) infection in goats (N = 316).

Variables	Unadjusted model		Adjusted model	
	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				
Lowest	ref		ref	
Second	-0.03 (−1.33, 1.27)	0.97	-1.41 (−1.71, 0.90)	0.54
Middle	0.16 (−1.14, 1.45)	0.81	-1.18 (−1.77, 1.41)	0.83
Fourth	0.43 (−1.18, 2.03)	0.60	0.24 (−1.49, 1.96)	0.79
Highest	-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.

(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).

Fig. 2 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 (**S4 Fig.**).

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

Table 3 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.

3.2.1. *Cattle*

The average estimated WTP for CBPP vaccination per cattle was GHC 8.63 (95% CI: GHC 7.08–GHC 10.19). Table 4 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).

3.2.2. *Sheep*

Average WTP for PPR vaccination per sheep was GHC 7.02 (95% CI: GHC 5.99–GHC 8.05). Table 5 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).

3.2.3. *Goats*

Average WTP for PPR vaccination per goat was GHC 6.66, 95% CI: GHC 5.89–GHC 7.44. Table 6 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).

Fig. 3 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 (S5 Fig.), 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 (S6 Fig.).

4. Discussion

In this study, we estimated ruminant livestock farmers' willingness to pay (WTP) for Contagious Bovine Pleuropneumonia (CBPP) and

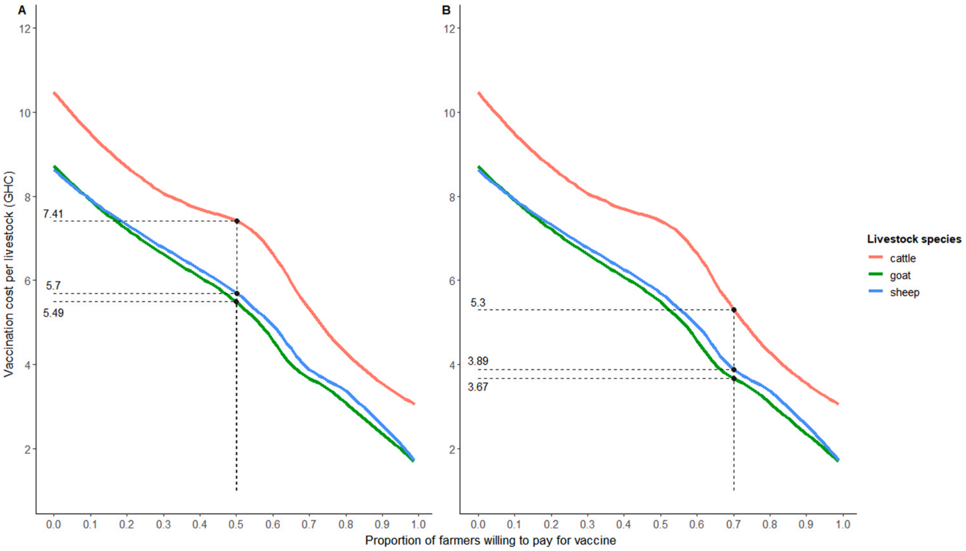

Fig. 3. Proportion of livestock farmers willing to pay for vaccination to protect their herds against CBPP infection in cattle, and PPR infection in sheep and goats in Ghana.[3]

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., 2020). 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, 2019). 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., 2022). 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 well-being 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% 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

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[3] Fig. 3: Fig. 3 shows the cumulative proportion of the farmers willing to pay for Contagious Bovine Pleuropneumonia vaccines for cattle, and Pestes-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.

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., 2023b). 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.

5. 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.

Ethics approval and consent to participat

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).

Availability of data and materials

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

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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.

Declaration of Competing Interest

The authors declare that they have no competing interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.prevetmed.2023.106028.

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