

Review

The livestock vaccine supply chain: Why it matters and how it can help eradicate peste des petits Ruminants, based on findings in Karamoja, Uganda



Daniel Acosta^{a,*}, Saskia Hendrickx^b, Sarah McKune^c

^a Feed the Future Innovation Lab for Livestock Systems, Department of Animal Sciences, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL, USA

^b Feed the Future Innovation Lab for Livestock Systems and Department of Animal Sciences, Institute of Food and Agricultural Sciences, University of Florida, Gainesville, FL, USA

^c Feed the Future Innovation Lab for Livestock Systems, Department of Environmental and Global Health, and the Center for African Studies, University of Florida, Gainesville, FL, USA

ARTICLE INFO

Article history:

Received 22 May 2019

Received in revised form 3 September 2019

Accepted 4 September 2019

Available online 13 September 2019

Keywords:

Livestock vaccine

PPR

Peste des petits ruminants

Supply Chain

Logistics

Karamoja

One Health

Gender

Vaccine Distribution

ABSTRACT

Understanding factors that hinder vaccination, including logistical and social constraints, is critical to finding the most effective approach for the global eradication of peste des petits ruminants (PPR). Vaccination projects should analyze the supply chain and take it into consideration when planning and creating a vaccination strategy. Adequate supply chain management of the PPR vaccine could lead to reduced cost, increased availability, and the construction of a data platform for other livestock vaccines. Integrating the supply chain of PPR vaccine with other veterinary or health commodities could reduce cost, as well as increase uptake. The use of a thermostable vaccine could potentially have a positive impact on the eradication of PPR in remote areas, such as the Karamoja subregion in Uganda, as it did with rinderpest across Sub Saharan Africa. In terms of vaccine delivery, the use of community animal health workers (CAHWs) could be beneficial in certain areas, such as the Karamoja subregion of Uganda, by alleviating supply chain constraints in the last-mile delivery, as well as increasing coverage and uptake. A gendered approach to livestock vaccines should also be considered, as decision-making power regarding livestock vaccination is gendered in many various contexts. The PPR eradication strategy—as well as other livestock vaccination programs—would be more effective and efficient if the supply chain management were considered as a key component in the process and efforts tailored, accordingly.

© 2019 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Contents

1. Introduction	6285
2. Methods	6286
3. Results	6286
4. Discussion	6288
5. Conclusion	6289
Declaration of Competing Interest	6290
Acknowledgements	6290
Conflicts of Interest	6290
Ethical Approval and Informed Consent	6290
References	6290

1. Introduction

Only two diseases have been eradicated worldwide, and those are smallpox in humans (1980) and rinderpest in livestock (2011). The eradication program of rinderpest marked the end of

* Corresponding author.

E-mail address: daniel.acosta@ufl.edu (D. Acosta).

devastating cattle pandemics, which affected both cattle and humans, whose livelihoods were dependent upon livestock. One of the biggest challenges for the eradication of the rinderpest virus was its entrenchment in pastoral areas of the Horn of Africa where conventional control methods met additional challenges, including extremely poor infrastructure, lack of security, and weak governance [1,2].

The United Nations Food and Agriculture Organization (FAO) and the World Organization for Animal Health (OIE) are currently leading a global effort to eradicate another animal disease: peste des petits ruminants (PPR) [3]. PPR is a disease of sheep and goats that has devastating impacts on small ruminant populations in Africa and Asia, with serious consequences on livelihoods. PPR is caused by a morbillivirus in the family of paramyxoviruses, which is related to rinderpest and measles in humans. Because of this relationship, it is possible that some historic vaccination strategies for these diseases may have relevance to the eradication of PPR [3]. The experience of other vaccination programs and strategies must also be reviewed, as they may have faced similar challenges and be positioned to provide insights and tools to advance PPR eradication efforts. One of the main challenges for vaccination programs in remote areas is the logistical challenge of distributing vaccines, but this is by no means their only challenge. Cultural and social challenges may create comparable, if not greater, barriers to the eradication efforts of PPR. Successful vaccination programs rely heavily on the supply chain. Historically, logistical challenges have been identified as the cause of low vaccination coverage in various efforts [2,4–8]. A well-designed supply chain can have a positive impact on vaccination efforts via reduced costs and improved coverage. Despite its seemingly essential nature to vaccination endeavors, the World Health Organization (WHO) states that the supply chain for human vaccines is often neglected [7], which is also the case for livestock vaccines based on results from this study. The objective of this research is to underscore the importance of the supply chain of the PPR thermostable vaccine, based on the literature and findings on the study in the subregion of Karamoja, Uganda.

2. Methods

Information presented here was obtained through a review of literature and an observational study utilizing participatory field methods in the Karamoja subregion of Uganda. The structured review of literature focused on peer reviewed journals but also included reports from FAO, OIE, WHO and project reports funded by The United States Agency for International Development (USAID). Combinations of the following keywords were used in Google Scholar, PubMed, and Science Direct databases: *vaccines, vaccination, strategy, Peste des Petits Ruminants, Measles, Rinderpest, eradication, supply chain, remote locations, Sub Saharan Africa, community animal health workers, community health workers, willingness to pay, One Health, livestock, and knowledge*. As well as the use of these keywords, the publications of specific authors, known for their role in the eradication of rinderpest were reviewed. These authors were: Jeffrey Mariner, Tim Leyland, Peter Roeder, Andy Catley, and Bryony Jones. Publications about rabies, Newcastle disease, and poultry were excluded, as the social and economic implications of small ruminants was determined too different than those used for poultry or dogs. Another criterion used was prioritizing more recent publications (2010–2018), however some publications from the early 1990s and 2000s were used as sources, as they brought valuable insight from the rinderpest eradication. The initial search yielded 105 publications, all of which were screened in full. From that collection, 56 publications were discarded due to the lack of applicability for the PPR eradication efforts. Of the

remaining 49, all were meaningful in conceptualizing and developing this review. Eleven of those were not cited directly, however informed and reinforced messages conveyed here.

For the participatory methods, fourteen interviews were conducted with: district veterinary officers, storage managers, veterinary drug shop owners, logistic specialists from NGO's operating in the region, lab technicians, and staff from the Ministry of Agriculture, Animal Industries and Fisheries (MAAIF). Sixteen focus group discussions (FGDs) were conducted with Community Animal Health Workers (CAHWs) and livestock owners. Assessments in the form of physical inspections were conducted in Uganda (Kotido District, Amudat District, Kaabong District, Moroto District, Kampala, and Entebbe). The objective of the semi-structured interviews varied depending on the group interviewed. In the case of CAHW's, the focus was placed on the process of livestock vaccination and treatment in general, more concisely: working conditions, lead times between storage facilities, incentives, and constraints. For livestock keepers: knowledge of vaccines, willingness to pay for vaccines (WTP), access to vaccines, and perception of the work being done by CAHWs. Selection of participants in FGDs of CAHWs was done with previous consultation with the DVO in each district to assess which of the CAHWs were still active. Participants of all FGDs were asked to participate and sign a consent if they agreed to participate in the nature of the study. Other stakeholders were interviewed to assess their involvement and estimate the cost and lead times in every level of the supply chain. Data was collected by the lead author with the assistance of translators when needed, throughout June–August 2018. The table below summarizes the data collection methodology, and the map shows the studied districts (see Fig. 1 and Table 1).

3. Results

Through interviews and assessments with DVOs, storage managers, and veterinary drug shop owners in the livestock vaccine supply chain of Karamoja, several challenges were identified, such as: poor infrastructure, inadequate cold-chain capacity, information scarcity, and insufficient funding. This is congruent with literature that describes many places in sub-Saharan Africa still facing these challenges [7,9,10]. Out of the four districts studied in Karamoja, only one met the criteria of necessary and appropriate equipment for safe storage of vaccines in the cold chain. Lack of reliable data on vaccine demand is another important issue identified. Lastly, the state of the roads also presents great challenges in the region particularly in the rainy season.

Most livestock vaccines in Uganda are stored in Kampala before being distributed to the respective district. In a similar fashion, human vaccines are stored in Entebbe before being distributed to their respective districts. There is the possibility for aggregation in the distribution of these vaccines sharing resources in order to reduce cost and improve availability of livestock vaccines, which in certain districts is extremely low. Even after leaving the central area, integration of animal and human vaccine supply chains at a district level could improve coverage and reduce cost. A bottleneck for child immunizations in Uganda is the last-mile delivery, from the district office, to the health office, and beyond due to lack of funds for transportation [11]. This is a constraint that is also present in the livestock vaccine supply chain in Karamoja, as the interviews with Veterinary Officers and CAHWs showed. In predominantly pastoralist regions, integration of human vaccines and livestock vaccines has the potential to not only reduce transportation costs, as Yadav et al. suggest, but to address many of the bottlenecks that occur beyond the district level [12].

Reducing vaccines temperature sensitivity could address some challenges specific to the cold chain that are still relevant in

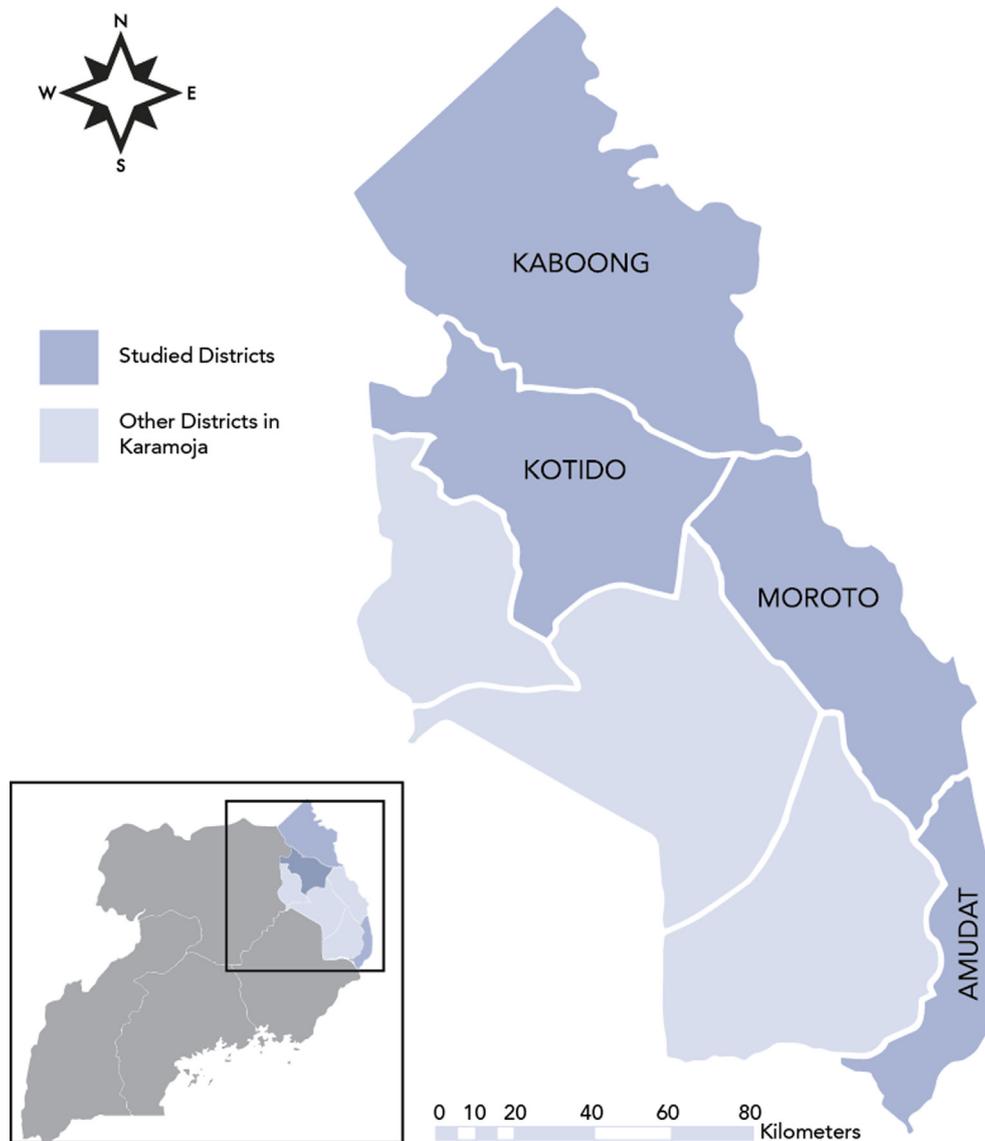


Fig. 1. Karamoja subregion of Uganda and the studied districts.

Table 1
Data Collection Method and Count.

Methodology	Number
CAHW Focus Groups	9 (average 5 participants)
Livestock Keeper Focus Groups	5 (average 5 participants)
Interview with VOs	2
Interview with DVOs	2
Other stakeholder interviews	7
Assessments/physical inspections	7

sub-Saharan Africa, such as an unreliable power grid, lack of refrigerators, and short cold-life of passive cooled containers [13]. The studied districts in the Karamoja subregion share this type of challenges, as refrigeration at district level was identified as the bottleneck of this supply chain. One key lesson from the rinderpest eradication effort was that thermostable vaccines can improve reach into remote locations where maintaining a cold chain can be demanding if not impossible [2]. The recent development of a thermostable vaccine for PPR will benefit the eradication efforts by facilitating access to the vaccine. A study in Niger's human immunization supply chain showed that the use of thermostable

vaccines could potentially help alleviate constraints within the supply chain [14]. For pastoralists who are historically less integrated into service systems, communities in countries affected by conflict, climatic stresses, and disease outbreaks, thermostability could be even more important.

The constraints mentioned above make vaccination efforts particularly challenging at the last-mile delivery. CAHWs are filling the role of last-mile delivery in the supply chain of veterinary services in many places of Sub-Saharan Africa. Pastoralist communities in Ethiopia, Kenya, and South Sudan identified CAHWs as the most accessible of the animal health service providers (AHSP) [15]. In South Sudan, CAHWs were rated as the most affordable AHSP as well as the option that offered the widest range of services and best quality of medicines [15]. High quality and variety of veterinary services at an affordable price can be very beneficial to improving food security among livestock owners. As stated in the Global PPR eradication strategy, development and training of CAHWs should be included as a component in the eradication plan for PPR in remote locations [3].

Private veterinarians can benefit by working with CAHWs as their mobility allow to them cover a broader area, but for this to

be sustainable there should be cost-recovery from the users [16]. Private veterinarians in Niger work with CAHWs to cover more area and increase their volume of sales [17]. The use of private veterinarians and CAHWs is proposed as part of a possible solution to overcome the constraint in livestock production in Ethiopia [18]. The use of CAHWs will also benefit vaccination uptake within some pastoral communities, as they are largely trusted by farmers [15,19]. CAHWs have played an important role in the control of diseases in livestock and in the eradication of rinderpest [20]. One of the main issues brought up by both livestock keepers and CAHWs during the FGDs was the need for both more CAHWs and more trainings for the existing CAHWs. Another key issue identified through interviews and FGDs was that in Karamoja, all livestock vaccines available were those provided by government or NGOs, with little to no access elsewhere, however when livestock keepers were asked about their willingness to pay for a vaccine available at the veterinary shop or through CAHWs, their response to how much they would be willing to pay ranged between 0 and 300 Ugandan Shillings, with 100 Ugandan Shillings as the most common response. This range represents only a portion of production price and is below the amount which CAHWs indicate they expect to be compensated for their services (around 200 Ugandan Shillings per animal vaccinated). In addition to this, veterinary drug shops as well as veterinary officers experience a highly variable lead time when it comes to veterinary supplies or vaccines. Vaccines ordered from Kampala have a lead time ranging from 2 weeks up to three or more months, as sometimes the warehouse in the capital is out of stock. One lesson learned about the CAHWs is that primary or secondary levels of education are not required for people to be effectively trained about proper use of livestock vaccines [21]. This is beneficial in terms of capacity building, as it would otherwise be a significant barrier to training members of certain livestock holding communities, such as the Karamojong and Pokot in Uganda. Even in remote locations with weak governance, like Somalia, CAHWs achieved 95% vaccination coverage for rinderpest using a thermostable vaccine, exceeding the government's service coverage of about 50–80% [21]. Pastoral CAHWs can move with livestock herds and travel to fixed points for veterinary drugs [21], thus partially eliminating the geographic barrier associated with reaching pastoral communities and making the planned schedule of vaccine delivery more effective. In Ethiopia, traditional government vaccination reached approximately 60% vaccination rate for rinderpest; CAHW then reached 83% vaccination rate, and no further cases of rinderpest were reported after this [15,22]. Similar results were obtained in South Sudan, where the use of CAHW achieved a 10.6 fold increase of vaccination coverage [15,23].

CAHWs play an important role in helping alleviate this constraint in Karamoja, as the number of veterinarians is extremely low compared to the number of livestock in the subregion. However, as much as they contribute, the number of trained active CAHWs is still a constraint for Karamoja, as even their numbers are low compared to the geographic area and livestock numbers they must cover.

4. Discussion

For any type of vaccination activity, mapping the supply chain can help stakeholders understand the current state and estimate costs of current practices, thus enabling them to propose changes that can increase responsiveness (higher capacity to respond to unusual surges in the demand) and efficiency (reduced costs). An important part of the livestock vaccine supply chain is a reliable long-term supplier. A setback in production or a faulty vaccine lot can have detrimental effects on the vaccination schedule and

long-term plan for eradication. In 1997 Milstein et al. proposed examining several factors when predicting the long-term viability of vaccine manufacturers in developing countries [24]. In 2016, Luter et al. updated the approach as an evaluation tool to analyze potential investments in vaccine development [25]. This methodology is oriented towards human vaccines, thus some aspects do not apply, such as the requirement that it be a WHO approved facility. However, this methodology can serve as a guide to create a parallel regulatory framework for livestock vaccines. Additionally, other more context specific factors should be considered, such as consistent lead times when the anticipated timeframe for vaccination is limited for reasons outside control of the project (rainy season, pastoralist movement, etc.). Even if the number of viable suppliers is limited, creating a selection procedure using Luter et al.'s updated methodology would allow governments as well as potential funding agencies to identify weaknesses and strengths in suppliers so that they can plan a supply chain strategy accordingly. It is recommended to incorporate supply chain experts at the stage of vaccine development and decision-making process [26], such as the selection of a manufacturer, thus potentially reducing logistical cost and increasing coverage through an efficient supply chain strategy.

Vaccination initiatives for PPR could benefit by using this methodology as a guide when selecting a manufacturer for the vaccine. As this disease is highly entrenched in Africa and Asia, it is likely that the most economically viable manufacturer will be in a developing country. Factors such as historical performance, governmental policies, national regulatory authorities, and product portfolio are some of the other factors to consider [25].

The logistical challenges in Karamoja make commercialization of livestock vaccines complicated, potentially resulting in low vaccination coverage of PPR and other livestock diseases. In areas where there is willingness to vaccinate, but farmers lack access to veterinary services, vaccination coverage is low [5], so interventions that address willingness to vaccinate but ignore challenges in the supply chain may be either inefficient or ineffective in increasing coverage. The scarce resources in this region must be maximized in order to achieve an adequate supply. For commercialization of livestock vaccines in the future, gathering data on vaccine demand and willingness to pay is of great importance because vaccines have a limited shelf life, therefore holding large inventories to respond to demand of high uncertainty may not be economically viable. This can lead to malpractice, resulting in the sale of expired/spoiled vaccines. Forecasting the demand using historical data combined with expert assessment could allow private veterinarians to understand, predict, and plan accordingly for the variable demand patterns, but reliable historical data of the demand of livestock vaccines would need to be available. For childhood vaccinations, UNICEF has developed a template to forecast quarterly demand, but unreliable data can result in inaccurate estimations resulting in surplus or lack of vaccines, adding unnecessary logistical burdens [4].

In human vaccine studies, technological advances have allowed computational models to analyze the potential impact that changes within the supply chain may have on vaccine distribution and logistics. A model analyzing the supply chain of vaccines in Nigeria determined that removing the regional level distribution might increase vaccine availability and reduce logistical costs [27]. A similar analysis in Benin determined that certain changes along the supply chain, such as removing the commune level distribution facilities, thus shifting from a four-level to a three level supply chain, could lead to reduced costs of operation and increased vaccine availability [28]. An analysis in Mozambique suggested that implementing alternative distribution systems using improved transport strategies would make the supply chain more effective and efficient [29]. These examples underscore the

potential for research and analysis of the vaccine supply chain to improve logistical operations in the field.

While insightful in many cases, these models have inherent limitations, including assumptions about the demand of vaccines, as those data are often not available. Livestock census information is often outdated and often doesn't include small ruminants. In addition, being discrete simulation models, they are restricted and cannot capture all possible variables that could affect costs or availability [30,31]. Computational models could be helpful as they could be used to analyze different scenarios when making strategic decisions. However, a first step should be to analyze the current livestock vaccine supply chain which is grossly understudied at this time. Fully understanding the livestock vaccine supply chain could lead to reduced costs and higher vaccine availability, both of which are challenges often faced by pastoralists and other livestock holders otherwise willing to vaccinate [5].

Given that there is less information on the supply chain and logistics of livestock vaccines compared to human vaccines, the global effort to eradicate PPR could be used as a platform to prompt researchers to gather data required for innovation in livestock vaccine delivery in remote areas. Current and future PPR vaccination initiatives should incorporate supply chain research and analysis, both to strive for efficiency and effectiveness, as well as to gather information for future small ruminant vaccination strategies. Lee and Haidari argue that supply chain courses should be incorporated into public health and public policy curricula [26], underscoring the importance of the supply chain of vaccines and medical supplies. Consequently, this same principle is applicable for livestock vaccines and veterinary supplies, as livestock health is often linked with food security. Others claim that even personnel involved in the vaccine supply chain should be trained in the strategic aspects of supply chain management, not only in the operational aspect as the current WHO modules do [4]. This principle should also apply for livestock vaccines.

Standardized record keeping of demand data should be encouraged during all types of vaccination programs, as this will allow the use of accurate forecasting methods in the future. One constraint faced by both pastoralists and animal health service providers in Karamoja and Kenya is a weak information and knowledge system which limits supply and demand of animal health services [8]. Another benefit of recording demand data is that it can help optimize transportation and even share the cost with other commodities, making vaccines cheaper and more accessible. Yadav et al. designed a framework for decision-making to integrate human vaccine supply chain with other health commodities in order to optimize and improve efficiency [12]. When reaching pastoralist communities, both the livestock and human vaccine supply chain could be integrated at various levels. Joint vaccination programs between human and animal health services might be beneficial for the PPR eradication effort. Shared logistical costs could decrease operational costs, increasing the efficiency of vaccination programs [32]. In some scenarios it will not only decrease cost, but also encourage children's vaccination. This was a lesson learned when designing vaccination strategies for the rinderpest eradication in South Sudan, where tribes only allowed for their children to be vaccinated after the program had vaccinated their cattle against rinderpest [1].

Benefits of joint vaccination could go both ways; livestock vaccination might increase if done alongside children's vaccinations. Experience of joint vaccinations for pastoralist communities in Chad, showed that pastoralists no longer refused vaccination in livestock if medical personnel accompanied the veterinarian [32]. Applying the One Health approach, which addresses the intersection of people, animals, and the environment, has been successful in many projects in remote locations [33]. A One Health approach should thus be considered within PPR vaccination programs, as

some communities may be more willing to vaccinate due to reduced cost of the vaccine (through logistical savings), while the credence that medical personnel have on the community's perception of the vaccines may sway others.

Another aspect that is rarely considered during vaccination programs is gender. Vaccination projects should take a gendered approach, including a gendered supply chain analysis and consideration of how women participate in and benefit from the supply chain – including end users. Such actions may empower women and could positively impact vaccination uptake; however, more research is needed to understand the effect that gender and intersectionality—how the experience of women and men vary across ethnicities, caste, age, etc.—have in vaccination uptake in different contexts. Research on gender and livestock vaccines should be promoted under the umbrella of the PPR eradication strategy, because small ruminants, like poultry, are considered women's livestock in many parts of the world. Given the dominant engagement of gender and women's empowerment in current agriculture and health development literature, and its very poor integration into livestock vaccine supply chain work to date, any integration of gender into the supply chain analysis should be accompanied by a supply chain management strategy that is positioned to respond to a potential rapid change in the demand for small ruminant and poultry vaccines. If the supply chain strategy is not considering this factor and significant increase in demand were felt, the additional strain put on the already heavily burdened bottlenecks could increase cost, reduce availability, and increase the risk of spoilage/mismanagement of vaccines. In Kenya, ownership of small ruminants and chickens is often considered women's domain, but ownership does not ensure decision-making power about the animals [34]. Vaccine adoption for livestock is gendered in certain contexts, with women less likely to adopt the use of this technology than men, as gender influences the drivers of vaccine adoption such as access to land, inputs, farmer expectation, wealth, and decision making power [35]. Alders et al. identify gender issues as one of the *internal factors* among the challenges of livestock vaccination in developing countries [36]. Ownership and decision-making power affect vaccination uptake, thus gender transformative approaches in livestock projects should occur in parallel with animal health services [37]. Under some contexts access to veterinary services may be equally accessible for men and women, though lower literacy rates and sociocultural factors may obstruct women's access to resources [38], such as vaccines.

5. Conclusion

Current PPR eradication efforts have a distinct opportunity to serve as a platform for the application of lessons learned from past vaccination initiatives and for asking and answering additional questions that will improve future vaccination strategies. That said, among the most important of lessons learned from the past is that context is one of the greatest variables to the success of the vaccination effort, so past lessons learned and new questions answered are unlikely to provide a prescriptive strategy for successful eradication in all settings. Rather, looking at past lessons learned and identification of important questions for the future should help hone the vaccination strategy that is most likely to work in a given area.

Regarding logistics, distribution, and management, there are important lessons from the past that could benefit the PPR eradication strategy. Regarding supply chain management, the need to assess distribution processes is highlighted in the literature as one of the biggest challenges for remote areas. Building capacity to record demand data would help create better forecasting methods, likely reducing future situations of either no stock is available or there is an unnecessary surplus of vaccines. This can also have a

positive impact reducing transportation costs by optimizing transportation routes. In resource scarce settings the optimization of resources could be a determinant in any eradication effort. Sub-Saharan Africa proved to be a challenge for the rinderpest eradication, but these obstacles were overcome, and important lessons were learned that can help the global effort to eradicate PPR and other livestock diseases.

The use of CAHWs and a thermostable vaccine can have positive results by alleviating the last-mile delivery constraints often faced when providing vaccines for pastoralist communities. The use of CAHWs in PPR efforts could reduce the geographical barriers in remote locations, as well as institutional barriers in settings where there is conflict or weak governance. Integrating gender into supply chain analysis and developing gender-oriented interventions can potentially increase vaccination uptake. These efforts should be accompanied by a comprehensive supply chain strategy to cope with the potential increase in demand of vaccines among women, which may be associated with increases in women's participation in and benefit from the supply chain.

The livestock vaccine supply chain is understudied, and there should be a more unified effort from researchers to strengthen the literature around it. Livestock plays a paramount role in food security, hence the importance of an efficient supply chain strategy to distribute livestock vaccines in food insecure countries. The PPR eradication strategy could serve as a platform to gather information on the state of livestock vaccine supply chains. This would strengthen future vaccination programs and reduce the barriers of livestock vaccine commercialization in remote areas where it is currently nonexistent.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This report is made possible by the generous support of the American people through the United States Agency for International Development (USAID) and its Feed the Future Innovation Lab for Livestock Systems managed by the University of Florida and the International Livestock Research Institute. The contents are the responsibility of the authors and do not necessarily reflect the views of USAID or the United States Government.

Conflicts of Interest

Authors have no conflict of interest.

Ethical Approval and Informed Consent

Ethical Approval both from the University of Florida's IRB (Study number: IRB201801216) and Uganda's IRB were obtained before the start of data collection. Written informed consent was obtained with the participants before conducting Focus Group Discussions and Interviews.

References

- [1] Normile D. Driven to extinction. *Science* (80-) 2008;319(5870):1606–9.
- [2] Mariner JC et al. Rinderpest Eradication: Appropriate Technology and Social Innovations. *Science* (80-) 2012;337(6100):1309–12.
- [3] OIE and FAO. Global Strategy for the Control and Eradication of PPR; 2015.
- [4] Kaufmann JR, Miller R, Cheyne J. Vaccine supply chains need to be better funded and strengthened, or lives will be at risk. *Health Aff.* 2011;30(6):1113–21.
- [5] Gitonga PN, Gachene CK, Njoroge E, Thumbi S. Small ruminant husbandry practices amongst Kajiado and Marsabit pastoralists and their effects on Peste des petits ruminants control strategies Small ruminant husbandry practices amongst Kajiado and Marsabit pastoralists and their effects on Peste des pet. no. October; 2016.
- [6] Metcalf CJE et al. Transport networks and inequities in vaccination: remoteness shapes measles vaccine coverage and prospects for elimination across Africa. *Epidemiol Infect* 2015;143(7):1457–66.
- [7] WHO. Immunization supply chain and logistics. no. March; 2014.
- [8] Kiara H, Odongo D, Karaimu P, Njiru M, Munene A. Delivery of animal health services in extensive livestock production systems. no. May; 2017.
- [9] International Monetary Fund. World economic and financial surveys: regional economic outlook; 2015.
- [10] Lakshminarasimhan C, Nguyen NT. Sub-Saharan Africa has particular logistical challenges such as inventory unpredictability, inadequate cold-chain capacity, and insufficient funding. no. September; 2017.
- [11] PATH. Immunization supply chain policy environment in Uganda Landscape Analysis and Advocacy Recommendations. 2016.
- [12] Yadav P, Lydon P, Oswald J, Dicko M, Zaffran M. Integration of vaccine supply chains with other health commodity supply chains: A framework for decision making. *Vaccine* 2014;32(50):6725–32.
- [13] Lloyd J, Cheyne J. The origins of the vaccine cold chain and a glimpse of the future. *Vaccine* 2017;35(17):2115–20.
- [14] Lee BY et al. The impact of making vaccines thermostable in Niger's vaccine supply chain. *Vaccine* 2012;30(38):5637–43.
- [15] Leyland T, Lotira R, Abebe D, Bekele G, Catley A. Community-Based Animal Health Workers in the Horn of Africa An Evaluation for the Office of Foreign Disaster Assistance. no. March; 2014.
- [16] Ahuja V. The economic rationale of public and private sector roles in the provision of animal health services. *Rev. Sci. Tech.* 2004;23(1):33–45. discussion 391–401.
- [17] Ministère D'Élevage. Service Vétérinaire Privé de Proximité. 2015.
- [18] Hadush A. Major Constraints of Veterinary Services Delivery System and Its Solution in Pastoral Areas of Ethiopia. 2015; 12(October): 5–12.
- [19] Bugeza J et al. Participatory evaluation of delivery of animal health care services by community animal health workers in Karamoja region of Uganda. *PLoS ONE* 2017;12(6):1–16.
- [20] Roeder P, Mariner J, Kock R. Rinderpest: the veterinary perspective on eradication. *Philos. Trans. R. Soc. B Biol. Sci.* 2013;368(1623). pp. 20120139–20120139.
- [21] Catley A, Delaney P, McCauley H. Community-based animal health services in the greater horn of Africa: an assessment for USAID - office of foreign disaster assistance in cooperation with the USDA - famine mitigation activity consultants. *Exch. Organ. Behav. Teach. J.* 1998.
- [22] Admassu B. Primary animal healthcare in Ethiopia: the experience so far. In: *Prim. Anim. Healthc. 21st century Shap.*, 2003. pp. 1–13.
- [23] FAO, Andrew J, Mariner JC, Leyland T. The world without rinderpest. In: *Proceedings of the FAO Technical Consultation on the Global Rinderpest Eradication Programme*; 1996. [Online]. Available: <http://www.fao.org/docrep/003/w3246e/W3246E09.htm>. [Accessed: 22-Jan-2018].
- [24] Milstien J, Batson A, Meaney W. A systematic method for evaluating the potential viability of local vaccine producers. *Vaccine* 1997;15(12–13):1358–63.
- [25] Luter N et al. An updated methodology to review developing-country vaccine manufacturer viability. *Vaccine* 2017;35(31):3897–903.
- [26] Lee BY, Haidari LA. The importance of vaccine supply chains to everyone in the vaccine world. *Vaccine* 2017;35(35):4475–9.
- [27] Assi TM et al. Removing the regional level from the Niger vaccine supply chain. *Vaccine* 2013;31(26):2828–34.
- [28] Brown ST et al. The benefits of redesigning Benin's vaccine supply chain. *Vaccine* 2014;32(32):4097–103.
- [29] Lee BY et al. Re-designing the Mozambique vaccine supply chain to improve access to vaccines. *Vaccine* 2016;34(41):4998–5004.
- [30] Lee BY. *Editorial Commentary*: digital decision making: computer models and antibiotic prescribing in the twenty-first century. *Clin. Infect. Dis.* 2008;46(8):1139–41.
- [31] Assi TM et al. Impact of changing the measles vaccine vial size on Niger's vaccine supply chain: a computational model. *BMC Public Health* 2011;11.
- [32] Schelling E, Bechir M, Ahmed MA, Wyss K, Randolph TF, Zinsstag J. Human and animal vaccination delivery to remote nomadic families, Chad. *Emerg. Infect. Dis.* 2007;13(3):373–8.
- [33] Greter H, Jean-Richard V, Crump L. The benefits of 'One Health' for pastoralists in Africa. *Onderstepoort J Vet* 2014;2012(Münch):2–4.
- [34] Waithanji E. et al. Development in Practice A gendered analysis of goat ownership and marketing in Meru, Kenya. 2015; 4524.
- [35] Waithanji E, Wanyoike S, Liani M. The role of gender and other socio-economic factors in the adoption of the contagious bovine pleuropneumonia (CBPP) vaccine.
- [36] Alders RG, Bagnol B, Young MP, Ahlers C, Brum E, Rushton J. Challenges and constraints to vaccination in developing countries. *Dev Biol* 2007;130(February):73–82.
- [37] Chanamoto NJC, Hall SJG. Gender equality, resilience to climate change, and the design of livestock projects for rural livelihoods. *Gen. Dev.* 2015;23(3):515–30.
- [38] Yisehak K. Gender responsibility in smallholder mixed crop-livestock production systems of Jimma zone, South West Ethiopia. *Livest. Res. Rural Dev.* 2008.