

Porcine Reproductive and Respiratory Syndrome Virus transmission among smallholder pig farms in western Uganda

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ABSTRACT

Pig production is a rapidly growing sector in Uganda, especially among smallholder farmers to whom it provides a vital source of income. However, the burden of productivity-limiting diseases such as Porcine Reproductive and Respiratory Syndrome (PRRS) poses a significant challenge. This is exacerbated by the paucity of information on the occurrence of these pathogens within the country, highlighting the need to study their transmission dynamics for effective control. Here, we modelled the transmission of PRRS in western Uganda and evaluated its control under strategies targeting closure of biosecurity gaps related to practices such as equipment sharing, free ranging, boar sharing, farm visits, and restocking. We used data from 398 pig-farming households to assess husbandry practices, and to estimate contact rates and distances for simulating the spread of PRRS among the 44,125 farms in the study area. Biosecurity measures were found to be low among pig farms in the region, with only 0.8 % of them keeping their entire herd confined all-year round, limiting access to unauthorized persons, and using disinfectants. Under the current state of biosecurity, a PRRS outbreak would result in 17.57 % of the pig farms in the region being infected within two years, with the medium and large-scale smallholder farms being most affected. The outbreak would persist beyond 2 years (with a 67.80 % likelihood), stabilizing around 700 days post-introduction; reaching a prevalence of 5.15 %; and with a median of 17 farms being infected daily during this endemic phase. However, eliminating visitor traffic could entirely halt PRRS spread, while eliminating risks associated with boar sharing, restocking, and scavenging would lead to reductions of 99.85 %, 99.44 %, and 40.67 %, respectively. Furthermore, even a moderate adoption of improved biosecurity measures related to farm visits or boar sharing, could significantly reduce the effects of PRRS in the region. For instance, reducing the frequency of farm visits or boar sharing by 25 % across all pig farms could reduce PRRS

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transmission by 99.61 % or 73.95 % respectively. This outcome could also be achieved through a targeted adoption rate of 50 % within large-scale smallholder farms coupled with a 25 % rate for medium-scaled ones. Our results highlight the necessity of promoting enhanced on-farm biosecurity practices in smallholder pig farms, given the challenges posed by productivity-limiting diseases such as PRRS, in Uganda's rapidly growing piggery industry.

1. Introduction

Pig production is one of the fastest growing livestock enterprises in Uganda with a potential to improve incomes and livelihoods of farmers and spur economic development (Twine and Njehu, 2020). Uganda's pig population has more than doubled in the past decade, reaching 7.1 million in 2021 from 3.2 million in 2008, with an annual growth rate of 6.3 % (UBOS, 2024). This rise denotes the increasing demand for pork and its products on the Ugandan market. Further, the number of households engaged in pig farming also saw a remarkable increase. Over the same period, the households engaged in pig-keeping increased by 96 %, climbing from 1.13 million in 2008 to 2.2 million in 2021 (UBOS, 2024). These statistics underscore the increasing appeal of pig farming as a viable livelihood option. The pig farming subsector is dominated by smallholder farms, which are typically households keeping fewer than 30 grown pigs, and are characterized by low inputs and low outputs (Ouma et al., 2013). These farms are often managed by women and youth, who are attracted by low capital requirements and the perceived quick returns associated with pig farming (Muhanguzi et al., 2012; Ouma et al., 2013). Pigs play a vital role in converting crop residues and food waste into valuable protein, generating income for households (Twine and Njehu, 2020). These small ventures act as a safety net, supporting families during financial shortages and even providing capital for other ventures (Behnke and Nakirya, 2012; Twine and Njehu, 2020). While industrialized pig projects are emerging in urban areas, the sector's growth is hindered by limited management knowledge and a high disease burden (Dione et al., 2014). Moreover, biosecurity measures are lacking in many smallholder farms, with sharing of breeding boars, inadequately controlled movement of pigs, unrestricted access to visitors and roaming pigs posing risks of disease transmission (Muhanguzi et al., 2012; Dione et al., 2017).

Within the last decade, studies in Uganda have revealed the presence of contagious respiratory and reproductive pathogens that are known to cause economic loss in pig farming operations (Jonsson, 2013; Dione et al., 2017; Wilfred et al., 2018; Oba et al., 2021, 2022). One of the pathogens identified is PRRS virus (PRRSV) which causes Porcine Reproductive and Respiratory Syndrome (PRRS) (Dione et al., 2017; Oba et al., 2021; Oba et al., 2022). PRRSV is an RNA virus belonging to the genus Arterivirus and family Arteriviridae. Two dominant strains of this virus are globally recognized, PRRSV-1 (European strain) and PRRSV-2 (North American strain). While both strains have been found to circulate in Uganda, the North American strain of PRRSV is more prevalent (Oba et al., 2022). This disease causes infertility, abortions, premature farrowing, mummified fetuses, stillborn and/or weak piglets, as well as a high pre-weaning mortality in infected herds (Lunney et al., 2010). Infected pigs are known to shed the virus in various bodily fluids such as nasal secretions, mammary secretions, placental fluids, semen, urine, and sometimes feces (Pileri and Mateu, 2016). Once infected, the pigs can be infectious for at least 42 days (Charpin et al., 2012). Nevertheless, the pigs may remain persistently infected for up to 250 days post-infection, with a declining likelihood of transmitting the infection to naïve pigs under natural comingling conditions (Rowland et al., 2003; Wills et al., 2003). The potential risk and impact of PRRS outbreaks in backyard smallholder pig farming operations remains unclear. And, by the time of this study, no vaccine is registered for use in the control of PRRS within Uganda. Given the importance and complexity of husbandry practices regarding biosecurity, there is a need to investigate the interplay of transmission risk factors that are unique to these farming

operations to enhance our understanding of disease transmission in such landscapes.

In two previous surveillance studies, PRRS was found to have a prevalence of 1.3 % and 13.8 % among pigs reared in Central and Northern Uganda, respectively (Dione et al., 2017; Oba et al., 2023). The authors posit that the higher prevalence reported in the latter study could be an indication of a raising PRRS transmission in the country over the years or a persistent infection within their study area (Oba et al., 2023). Additionally, Hasahya and colleagues (2021) modelled the transmission of PRRS in Lira District, in Northern Uganda, yielding a herd level prevalence of 36.75 % within a year of introduction. It is worth noting that pig husbandry practices play a crucial role in influencing the epidemiology and control of PRRS outbreaks. Hence, understanding the diverse and complex nature of pig husbandry practices across different communities and landscapes in Uganda can guide the formulation of efficient strategies for management of PRRS in the country. Building on previous research, the current study modeled the transmission dynamics of PRRS across a wider geographical area, in Western Uganda. We aimed to offer a comprehensive insight into the spread of PRRS within Western Uganda. Unlike Hasahya et al., who studied both movement restriction and vaccination as potential control strategies, we focus solely on the contribution of movement restrictions and implementation of farm biosecurity protocols — the predominant strategies currently employed across this region during outbreaks. And by covering a broader geographical area than in previous studies, we were able to more effectively account for the diverse husbandry practices that typify pig farming within the western region and the rest of the country.

2. Materials and methods

2.1. Study area and design

The study was conducted in the areas surrounding Queen Elizabeth and Kibale National parks along the Albertine rift in Western Uganda. This area was selected because it covers the main pig farming districts in Western Uganda. Additionally, the proximity to the two national parks with rich biodiversity including wild Suid species means that PRRS transmission has implications for both pig husbandry among communities and wild Suid conservation. Study activities were done in the 11 districts (Kabarole, Kyenjojo, Kamwenge, Bunyangabu, Kasese, Kitagwenda, Rubirizi, Bushenyi, Mitooma, Rukungiri and Kanungu), which border these national parks (Fig. 1).

The study employed a cross-sectional design, and the collected data then used to describe farm level impacts of PRRS. With this information, an epidemiological modelling approach was applied to simulate the impacts of PRRS outbreaks in the region. The sample size for the survey was determined using the following formula provided by Daniel and Cross (2018).

$$n \geq \frac{N * X}{(X + N - 1)}$$

where,

$$X = \frac{(Z_{\alpha/2})^2 * p * (1 - p)}{MOE^2}$$

and $Z_{\alpha/2}$ is the critical value of the Normal distribution at $\alpha/2$ (e.g., for a

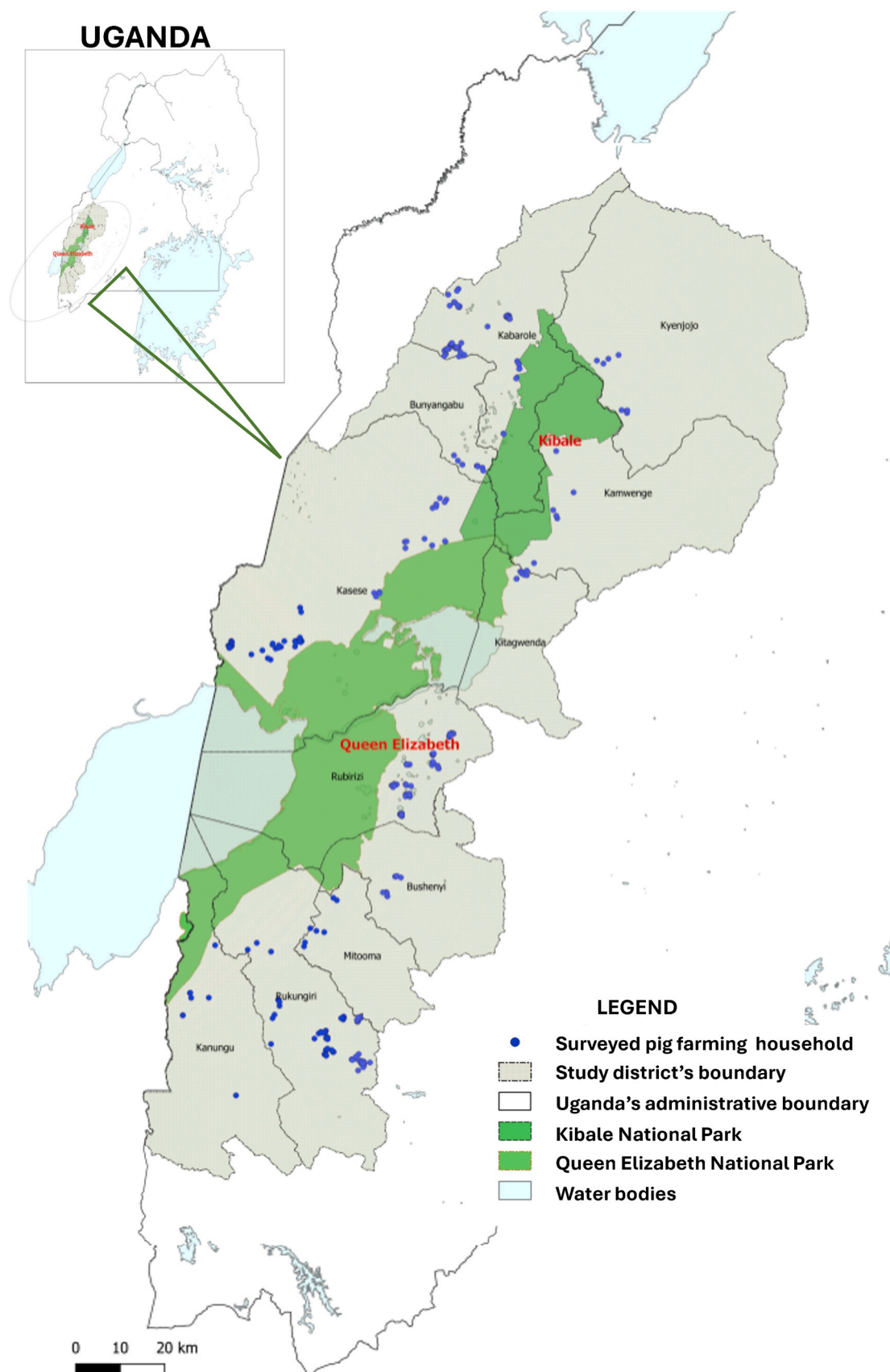


Fig. 1. The study site. A map of western Uganda showing Kibale and Queen Elizabeth National Parks, the districts bordering them, and the distribution of the households that were surveyed within the region.

confidence level of 95 %, α is 0.05 and the critical value is 1.96), MOE is the margin of error, p is the sample proportion, and N is the population size. Note that a Finite Population Correction has been applied to the sample size formula.

$$n \geq \frac{40000 * 384.16}{(384.16 + 40000 - 1)}$$

$$n \geq 3841600/10383$$

$$n \geq 380$$

We estimated that there were 40,000 households engaged in pig farming within the study region. To achieve a 95 % confidence level, it was determined that a sample size of 380 pig-farming households would be required. To account for potential non-compliance among respondents, a total of 398 households were included in the survey. Each farm/ household included was geocoded using a handheld GPS device (GPSMAP 64 s, Garmin® Ltd, Olathe, USA)

2.2. Household selection and data collection

In each of the study districts, the District Veterinary Officer (DVO) selected 2–5 sub-counties that were known for having a high concentration of pigs or pig-farming households. Subsequently, a list of candidate pig-farming households was compiled by the DVO in collaboration with the local council leaders. The list was disaggregated at subcounty, parish and village levels with the village being the smallest administrative unit spanning approximately 2 kilometres in radius. Households on the list were randomly visited by the field team until at least 5 pig-farming households were interviewed per parish.

The data collection tools included a structured questionnaire with both closed and open-ended questions that was pretested in Mbarara, Kitagwenda and Rubirizi districts and adjustments made accordingly, especially for accurate estimation of distances. To improve reliability in distance estimation, especially in remote areas, respondents were encouraged to use reference points like the length of a football pitch or distances between known towns or landmarks. These estimates were at times supported through consensus with the guide provided by the local village leader. Furthermore, field assistants experienced in agricultural extension and proficient in both English and at least one of the relevant local languages were recruited and trained to ensure accurate questionnaire administration. This approach aimed to maintain the integrity and meaning of the data collected without any loss in translation. The first, second and third authors were involved in the pretesting of tools, training of field assistants and supervision of field activities to ensure consistency and quality of the data collected.

A total of 398 households were interviewed. The surveyed households were distributed across a total of 113 villages, located within 73 parishes, in 39 of the sub-counties in the 11 districts within the study area. Informed consent was obtained from each household head before data collection. Data was collected in face-to-face interviews with the individual farmers/household representative at their home or farm premises. The interviews were conducted mainly in the native languages, Runyankole-Rukiga, Runyoro-Rutooro and Lukhondo (using translated questionnaires) and occasionally in English. The questionnaire captured data on basic household information as well as the potential risk factors of PRRSV in the region such as patterns of stocking, farm visits, boar sharing, *etcetera* (Appendix A). After the interviews, the investigator observed and recorded data on the farm structure, stocking, and biosecurity measures in place using a dedicated checklist (Appendix B). The information gathered from the interviews together with the observed practices was used to profile the farm and to estimate the average contact rates with other farms.

2.3. Model framework and parameterization

We used the North American Animal Disease Spread Model

(NAADSM) to simulate the spread of PRRSV among the smallholder pig farms in the study area (Harvey et al., 2007). This stochastic model operates on a population of herds by utilizing user-defined parameters to simulate the spread of a contagious disease within the population.

2.3.1. Modelled pig herd population

The total number of households engaged in pig farming within the study area was not directly available at the time of the study. To establish this number, we obtained the number of households per district in the study area from the 2014 population census (UBOS, 2016). We then obtained the estimated household proportion that keeps pigs by expert opinion through key informants including the district veterinary officers, the NGOs, and the average was 6.5 %. Using this proportion, we computed the number of pig-keeping households per district, which yielded a total of 44125 pig-keeping households in the study region (5). We then distributed the total number of pig-farming households into the different production groups according to the proportions that have been previously reported (Ouma et al., 2013)(Table 1).

The exact farm geolocations within our study area were unattainable due to the absence of such a database in the country at the time of writing this article. We therefore randomly generated GPS coordinates for the estimated total of 44,000 pig-farming households within the study region. Natural features such as lakes and national parks were marked to avoid distribution of the smallholder farms in these spaces. The pig keeping households were classified into production types based on the sizes as informed by the data collected from the study area as well as literature. Smallholder farms with 1–4 grown pigs that were confined were grouped into small (S) smallholder farms, those with 5–11 grown pigs that were confined into medium (M) while those with 12 and more grown pigs confined as large (L) smallholder farms. There were also smallholder farms that were either leaving the adult pigs on free range and others would confine the adults but leave the piglets to free range or the adults were confined sometimes but occasionally released to roam. Such smallholder farms were classified as free range and in relation to the size of the farm, these were the categories according to their

Table 1

Values for simulation of the spread of PRRSV among smallholder pig farms in eleven districts that board queen Elizabeth and Kibale national parks in western Uganda.

Parameter	Value	Reference*
Pig population		
Total number of pig-keeping households	44,125	KII, expert opinion, and DVO
Small-scale smallholder farms	16,450 (37.3 %)	KII, expert opinion, and DVO
Medium-scale smallholder farms	7457 (16.9 %)	KII, expert opinion, and DVO
Large-scale smallholder farms	3733(8.5 %)	KII, expert opinion, and DVO
Small-scale free-range smallholder farms	12,911 (29.3 %)	KII, expert opinion, and DVO
Medium-scale free-range smallholder farms	2603 (5.9 %)	KII, expert opinion, and DVO
Large-scale free-range smallholder farms	971 (2.2 %)	KII, expert opinion, and DVO
PRRS disease state parameters		
Latent period	1 day	(Charpin et al., 2012)
Infectious clinical period for small- & medium-scale farms both confined and free-ranging)	48 days	(Charpin et al., 2012)
Infectious clinical period (Large and large free range)	60 days	Assumptions based on Charpin et al. (2012)
Natural immunity	(185.5days)	(Andraud et al., 2018)
PRRS spread parameters		
Probability of transmission by direct contact	0.6	(Lee et al., 2021)
Probability of transmission by indirect contact	0.021	Assumptions based on Muñoz et al. (2022)

* KII, Key Informant Interviews; DVO, District Veterinary Office(r)

corresponding confined farm category sizes as follows; small-free range (SF), medium-free range (MF) and large-free range (LF). We had a total of six production groups.

2.3.2. PRRS manifestation parameters

NAADSM is an SIR (susceptible-infectious-recovered) transmission model meaning that in a PRRS outbreak, the herds would transition from a state of susceptibility to PRRS, through their infectious phase up to when they would recover or be removed from the population (through death or destruction). In the model, recovered units (pig herds) would return to the susceptible state and possibly get re-infected, given sufficient time. Parameters about the infectivity, duration of infectiousness, and immunity in pig herds with respect to PRRS remains unclear, particularly within the context of small-scale farming practices in developing countries such as Uganda. Nonetheless, with these limitations in mind, certain inferences can be drawn from existing data.

It has been reported that the average infectious period in a PRRS-infected pig is 48 days, with viral shedding commencing 2 days post exposure (Charpin et al., 2012). Considering their small herd sizes, we assumed that in the event of an infection within a small or medium-scale smallholder farm, all animals would be infected within 2 days. We further assumed that the infected small or medium-scale herd (unit) in our model would remain infectious for a period of 48 days. For a large-scale smallholder farm, it may not be possible for all the pigs to be infected within two days. We thus postulated a period of two weeks for the complete infection of all pigs and subsequently, a state of infectiousness stretching to 60 days. For all herd types, we assumed that following recovery from PRRS infection, they would remain immune for the next 185.5 days based on data reported by Andraud et al. (2018).

2.3.3. PRRS spread parameters

To model the spread of PRRS, NAADSM also required data on frequency of contact between the farms and the probability of infection occurring as a result of the contact. We calculated the frequencies of contact (direct and indirect) between the various smallholder farm within the study area using the information obtained in the field survey. Channels of direct contact included introduction of new pigs from and boar sharing between the farms while those of indirect contact included sharing of equipment, free ranging / scavenging practices as well as human traffic between pig farming households. The average contact frequencies (both direct and indirect) among different categories of farms within the study area were computed on daily time scales for the model.

Information on the probabilities of infection of pigs with PRRS in cases of direct and indirect contact with an infective herd is inconclusive, more so under field settings. Previous studies have reported a probability of direct transmission ranging from 0.15 to 1.00 throughout the infectious phase of the source pig (Neumann et al., 2007; Charpin et al., 2012). We therefore assumed an average probability of infection of 0.6 following direct contact with a PRRS-positive farm in the modelled population. Regarding indirect contact, we assumed an average probability of infection of 0.021 in this community. This estimate was derived from the probabilities reported in a well-designed study on the transmission probabilities of African Swine Fever (ASF) through fomites (Muñoz et al., 2022). We adopted probabilities for farms with low stocking densities comparable to those that dominated our study area.

2.4. Scenarios

The model was simulated for 730 days with 500 iterations. To study the drivers of transmission in the study area a total of 6 hypothetical scenarios were developed and modelled. In the baseline scenario (scenario1), we assumed no control measures. In scenario 2, pig farmers seize to share equipment; in scenario 3, pigs are no longer allowed to scavenge or freely range the landscape; in scenario 4, farmers seize the

practice of sharing boars as a reproductive management strategy on their farms; in scenario 5, farmers seize to accept visitors on their pig farms; and in scenario 6 farmers stop buying and selling stock from neighboring farms (This can be translated, practically, as quarantining pigs before they're introduced into the herd to eliminate this risk factor).

To assess the feasibility of a gradual improvement in biosecurity practices, we developed scenarios in which adoption rates across all pig farms reached 25 %, 50 % and 75 %. These scenarios were developed for farm visits and boar sharing. We further developed scenarios in which adoption of improved biosecurity in these practices reached 50 % among large-scale smallholder farmers in addition to a rate of 25 % among small-scale ones.

2.5. Model assumptions and limitations

This work involved a few assumptions. First, we assumed introduction of PRRS into a naïve population. Though PRRS has been confirmed in other parts of the country including the central region and parts of the northern region, its prevalence in the study area is not well known. In an ongoing study, by our group, on the prevalence of porcine respiratory pathogens in the study area, PRRSV was not detected among sampled pigs in western Uganda (unpublished data). We therefore simulated introduction of PRRS into a PRRS-free region. Additionally, we assumed that a homologous strain of the virus was introduced and did not undergo mutations throughout the simulation period; and that when one animal on the farm was infected, the whole farm was considered infectious. While in real field settings, several subtypes may circulate and not all animals within a herd may get infected, these assumptions were useful. For the former, a single uniform strain simplifies the model, and in the latter case, herd level considerations are effective and practical for disease control at strategic levels of livestock disease control.

We further assumed that airborne spread was insignificant within the pig farms in the study area. While there is some evidence that airborne spread of PRRSV may occur, the conditions in our study area would have been less conducive. Mainly because of the typically low density of pigs within the smallholder farms in the region (Brito et al., 2014; Arruda et al., 2019).

Although these limitations exist, and have to be considered in interpreting our results, the model does provide a valuable basis for decision making and the design of disease control strategies.

2.6. Sensitivity analysis

We carried out a sensitivity analysis to evaluate the impact of both the direct and indirect probability combinations by changing them from 0.6 and 0.021 respectively. The direct contact probability was altered from 0.6 (in the baseline scenario) to 0.5 and 0.8 while the indirect contact probability was altered from 0.021 (in the baseline) to 0.0.05 and 0.1. We tested all combinations of these probabilities of direct and indirect transmission i.e. (0.8 and 0/1), (0.8 and 0.05), (0.8 and 0.021), (0.6 and 0.1), 0.6 and 0.05), (0.5 and 0.1), (0.5 and 0.05) and (0.5 and 0.021). The results were compared with the baseline scenario.

3. Results

3.1. Farm characteristics and biosecurity practices

Three hundred and ninety-eight ($n = 398$) pig keeping households were interviewed in eleven districts in the Albertine rift region (Fig. 1). Entries from three (3) households were disqualified due to missing data, and 395 households were considered for this further analysis. The analysis showed that, 27.1 % of the households reared pigs under confinement at a small-scale, 23 % at a medium-scale, and 17.5 % at a large-scale. The rest of the respondents that did not confine their pigs included, 21.3 % who kept the pigs at small-scale (small-scale free-range), 8.1 % at medium-scale (medium-scale free-range), and 3 % at

large-scale (large-scale free-range). The respondents described the breeds of pigs that they kept as 'exotic' (44 %), mixed (a combination of the 'exotic' and native breeds) (33 %) or native breeds (23 %). The main reasons for keeping pigs were to produce piglets and raise porkers (54 %), solely for piglet production (24 %), solely for porker production (20 %) while only 0.5 % kept the pigs for production of replacement gilts.

The study explored the characteristics of smallholder pig farming operations in the Albertine Rift region, with a particular focus on practices related to biosecurity management. The results indicated that 26.91 % (106/394) of the respondents either kept all or part of their pig herd outdoors (Fig. 2A). Among these, 11.68 % (46/394) of the interviewed households did not have housing structure for their pigs and relied on a tethering system for pig rearing. Only 42.53 % (168/395) of the respondents were confident that their pigs do not freely roam and scavenge within the community during their on-farm life (Fig. 2B). In 24.81 % of the surveyed farms, the pig herds were confined, but piglets and weaners frequently exited the pens and roamed beyond farm premises. This was partly because they were small enough to escape through openings in the pig pens, or due to the utilization of a tethering system, where piglets are not tethered, or simply because farmers permitted them to scavenge, believing it to be beneficial for their well-being. On 32.66 % (129/395) of the surveyed pig farms, all or part of the herd were reported to occasionally roam freely and scavenge. This frequency of scavenging was higher than expected, based on reports from the DVOs in the respective study districts during our entry interviews. A possible explanation for this could be a low importance placed on farm structures in these resource-constrained communities leading to a high frequency of animals straying beyond farm premises even under systems that are intended to be confined. Further, none of the respondents practiced a completely free-ranging or scavenging system throughout the year. The respondents attributed this to the agrarian way of life within their communities which required that pigs be confined (typically within pens or by tethering) to minimize crop raiding. And after the harvesting season, the pigs would be released to feed on crop residue in the gardens, essentially converting crop waste into valuable animal protein.

In total, only 7.36 % of the 395 farms surveyed restricted access to only authorized persons and had a functional perimeter fence in place to enforce this restriction (Fig. 2C). Most farms (78.43 %) did not have any restrictions or fencing in place, while 14.21 % partially restricted access to their pigs. Additionally, we found that only 3.80 % of the surveyed farms (15 out of 395) had footbaths, and when considering their proper utilization, this proportion further reduced to 1.8 % (7 farms) (Fig. 2D). Overall, we found that only 3 out of the 395 farms followed all the basic

biosecurity measures we evaluated, which included confining pigs in well-maintained enclosures, restricting access to authorized personnel, and using disinfectants in footbaths at all entry points to the farm premises. Among the remaining 392 farms, a substantial degree of overlap was observed in the deficiencies relating to these biosecurity indicators (Fig. 2E)

3.1.1. Contact rates

The contact rates computed for the scenarios are presented in Tables S2 and S3. Overall, there were higher rates of indirect than direct contact between pig herds within the study area. The highest contact rates were found to occur between small-to-small farm combinations. These farms had a daily direct contact rate of 0.00804, which means that on average, each small pig farm contacts another small pig farm directly once every 4 months. Additionally, there was a daily indirect contact rate of 0.47574, meaning that indirect contact (such as visitors or sharing equipment) between these farms occurred once every 2 days. Several farm combinations, particularly those between free-ranging farms, were found to have the lowest contact rates (Table S3). This is partly because the practice of allowing pigs to freely roam and scavenge was commonly practiced on farms that were relatively isolated amidst cultivated landscapes.

3.1.2. Contact distances

The modelled distances between combination types are presented in (Table S4). Direct contact between large scale farms and the other farm types were the highest, at times exceeding 100 km. This was due to the fact that there were a relatively small number of large-scale farms, and they were often seen as a reliable source of quality pig genetics by most farmers when considering stocking or restocking their own pig farms. On the other hand, indirect distances were shorter, ranging from as low as 0.1 km to a maximum distance of 5 km. Overall, the mode distance was 0.5 km, which indicated a high degree of contact between neighboring farms when access restrictions are rarely applied.

3.2. Patterns of PRRS infection among pig farms in the Albertine Rift region across scenarios

Given the stochastic nature of our model, we used the median values of infected herds resulting from 500 iterations of each of the modeled scenarios to evaluate the transmission dynamics of PRRS within the study region. In the baseline scenario (scenario 1), which assumed no control measures, the model revealed that within 2 years of PRRS introduction, up to 7747 (17.6 %) of the farms within the region would be infected (Fig. 3.A(1) & B(1)). Notably, PRRS would impact the

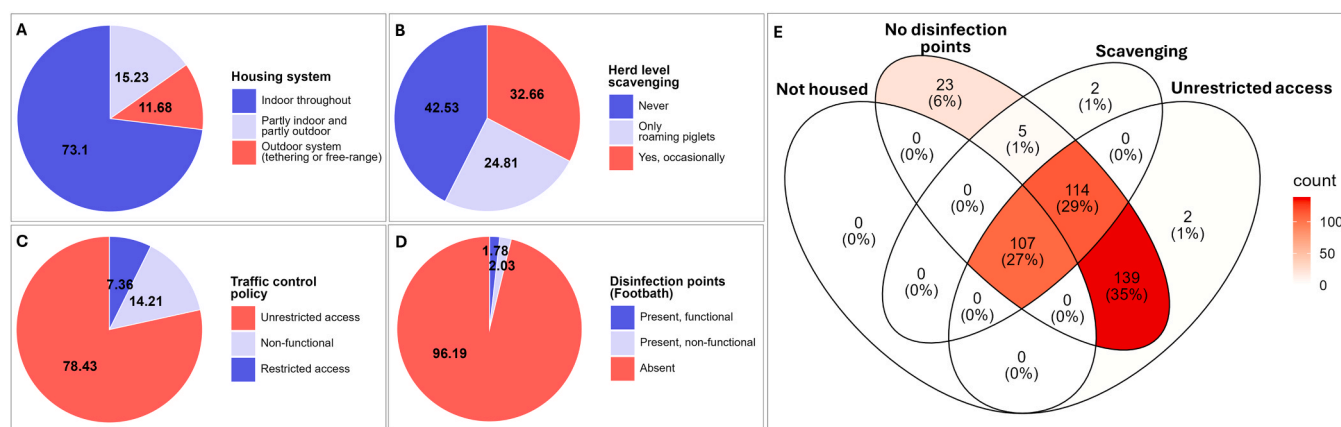
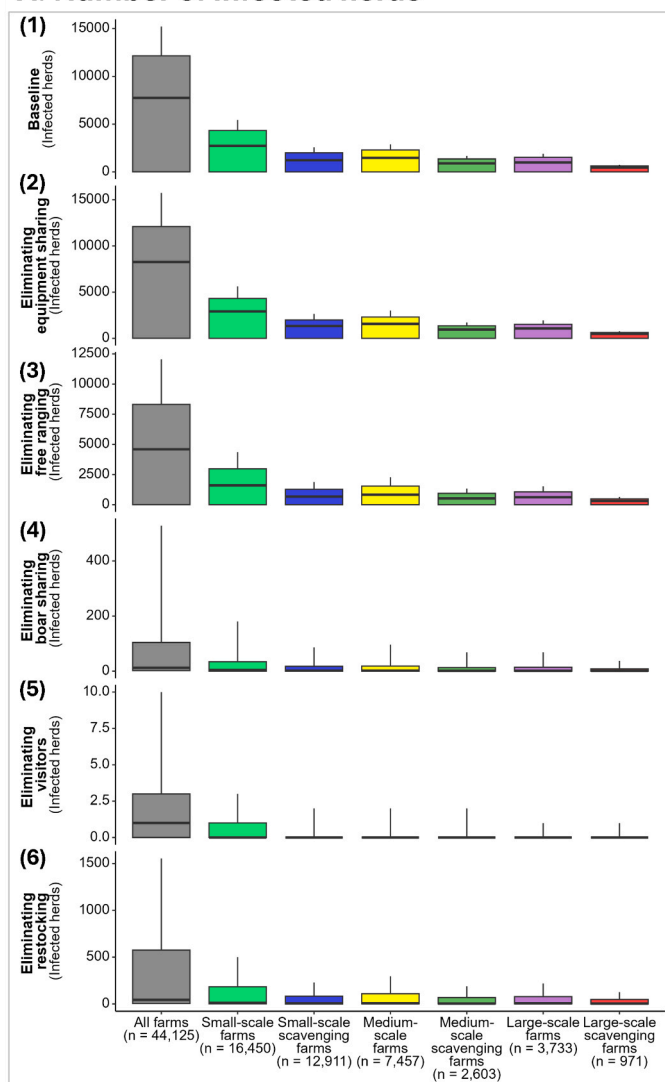


Fig. 2. Biosecurity-related management practices on the surveyed pig farms. Pie charts showing; A, the housing systems for farmed pigs in the surveyed households; B, free ranging or scavenging by the pigs; C, adherence to access control measures for unauthorized persons; and D, the presence and utility of points of disinfection (e.g. footbaths) at the entry point(s) on the farm premises (n = 395). The Venn diagram(E) shows co-occurrence of gaps in biosecurity management among 392 of the surveyed pig farms. Three (3) of the 395 surveyed farms, were found to have all the assessed biosecurity measures fully operational.

A. Number of infected herds



B. Proportion of infected herds

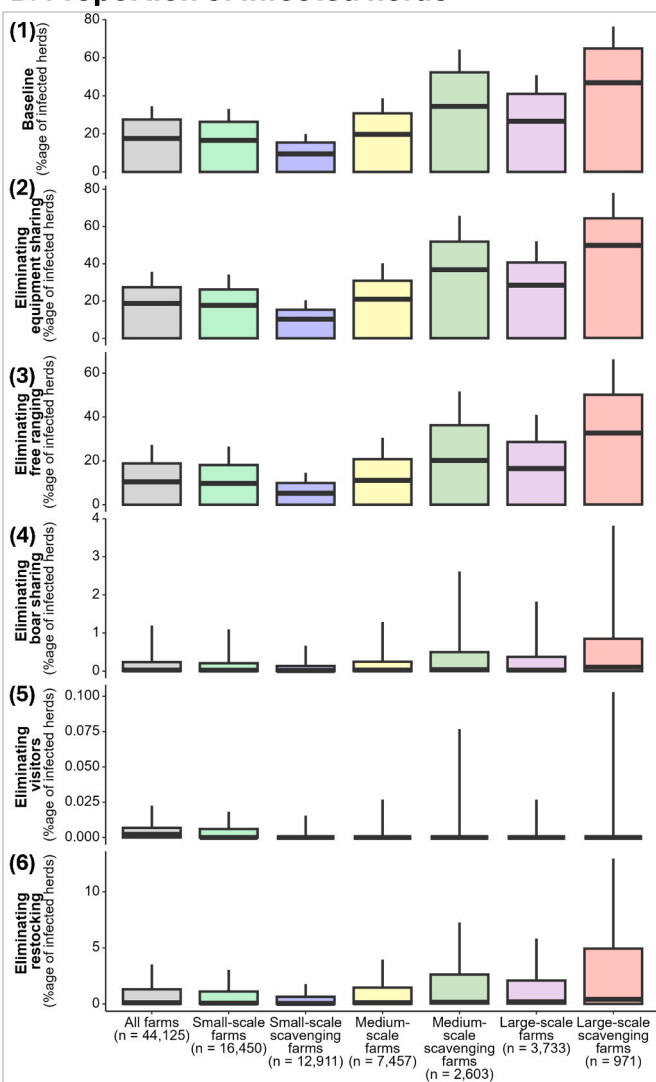


Fig. 3. PRRS infected pig herds in the modelled scenarios. Box and whiskers plots showing A. the number of pig herds infected across the modelled scenarios and B. the relative proportions of the farm types affected in each scenario (*scenarios 1–6*). The box represents the interquartile range, and the whiskers represent the range between the 5th and the 95th percentile.

medium- and large-scale farms, especially those allowing pigs to scavenge, resulting in 34.4 %, and 46.9 % of them being infected, respectively. While, among medium- and large-scale farms where free ranging was not allowed, 19.7 % and 26.6 % would be infected with PRRS, respectively. The results also indicated that lower proportions of the small-scale farms would be impacted by PRRS; a median of 9.46 % and 16.6 % of the small-scale farms with, and without scavenging pigs would be infected, respectively.

The effect of controlling transmission factors such as human traffic (visitors), boar sharing, equipment sharing and restocking to reduce PRRS spread were evaluated using output from the corresponding scenarios. Results showed that effectively eliminating visiting as a transmission factor (*scenario 5*, no visitors) had the highest impact on the spread of PRRS across all farm types in the study region. The spread of PRRS would be reduced by almost 100 % across all farm types in the region in a scenario where visitors are fully eliminated (Fig. 3.A(5) & B (5)). Additionally, the model indicated that the elimination of boar sharing (*scenario 4*) would result in a 99.85 % reduction in PRRS spread, bringing down the proportion of infected farms from 17.6 % to 0.03 % within the region (Fig. 3.A(4) & B(4)). Furthermore, mitigating risks

associated with restocking (*scenario 6*) would lead to a 99.44 % decrease in PRRS spread, with only 0.098 % of farms infected within 2 years compared to the baseline of 17.60 % in the region (Fig. 3.A(6) & B(6)). In *scenario 3* where free roaming and scavenging by farmed pigs were eliminated, the spread of PRRS would see a reduction of 40.67 % (from 17.6 % to 10.4 % infected herds) (Fig. 3.A(3) & B(3)). However, eliminating equipment sharing (*scenario 2*) had a negligible effect on PRRS transmission in the region, partly because there was a significantly low level of equipment utilization on the pig farms in the region (Fig. 3.A(2) & B(2)).

During simulation, the PRRS outbreak ended within the 2-year period in only 161(32 %) of the 500 iterations. Table 2 shows the median number of infectious smallholder farms at the end of the simulated 2 years of PRRS spread within the region. The model shows that the prevalence of PRRS would be 5.19 % by day 730 of disease introduction.

3.3. Transitions in biosecurity practices: restricting access to farms and reducing boar sharing

The impact of PRRS among the smallholder pig farms in this region

Table 2

Summary of infectious smallholder farms at the end of the simulation period (Day 730).

	Scenario	Overall	Proportion
01	Baseline	2273.0	5.1513
02	No equipment sharing	2254.0	5.1082
03	No free range	1655.0	3.7507
04	No boar sharing	37.5	0.0850
05	No visitors	2.5	0.0057
06	No Restocking	118.0	0.2674

will be greatly reduced by modest adoption of biosecurity measures that limit unauthorised access as well as reductions in boar sharing. Our data shows that reducing farm visits by 50 % and 25 % among large and medium-scale smallholder operations, respectively, would lead to a 99.61 % reduction in PRRS transmission, lowering the median number of infected farms to 30 compared to 7747 in the baseline. This reduction in PRRS impact would be comparable to the scenario in which farm visits were uniformly reduced by 25 % across the entire region (Fig. 4A). We also find that a 25 % reduction in boar sharing practices across the region would result in a 73.95 % reduction in number of PRRS infected herds. Again, a comparable reduction in infections would be achieved in a scenario where boar sharing was reduced by 50 % in large-scale and by 25 % in the medium-scale smallholder farms within the region (Fig. 4B).

3.4. Sensitivity analysis

A sensitivity analysis was carried out by comparing the output of different combinations of direct and indirect probabilities as shown in Table 3. Increasing the probability of direct contact while maintaining the indirect probability had a minimal effect on the outcome. Adjusting

Table 3

Sensitivity analysis results.

Combination of probabilities of infection for direct and indirect contact when the source is positive	Median number of infectious farms	Percentage of infectious farms
0.5 direct contact and 0.1 indirect contact	1447.0	3.30
0.5 direct contact and 0.05 indirect contact	6556.5	14.96
0.5 direct contact and 0.021 indirect contact	1751.5	4.00
0.6 direct contact and 0.1 indirect contact	851.5	1.94
0.6 direct contact and 0.05 indirect contact	7450.0	17.00
0.8 direct contact and 0.1 indirect contact	720.0	1.64
0.8 direct contact and 0.05 indirect contact	6993.0	15.96
0.8 direct contact and 0.021 indirect contact	3089.0	7.05

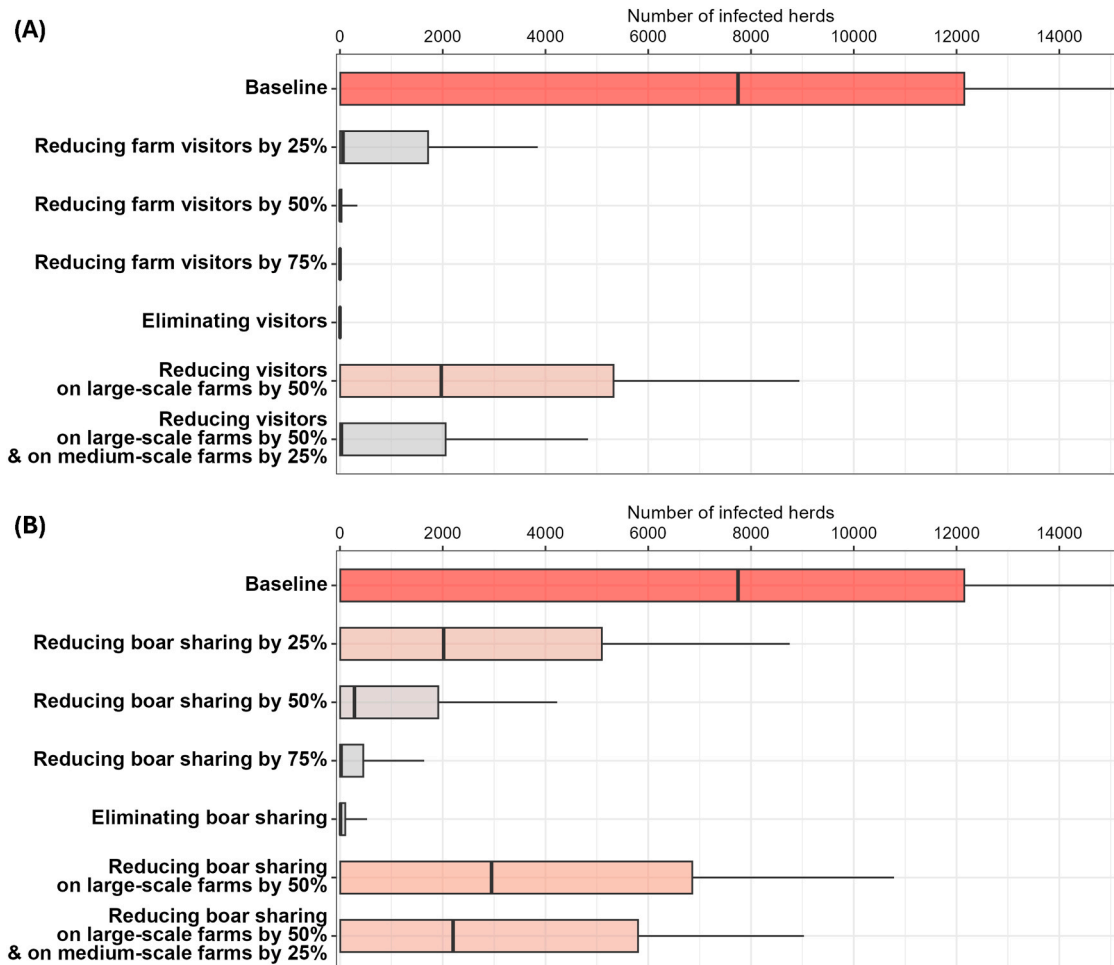


Fig. 4. Transition scenarios. Potential impact of the various transformations in biosecurity practices on the spread of PRRS in western Uganda. Transformations in farm access (A) and boar sharing (B) on smallholder pig farms.

the probability of indirect contact resulted in high infections when the value was set at 0.05, but much lower infections when the value was set at 0.1 (Table 3).

3.5. Epidemic curves

In this model, PRRSV transmission rose exponentially during the first 600 days of introduction peaking at about 750 days before relatively levelling off till the end of the 10-year period of simulation (Figure S1). The model predicts that during this endemic phase, approximately 40 smallholder pig farms would become infected each day within the modelled population of 44,125 herds in the study region.

4. Discussion

In this work we use a modelling approach to study the main drivers of PRRS transmission within the heterogeneous husbandry setting in western Uganda. We describe the biosecurity gaps in the smallholder pig farms in the region; assess the potential impact of PRRS outbreaks among them; and evaluate the potential for PRRS control through the closure of specific biosecurity gaps. This work is important because it points to opportunities for controlling PRRS and other productivity-limiting diseases through emphasizing on-farm biosecurity in porcine disease control campaigns.

The prevailing practices in pig husbandry within western Uganda are likely to facilitate an endemic occurrence of PRRS. Significant gaps in biosecurity were identified on the smallholder pig farms. We found that up to 27.1 % of the farms did not restrict access to their herds, did not use disinfectants, and that their pigs occasionally roamed and scavenged within the community. Only 0.8 % of the pig farms surveyed, practiced what we termed as good biosecurity (i.e., confinement of the entire herd, restricting access to unauthorized personnel and use of disinfectants at entry points to the farm). The low-level biosecurity practices in pig farms within western Uganda are similar to those reported in other agroecological zones within the country (Ouma et al., 2013; Dione et al., 2014, 2017). These gaps in biosecurity, combined with the contact dynamics estimated between pig herds in our survey, are predicted to enable the spread of PRRS, leading to an endemic disease state at a prevalence of about 5 %. Although, in a related study we were unable to detect PRRS among domestic pigs reared at the wildlife livestock interface in these study districts (unpublished data), the output from our model is comparable to reports in previous surveillance studies in central and northern Uganda where seroprevalences ranged from 1.3 % to 13.8 % (Dione et al., 2017; Oba et al., 2023). Therefore, as the sector grows, it is crucial that measures are implemented to promote biosecurity on pig farms to limit the potential impact of PRRS on production and productivity.

Restricting access to pig farms provides the most efficient pathway for reducing the impacts of PRRS outbreaks in the region. Our results suggest that indirect contact between farms through visitors greatly drives the spread of PRRS. Completely eliminating visitors would achieve a 99 % reduction in the spread of PRRS. However, completely sealing off all pig farms from visitors is not a realistic target in these close-knit communities. Nonetheless, even a 25 % reduction in access to farms by visitors will significantly reduce transmission of PRRS. Therefore, encouraging farmers to set up their pig farms away from high human traffic locations and to fence off pig farms as a means of preventing unauthorised access could greatly contribute to control of PRRS and other porcine pathogens. We considered the option of reducing frequencies of farm visits by 50 %, and by 25 % among the large-scale and the medium-scale smallholder farms, respectively, and found it to achieve the same level of disease control as targeting one-fourth of all pig-keeping households across the region. The decision to explore biosecurity improvements in these larger farm categories was motivated by the debate over whether greater impact could be attained by supporting the more innovative and commercial producers such as medium and

large-scale smallholder livestock producers. According to proponents of this point of view, adoption of measures such as those advocated here would be limited among the small-scale farmers and thus, a broad national policy targeting all levels of production is likely to be costly and to have limited impact (Aliber and Hall, 2012). While targeting medium and large-scale pig farming operations, especially when budgets are constrained, would be more effective as these farmers are more likely to adopt improved practices to protect their investments (Derpsch et al., 2016).

Reducing risks associated with boar sharing practices and restocking among smallholder pig farms will significantly contribute to PRRS control. A 25 % reduction in the frequency of boar sharing across all pig farms in the region would reduce outbreaks by 74 %. Again, targeting a reduction in boar sharing among large and medium-scale farms would attain similar reductions in PRRS spread. Boar sharing and restocking, as with all movement of animals between herds are recognized as risk factors in disease transmission (Nantima et al., 2015; Alarcón et al., 2021). Various strategies to reduce the risk of disease introduction via restocking have been suggested including, the testing and quarantining of new pigs prior to, and immediately following their arrival on the recipient farm (Alarcón et al., 2021). On the other hand, eliminating risks associated with boar sharing, would require either maintaining a breeding boar on the farm or adopting artificial insemination techniques. However, adoption of these strategies may be inaccessible to, and could raise the cost of production for small-scale farmers in the region. Further, artificial insemination could be a conduit for transmission of PRRS and other infectious diseases (Maes et al., 2016; Nathues et al., 2016; Friedrichs et al., 2022). Therefore, as strategies are designed to promote pig genetics and breeding technologies in the sector, considerations should be made to ensure equitable access while maintaining their sanitary application.

Strategies aimed at reducing equipment sharing and free ranging practices will be necessary but are projected to have a modest impact. Our analysis showed that targeting free ranging would contribute a 40 % reduction in PRRS spread. Previous work done in Northern Uganda only considered free ranging among small-scale smallholder pig farms (Hasahya et al., 2021). However, our survey revealed that free ranging also occurred in medium and large-scale smallholder farms, including those that operated 'confined' systems. Many of the pig farmers were either indifferent to, or in some cases, actively permitted the free roaming of piglets. This prevalent practice underscores a significant gap in awareness regarding the critical biosecurity threats posed by allowing piglets to wander freely. It has been reported that piglets can venture as far as 650 m away from their dams, which increases the likelihood of directly interacting with neighboring pig herds and fomites within the environment (Jensen, 1986). It is because of such implications that we decided to include roaming piglets into our model. In our model, equipment sharing had no impact on PRRS transmission as it was not common for farmers to use equipment and those that used equipment were unlikely to share them.

5. Conclusion

Our study demonstrates the potential of strategies aimed at improving husbandry practices to effectively control outbreaks in pig farming. Government initiatives like vaccination and movement restriction to control livestock disease have had mixed success due to implementation challenges. This is because farmers perceive such measures predominantly as being punitive or impositions from technocrats (Ogweng et al., 2021). There is, therefore, a need for a transformative shift in the management of livestock diseases towards approaches that aim to motivate farmers to adopt improved on-farm biosecurity, rather than relying solely on regulatory measures. Future research should focus on identifying the motivators that encourage farmers to adopt improved biosecurity measures.

CRediT authorship contribution statement

Andrew Wange Bugenyi: Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Emmanuel Hasahya:** Writing – review & editing, Software, Formal analysis, Data curation. **Emilly Niwandinda:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Charles Masembe:** Writing – review & editing, Funding acquisition, Conceptualization. **Jaeyoung Heo:** Writing – review & editing, Funding acquisition. **Joseph Byaruhanga:** Writing – review & editing, Methodology. **Paul Bogere:** Writing – review & editing, Methodology. **Halid Kirunda:** Writing – review & editing, Project administration. **Pablo Alarcón:** Writing – review & editing, Supervision, Conceptualization.

Ethics statement

This research was granted approval by the Institutional Research Ethics Committee at the National Agricultural Research Organisation in Uganda (Reference Number: NARO/REC/A01/17/11/2022). Before being included in the study, we obtained informed consent from the participants, indicating their voluntary agreement to participate after being fully informed about the study's purpose, procedures, and potential risks or benefits.

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Declaration of Competing Interest

The authors declare 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.2025.106590](https://doi.org/10.1016/j.prevetmed.2025.106590).

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