A framework for the evaluation of strategies to reduce risk of foot and mouth disease transmission associated with the trade of beef from East African cattle systems: a progressive and participatory approach

A THESIS SUBMITTED TO THE FACULTY OF THE
UNIVERSITY OF MINNESOTA BY

Julie Adamchick

IN PARTIAL FULFILLMENT OF THE REQUIERMENTS
FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

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September 2021

Acknowledgements

I could not have produced this work without the support and contributions of many others, a few of whom I would like to take the opportunity to recognize here.

Thank you to Andres Perez, my advisor, for the mentorship through this thesis and this graduate program. You're an inspiration to never be intimidated by big ideas or daunted by things that seem hard. I've benefited from your creativity, adaptability, and optimistic perseverance. I appreciate and admire how you value people, want the best for them, and foster networks of competent and interdependent individuals. I look forward to remaining a part of yours.

To my other committee members: thank you for the support and encouragement in many forms. Mark Rutherford, for always being available, understanding, and ready with a dose of perspective. Joleen Hadrich, thank you for being willing to listen and help with any idea I threw at you. You've encouraged me to believe in and think for myself, with words and by your example. Gerard Cramer, I appreciate your drive to both learn and apply, and to do both with excellence. Your support and enthusiasm over many years have helped me to keep putting one foot in front of the other when the trail is rough. And Karl Rich, thanks for taking a Skype call from an inquisitive vet five plus years ago. Your work, input, and doors you have opened have shaped how I see the world and the path I am on. I appreciate your effort to make inconvenient committee meetings from the other side of the globe and hope not to be strangers while in the same time zone.

Maria Sol Perez Aguirreburualde, I think I'm actually at a loss for words. For your mentorship and friendship, as a collaborator and a source of stability: thank you.

To the team at CAHFS and especially the crew who designed and rolled out ProgRESSVet East Africa cohort 1 in the middle of a global pandemic: Mary Katherine O'Brien and Anna Pendleton, this would not have happened without you. To the other CAHFS students and researchers, I've learned so much from your work and your experiences; thank you for sharing.

To the veterinarians of ProgRESSVet Kenya and Uganda, Cohort 1, I express deep appreciation for your enthusiastic participation in the Test Drive activities and your commitment to working hard to improve yourselves and your communities. Thank you for your contributions.

Anna Munsey, Silver Ochwo, Michael Mahero, George Omondi, Kim VanderWaal: thank you for your contributions of experience, perspective, data, and resources to build my understanding of FMD in East Africa.

Thank you to my funding sources: the Bill and Melinda Gates Foundation, USDA National Needs Grant, and MnDRIVE Global Food Ventures professional development fellowship. I'm deeply appreciative of the opportunity to get paid to learn.

I'm especially grateful to the UMN Dairy Group faculty and students. Sandra Godden, Gerard Cramer, Erin Royster, Luciano Caixeta, Whitney Knauer – thanks for helping me keep one foot in a world that felt familiar and for being available for any type of support I needed. Sam Rowe and Erin Wynands: for being fellow epi nerds, letting me learn from your work, and celebrating the big and the small moments together; this program was richer for having you in it.

A special acknowledgement goes to Daryl Nydam and Lorin Warnick. Thank you for your belief and investment in me and in all of your students. You encouraged me to love population medicine and have helped me to find my own path (while challenging me to be practical and keep things moving). I'm ever appreciative.

To my family, thank you for being supportive as I went back to school again, even when unable to articulate exactly what I was doing or why. Mom, Dad, Kyle, Suzanne: you are a source of encouragement, support, and inspiration.

And Matt and Terri, my amazingly faithful and dogged companions. Matt, in the time I've done this work you completed your own graduate degree and ran ultramarathons while working full time and being the most supporting and sustaining person for me and the pets and Baby A. You are a fountain of selflessness and perseverance and encouragement. Thank you for always finding a way to make me laugh.

Dedication

To Baby A: Here's to instilling in each other the compassion, curiosity, and courage to care about the future of the world and the people here.

Abstract

The objective of this work was to characterize the probability of FMD infection among cattle at slaughter in Kenya and Uganda and to evaluate the cost-effectiveness of interventions to reduce that risk. The purpose was to generate evidence and insight for plans about how (and if) to pursue entry to international beef markets which would require demonstrating an acceptable risk of FMD transmission associated with exported goods. This was achieved through three sequential aims.

The first aim was to characterize the risk pathways and processes in order to determine the appropriate populations, structure, and variables to construct a model for risk assessment among cattle at slaughter in Kenya and Uganda. This was achieved in partnership with Kenyan and Ugandan veterinarians, who were participants in a year-long e-learning capacity-building course, to characterize risk pathways and selected parameter values. This approach addressed two major and related hurdles to traditional risk assessment: a) data scarcity especially to the level of granularity needed in places that tend to have diverse and informal value chains, and b) tapping into unwritten local knowledge / subject matter expertise in a way that generated credible information in a format that can be used for quantitative analysis. The dual training-research activity was also a beneficial experience for participants to model and analyze a problem and system from their professional work.

The second aim was to estimate the probability (risk) of FMD at slaughter under current conditions -- the baseline risk. This required quantifying input values and distributions for the variables identified in aim one and translating the conceptual relationships into a probabilistic mathematical model. The risk estimates and sensitivity analyses provided insight about influential factors that could be leveraged to lower the probability of FMD among beef cattle at slaughter from select populations.

The third and final aim was to evaluate the cost-effectiveness of possible interventions that could reduce risk in specific value chains. Scenarios were generated using the insights from aim two and compared based on estimated costs and level of risk expected to achieve. This provided insight about specific steps that could be taken as well as a more general gradient of what scale of risk reduction might be expected from a given investment. This information can be combined with information about benefits, limitations, and tradeoffs to support decisions about investments related to FMD control and ambitions for international trade.

The output and process of this work provide useful contributions to improve decision-making regarding investments for animal health and trade in regions with endemic trade-sensitive diseases. In Kenya, a feedlot-focused, abattoir-partnered approach may reach the lowest achievable risk. Specific opportunities need to be evaluated in terms of the capacity of necessary stakeholders, cost of sanitary and traceability investments, costs of production, and competitiveness of the resulting product. In both Kenya and Uganda, regionally-focused investments that combined livestock identification and traceability systems with vaccination among willing producers in partnership with an ambitious export abattoir improve FMD control and animal health while reducing risk in the product produced and taking steps toward foundational traceability and disease control capacity. The framework of incremental progress with a focus on risk of the

final commodity complements the Progressive Control Pathway for FMD, providing a way to benchmark slow and steady forward motion, and should be used to evaluate disease control and SPS interventions that intend to achieve market access. Participatory approaches that embed data collection for decision analysis into training opportunities for local professionals are a rich way to improve the quality of data and analysis while also building capacity of participants to appreciate the complexity of systems in which they work and the value of analytical approaches to decision-making.

Key findings from each chapter:

- Aim 1 (chapter 3):
  - Risk processes differ between management systems, with an especially clear delineation in Kenya between agro-pastoral/pastoral and ranching/feedlot system groups-- highlighting the important interactions between management factors and health or risk dynamics.
  - FMD infection and sale for slaughter are not always independent events for cattle in Kenya and Uganda, suggesting it would be judicious to characterize the relationship between sale and disease of cattle in the population of study when examining the movement or sale of animals in endemic environments.
  - The motivations and actions of value chain actors influence the ultimate risk level in a product, demonstrated through the need to include a distinct event for whether or not a disease event is reported after a positive diagnosis.
- Aim 2 (chapter 4):
  - The overall risk of FMD infection at slaughter was substantially lower for cattle originating from Kenyan feedlots and ranches compared to the other six systems evaluated.
  - In Uganda, semi-intensive and ranching systems showed the potential to reach similarly low risk levels if able to severely limit the exposure to new infections after leaving the herd.
  - Reduction or elimination of commingling before slaughter was the most effective intervention to reduce risk of infection at slaughter for most systems.
  - For Kenyan ranches, the detection and removal of infected animals was identified as a potentially important point for intervention.
- Aim 3 (chapter 5):
  - Preventive mass vaccination was the least cost-effective strategy evaluated, even for a relatively small region. It would require a relatively high investment for not the best return with many obstacles on the path, and may not be an advisable strategy especially for the purpose of targeting export opportunities.
  - Strategies that involved voluntary rather than compulsory participation had more favorable cost-effectiveness ratios.

- The greatest reduction in risk at the lowest cost was obtained through a voluntary program that combined a livestock ID and traceability system with biannual preventive vaccination and a premium price at slaughter for participants.

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List of abbreviations

CBT	Commodity-based trade
FMD	Foot and mouth disease
LITS	Livestock identification and traceability system
OIE	World Organization for Animal Health
PCP	Progressive Control Pathway
VS	Veterinary Services
WTO	World Trade Organization

Chapter 1: Introduction

Increases in global population and income are expected to increase global demand for animal-source foods in upcoming decades; the number of livestock in sub-Saharan Africa could triple by 2050 (FAO, 2018). Accounting for regional trends in population growth and climate change, up to fifty percent of people could rely on imported food by 2050 (Fader et al., 2013). Livestock are a vital source of nutrition, income, and insurance for many of the world's most poor and vulnerable populations. International trade of livestock products is necessary for ensuring people have available and affordable food; it can also be seen as an opportunity for livestock-rich, low- and middle-income countries to promote economic development through agricultural exports (Bennett and Rich, 2019).

However, the global trade of livestock is also a source of risk to animal and public health. Livestock systems are associated with the emergence and re-emergence of zoonotic diseases (Rohr et al., 2019), and the spread of pathogens through the movement of feeds, animals, and food products can be rapid and devastating. Recent epidemics of Covid-19, African Swine Fever, Porcine Epidemic Diarrhea, Highly Pathogenic Avian Influenza, and Infectious Salmon Anemia are a handful of examples of the impact that can occur.

Members of the World Trade Organization (WTO), which includes 164 countries comprising 98% of the world's trade, agree to a set of rules and procedures that govern the continuation of free and open trade while enabling countries to enact scientifically-justified measures to protect their own animal and public health. The OIE (World Animal Health Organization) is the scientific authority on trade matters related to animal health, and the National Veterinary Services of each country are the competent authority responsible for achieving and maintaining conditions for safe trade of animals and animal-source foods.

This thesis focuses on one particular disease, foot and mouth disease (FMD), and the effort of two countries (Kenya and Uganda) where the disease is endemic and perceived to restrict opportunities for international trade of livestock and products, particularly beef. Chapter 2 reviews in more detail the concepts of the WTO procedures, risk analysis and veterinary services with relation to diseases of livestock and international trade. The rest of this introduction provides background related to FMD in East Africa and the objectives and activities of the project.

East African cattle systems

Livestock and animal products comprise a large portion of the economy for East African countries, including Kenya and Uganda. The livestock sector of Kenya contributes 12% of national gross domestic product and employs approximately 10 million people (Kenya Markets Trust, 2019). In Uganda, livestock accounts for 4.3% of national GDP, 58% of households own livestock, and 92% of those are subsistence farmers (FAO, 2019a).

In Kenya, 38% of households (3.6 million households) keep cattle and many others are employed along the livestock value chain (Gikonyo et al., 2018b). In the arid and semi-arid lands (ASAL's), which occupy most of the country's land area, 90% of the population raise cattle (for both beef and milk production) (FAO, 2019b). There are 18.8 million cattle (about 75% of which are beef cattle), 26.7 million goats, 18.9 million sheep, 3.2 million camels, 44.6 million poultry, 1.9 million donkeys, and 0.5 million pigs (FAO, 2019b). Beef cattle production can be categorized into four production systems (Gikonyo et al., 2018a). The most prevalent system, with 43% of the country's total cattle population, are pastoral systems practiced in the arid and semi-arid areas. Semi-intensive systems, also called agro-pastoral, are mixed crop and livestock systems and contain 29% of the cattle population. Ranches are highly commercial, extensive systems with large herds that include 4% of cattle, and feedlots, with 0.2% of all cattle, are capital-intensive systems that keep animals just for finishing (about three months) and sell to prime markets (Gikonyo et al., 2018a). Kenya has seven distinct agroecological zones based on agricultural and climate factors (Kibore et al., 2013) as well as rich wildlife ecosystems; twelve percent of Kenya's land area is considered protected (The World Bank, n.d.).

In Uganda, one quarter of the population partly or fully depend on cattle for their livelihoods (Nizeyimana and Felis, 2018). There are 14.2 million cattle, 16 million goats, 4.5 million sheep, 47.6 million poultry, and 4.1 million pigs (FAO, 2019a). The cattle population is concentrated along the "cattle corridor" extending from southwest to northeast regions of the country with the highest density of cattle in the pastoral areas of Karamoja in the Northeast. Beef cattle production can be categorized into four production systems. Agro-pastoral, which are smallholder, mixed crop-livestock systems, are the most prevalent and widely distributed and account for about 49% of the cattle population. Pastoral systems comprise 41% of the population, concentrated in the Northeastern region of the country and moving to follow pasture and water availability for their herds. Commercial ranching (8% of cattle population) and semi-intensive (2%) systems are more market-oriented systems located primarily in the Southwest and Central parts of the country (Mubiru et al., 2018). The country can be divided into ten agro-ecological zones based on climate, soil, and farming conditions (Mulumba et al., 2012; Wortmann and Eledu, 1999)(Mulumba, Wortmann). Sixteen percent of Uganda's land area is designated as protected areas, including national parks and wildlife reserves where wildlife roam freely (The World Bank, n.d.).

Foot and mouth disease virus

Foot and mouth disease is a highly contagious, viral disease of cloven-hoofed livestock and wildlife species, including swine, cattle, buffalo, sheet, goats, and others. Infection with foot and mouth disease virus (FMDV) causes vesicular lesions on the mouth and tongue, feet, and mammary epithelium (Alexandersen et al., 2003). Associated clinical signs include fever, lameness, salivation and loss of appetite. Mortality rates associated with FMD are typically low, though some mortality may be seen in young animals. Primary infection is of the pharynx, followed by systemic disease with viremia and characteristic vesicular lesions (Alexandersen et al., 2003). Typical disease progression in susceptible cattle includes stages of latent (pre-infectious), incubation (pre-clinical), and infectious (subclinical and clinical) phases of acute infection (Yadav et al., 2019). In cattle protected against clinical disease by vaccination or natural infection, nasopharyngeal infection is followed by so-called "neoteric" subclinical infection, in which infected animals do not develop lesions but may shed infectious virus in oral and nasal secretions (Buckle et al., 2021; Stenfeldt and Arzt, 2020). After clinical infection, some cattle clear infection within 10-28 days while others establish persistent infection of the nasopharynx (Stenfeldt et al., 2016). Experimental and field reports of persistently infected cattle indicate that the duration and prevalence vary according to setting and study design, but can include 50-60% of the affected population for seven to twenty months after acute infection occurred (Balinda et al., 2010; Bertram et al., 2020; Hayer et al., 2018b; Stenfeldt and Arzt, 2020).

These infection dynamics create complications for achieving and demonstrating freedom from disease. Where livestock are routinely vaccinated, serology is needed to demonstrate the absence of circulating, subclinical disease (OIE, 2019). The specter of persistently infected carriers haunts regions where there have been outbreaks within animals' lifetimes (Stenfeldt and Arzt, 2020). In some populations, notably southern Africa, wildlife populations are clinically-unaffected reservoirs of endemic disease (Jori and Etter, 2016). While carriers do not regularly transmit new infections to susceptible individuals, there is experimental and anecdotal support for the potential that such transmission could occur (Stenfeldt and Arzt, 2020).

There are seven serotypes of FMDV (O, A, C, SAT-1, SAT-2, SAT-3, Asia-1) with no cross protection (protective immunity against one serotype does not confer resistance to infection with other serotypes) (Belsham, 2020; Knowles and Samuel, 2003).

FMD epidemiology and challenges in East Africa

Multiple serotypes of FMDV are present within Kenya and Uganda: O, A, SAT-1 and SAT-2 the most common; C has not been isolated in East Africa since 2004 and SAT-3 has been isolated but is not believed to be widely distributed (Mwiine et al., 2019). New strains within serotypes emerge and spread with the movement of animals within and between countries. There are susceptible wildlife populations that may be a disease reservoir, but molecular epidemiology indicates that movement and transmission between cattle populations has driven the spread and evolution of disease (Casey-Bryars et al., 2018; Omondi et al., 2019). The diversity of cattle systems and particularly the movement of pastoral herds across borders and through areas where smallholder and commercial farms are located present a particular challenge to the control and prevention of disease transmission.

In southern Africa, regular mass vaccination combined with physical separation of wildlife and livestock have achieved reasonable control of disease (Jori and Etter, 2016; Tekleghiorghis et al., 2016). In eastern Africa, both ecosystems and cattle production systems differ (more dependent on the free movement of animals, less commercially-oriented) and these same strategies are not directly transferable (Ferguson et al., 2013).

Common strategies for disease control include movement controls and ring vaccination in the face of outbreaks. The effectiveness of such measures are challenged by lack of resources for robust responses, delays in obtaining and delivering an effective response (median reported times between recognition of outbreak and deployment of vaccines in Uganda of 25 and 52 days in two separate surveys (Muleme et al., 2012; Munsey et al., 2019)) and underreporting of disease events, compounded by difficulty delivering veterinary service to remote areas. Vaccination is used primarily as a reactive rather than proactive measure of disease control in Uganda (Muleme et al., 2012; Munsey et al., 2019); routine preventive vaccination has increased in Kenya in recent years (Compston et al., 2021). Trivalent or quadrivalent vaccines containing serotypes O, SAT 1 and SAT 2 plus or minus A are commonly used but matching against field isolates is rarely if ever performed (Compston et al., 2021).

Reporting of outbreaks is often delayed or does not occur; there is limited surveillance for disease. Official outbreak reports differ by source (Compston et al., 2021) and appear to underestimate the occurrence of disease when compared to seroprevalence estimates. A large cross-sectional survey found 60% (77/128) of randomly-sampled herds in Uganda to be positive for antibodies against FMD non-structural proteins (indicative of exposure through infection, not vaccination) (Munsey et al., 2019), with a mean within-herd prevalence of 31.4% among positive herds. A cross-sectional survey in Kenya reported a national seroprevalence of 52.5% in 2013 (Kibore et al., 2013); a recent study focused on cattle in herds near the Maasai Mara National Reserve boundary found an apparent animal-level FMD seroprevalence of 83.8% with the highest prevalence among herds located within 20 km of the park (Nthiwa et al., 2020).

Foot and mouth disease causes economic losses to cattle owners and regions where it remains endemic, with an estimated global cost of over $6.5 billion dollars attributed to disease and vaccination (Knight-Jones et al., 2017). Animal sickness, mortality, and poor production cause losses of household income and food security (Barasa et al., 2008) and inefficiency in herd reproductive and growth performance (Chaters et al., 2018; Knight-Jones et al., 2017). Control is costly, including costs experienced by the farmer (treatment costs, the impact of movement restrictions) and the region (vaccination and outbreak response (Perry et al., 2020), ecosystem consequences of veterinary cordon fences (Thomson et al., 2013a). Trade restrictions implemented based on FMD status can prevent access to high value international markets (Perry and Rich, 2007).

FMD and international trade from East Africa

Investments and improvements in livestock health have been posited to provide pathways out of poverty through three primary routes -- increasing security of assets, removing constraints to intensification and specialization, and improving access to higher value markets (Perry and Grace, 2009; Perry et al., 2002). Countries such as Kenya and Uganda may consider opportunities to capitalize on livestock resources to generate income and economic development for the country and agricultural sector (Republic of Kenya, 2013). One way to do that would be to export beef to international markets to receive some combination of a higher price and greater demand, resulting in more revenue.

The presence of endemic FMD is a barrier to selling beef to countries where FMD is eradicated or who are actively trying to control it and therefore prevent entry of any virus from other places (Paton et al., 2010). While FMD may not be the only hurdle to overcome in order to enter, compete, and thrive in international beef trade, it is a necessary one depending on the markets being targeted.

The standard pathway is to eliminate FMD from a region and then enter international trade (Clavijo et al., 2017; Sutmoller et al., 2003). Namibia and Botswana in southern Africa have controlled the FMD well enough to develop consistent export markets, achieved through mass vaccination and regionalization (Bennett and Rich, 2019). However, most African countries have been unable to follow in this success, due to challenges including the co-existence of livestock and wildlife in integrated ecosystems, presence of multiple FMD serotypes and evolving strains with no cross-protection, the low perceived benefits for producers to invest or buy into control efforts, and the fragmented and poorly resourced infrastructure for animal health service delivery. (Compston et al., 2021; Maree et al., 2014). These factors and others make it difficult for countries where the disease remains endemic to create geographically-defined regions where FMD is eliminated, the traditional route to progressively control and eradication. An internationally-used framework for FMD control, known as the Progressive Control Pathway (PCP), outlines a series of steps to guide countries in advancing toward improved FMD awareness and control, intended to provide a template for forward motion regardless of a country's starting place (Ismayilova, 2017; Rweyemamu et al., 2008). However, the steps emphasize geographically-based disease control and progress has been elusive for some countries to achieve and, followed to the point of freedom from disease, may disrupt inherent ecosystem and cultural dynamics of regions such as sub-Saharan Africa (Ferguson et al., 2013).

One other avenue to international trade is to focus on the risk, to the importing country, associated with the product being exported (e.g., deboned beef), an approach known as commodity-based trade (CBT) (Rich and Perry, 2011b). For example, regarding FMD, market access via CBT would be based on the probability of transmission of FMD virus associated with the import of deboned beef produced from a particular supply chain and its set of animal production, slaughter, and processing procedures (Paton et al., 2010; Thomson et al., 2013b). There has been work out of southern Africa to establish a set of standardized protocols that would achieve an acceptable level of risk (Thomson et al., 2018), motivated by the endemic wildlife reservoir in southern Africa that impedes achieving the status of zonal freedom from disease. Ultimately though, the idea of CBT is mostly theoretical and not known to be the basis of actual trade agreements, and therefore not prescriptive or with established precedent.

This ambiguity means there is no single set of established steps to follow that will likely lead to international acceptance according to the risk-based tenets of CBT. Conversely, the spirit of CBT is that livestock production and processing could be done in a way that is adapted to local conditions (social, environmental, economic) if it can be demonstrated that the steps taken are effective to reduce the risk associated with the product to a level acceptable to trading partners. These ideas align with the WTO principles of risk assessment and equivalence, covered in more detail in Chapter Two (World Trade Organization, n.d.). What follows is the opportunity to think creatively about what is possible and how that could be achieved for countries with endemic FMD who have struggled to advance toward zonal freedom from disease but believe that participation in international markets could be a rewarding prospect for their livestock sector. What type of steps taken throughout the lifetime of the animal and harvest and handling are feasible and would be adequate to produce beef acceptable for international trade? How could steady, incremental progress be made toward achieving an acceptably low level of risk in the exported product?

The other consideration not to lose track of is whether that product, once granted access -- contingent on both achieving / demonstrating acceptable risk AND international acceptance of the CBT approach -- would perform as hoped (Naziri et al., 2015; Rich et al., 2009; Rich and Perry, 2011b). It would need to be competitive on some combined basis of quality and price with beef produced with potentially greater volume and efficiency from other parts of the world. In addition to the current actors, acceptance of CBT would open doors to other countries with similar ambitions including those which produce more and/or better and/or cheaper products than what Kenya or Uganda currently offer. Any possibility of achieving market access via CBT would require substantial investment in disease control, sanitation, and certification systems that would further increase the cost of production. These factors have led analyses in Ethiopia, Namibia, and Zimbabwe to conclude that pursuing international trade via CBT may not be worthwhile compared to other investment opportunities (Naziri et al., 2015; Queenan et al., 2017; Rich et al., 2009).

Given all of that, it would be valuable for FMD-endemic, beef trade-aspiring countries such as Kenya and Uganda to gauge what actions and systems would be needed to reach an acceptable level of risk, and the cost and capacity required to support such investments. That information could be used to assess the benefits expected from those investments, including how much (if any) revenue could be expected from those pathways (given access) and what domestic benefits for animal health and productivity or increased sanitary capacity would also be anticipated. Potential trade-offs should also be considered, especially considering the scarcity of economic and human resources for health infrastructure. Would a focus on FMD management in specific supply chains come at a loss to other diseases, production sectors, public health or consumer wellbeing? What would be the opportunity cost of investing in this strategy rather than other opportunities to support the efficiency and resilience of livestock systems? Who would be expected to benefit from the investment and over what time frame?

There is little information available on the risk of FMD transmission associated with beef produced from East Africa. The generic risk reduction achieved by post-harvest steps of inspection, processing, and storage of deboned beef according to OIE specifications has been extensively assessed, with the conclusion that substantial risk reduction occurs at and after slaughter but achieving an acceptably low ("negligible") risk level requires pre-harvest risk management in the livestock supply chain (Paton et al., 2010).

Cattle in East Africa come from diverse production systems and value chains and little is known about the prevalence of FMD among cattle at slaughter or how it varies based on production system of origin. Although previous studies have assessed the epidemiology (Casey-

Bryars et al., 2018; Kibore et al., 2013; Mwiine et al., 2019), risk factors (Ayebazibwe et al., 2010; Munsey et al., 2019; Nthiwa et al., 2020), and challenges of FMD control (Compston et al., 2021; Maree et al., 2014; Tekleghiorghis et al., 2016) in Kenya and Uganda, the risks for FMD in cattle and deboned beef originating from both countries have not been quantified. Infection risk among animals at slaughter is dependent on the events that occur between the farm and abattoir in addition to the herd-level disease risk (Paton et al., 2010), especially considering the important risk presented by animals in the early incubation phase of disease (Sutmoller, 2001). Kenya and Uganda each have several beef cattle production systems (Cecchi et al., 2010; Gikonyo et al., 2018a; Mubiru et al., 2018) and complex ruminant value chains (Alarcon et al., 2017). In order to complete a risk assessment that can usefully guide each country toward steps to reduce risk, it is important to include information about the distinct risk factors associated with the production, sale, and transport of beef cattle from each management system

Objective

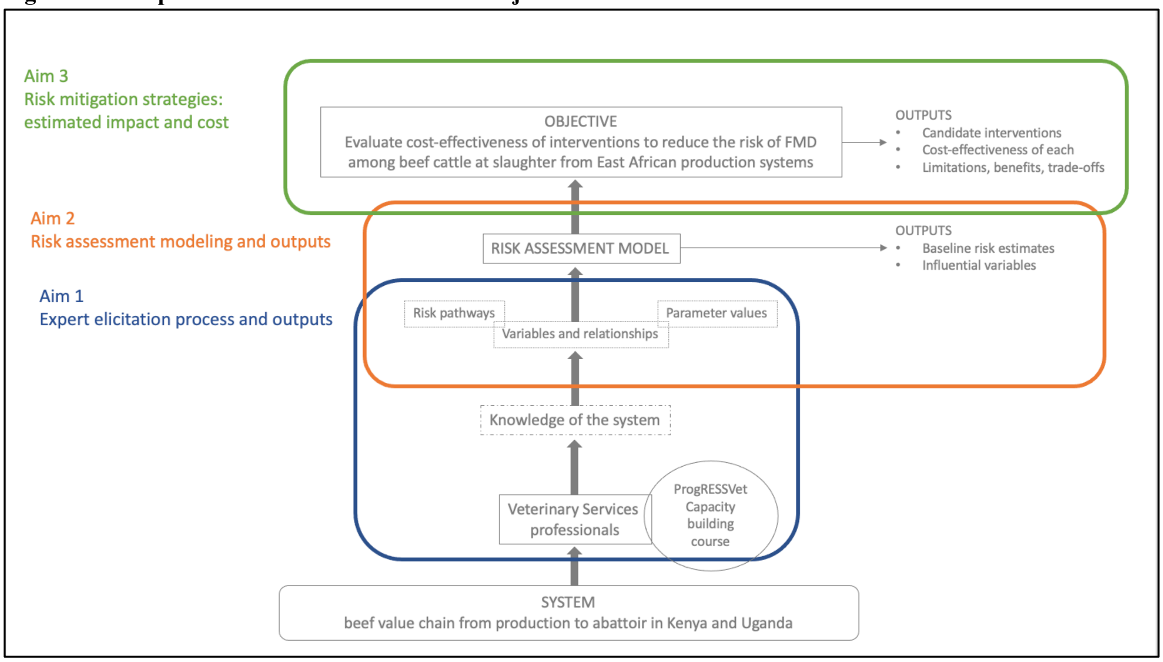
The objective of this work was to characterize the probability of FMD infection among cattle at slaughter in Kenya and Uganda and to evaluate the cost-effectiveness of interventions to reduce that risk. The purpose was to generate evidence and insight for plans about how (and if) to pursue entry to international beef markets which would require demonstrating a negligible risk of FMD transmission associated with exported goods. This was achieved through three sequential aims, as outlined in Figure 1-1.

The first aim was to characterize the risk pathways and processes in order to determine the appropriate populations, structure, and variables to construct a model for risk assessment among cattle at slaughter in Kenya and Uganda. Chapter three describes how this was achieved in partnership with Kenyan and Ugandan veterinarians, who were participants in a year-long e-learning capacity-building course, to characterize risk pathways and selected parameter values. This approach addressed two major and related hurdles to traditional risk assessment: a) data scarcity especially to the level of granularity needed in places that tend to have diverse and informal value chains, and b) tapping into unwritten local knowledge / subject matter expertise in a way that generated credible information in a format that can be used for quantitative analysis (Grace et al., 2008).

The second aim was to estimate the probability (risk) of FMD at slaughter under current conditions -- the baseline risk. This required quantifying input values and distributions for the variables identified in aim one and translating the conceptual relationships into a probabilistic mathematical model. Select parameter values were estimated through a participatory process with the VS participants, these are described in chapter three. The remainder of the parameterization and modeling process and results are described in chapter four. The risk estimates and sensitivity analyses produced here provided insight about influential factors that could be leveraged to lower the probability of FMD among beef cattle at slaughter from select populations.

The third and final aim was to evaluate the cost-effectiveness of possible interventions that could reduce risk in specific value chains. Scenarios were generated using the insights from aim two and compared based on estimated costs and level of risk expected to achieve. This provided insight about specific steps that could be taken as well as a more general gradient of what scale of risk reduction might be expected from a given investment. This information is not a finish line but rather a starting place for local stakeholders and decision makers to ask the questions about benefits and tradeoffs that can lead to an informed decision about investments related to FMD control and ambitions for international trade.

Figure 1-1: Map of three aims to achieve thesis objective



Chapter 2: Choosing awareness over fear: risk analysis and free trade support global food security

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Published in Global Food Security, available at: https://doi.org/10.1016/j.gfs.2020.100445

Abstract: Livestock production and global trade are key components to achieving food security, but are bedfellows with the risk for emergence and spread of infectious diseases. The World Trade Organization's Agreement on the Application of Sanitary and Phytosanitary Measures outlines provisions for member countries to protect animal, plant, and public health while promoting free trade. The capacity for risk analysis equips countries to increase access to export markets, improve local animal health and food safety regarding known hazards, and build the institutional capacity to respond to unexpected events. The COVID-19 pandemic has highlighted the need to detect, report, and implement effective response measures to emerging challenges on a local and global scale, and it is crucial that these measures are implemented in a way that supports food production and trade. The use of risk analysis coupled with sound understanding of underlying system dynamics will contribute to resilient and enduring food systems.

Introduction:

Food security has been defined as "a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (Barrett, 2010). Despite reductions in hunger and poverty levels, over 26% of the world population still experiences moderate or severe food insecurity, with the majority in Asia and Sub-Saharan Africa (FAO et al., 2019). Food insecurity is an important item in the international agenda; the second goal of the 2030 Agenda for Sustainable Development, adopted by all United Nations (UN) Member States in 2015, is to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture" (United Nations, 2015). That goal is challenged by major events such as the COVID-19 pandemic, which the UN has estimated could almost double the number of people suffering from acute hunger by the end of 2020 (United Nations World Food Program, 2020). The conundrum here is that, although livestock production and global trade are necessary components for achieving food security, they are each vulnerable to the impacts of, as well as potential contributors to, such infectious disease events.

Animal-source foods do and will continue to play an important role in meeting energy and nutrition needs. Regions severely affected by food insecurity are experiencing both population and income growth. The total population of the 47 least developed countries is growing 2.5 times faster than that of the rest of the world. Per capita consumption of animal-source foods is increasing, driven by higher incomes and associated dietary preferences (Godfray et al., 2018; Rohr et al., 2019). Total meat consumption is projected to rise substantially through 2050, mostly in low- and middle-income countries (Godfray et al., 2018). The global livestock herd will expand accordingly. Models from the Food and Agriculture Organization of the UN (FAO) project the number of livestock in sub-Saharan Africa could nearly triple by 2050 compared to 2012, considering increasing population and incomes (FAO, 2018).

Urban areas will absorb nearly all of global population growth, underscoring the importance of adept food distribution systems within and between countries (Reardon et al., 2020; United Nations Department of Economic and Social Affairs Population Division, 2019). Most countries are more dependent on imports than 20 years ago ("The world's food system has so far weathered the challenge of covid-19," 2020), and an estimated 50% of people could rely on imported food by 2050 when factoring in population growth and climate change (Fader et al., 2013). International trade will play a strategic role in supporting sustainable food production and supply (FAO, 2018; HLPE, 2016). This scenario presents an opportunity for countries to participate in agricultural trade, contributing to the supply of available nutrition in rapidly growing regions while also developing their own economies (Parshotam, 2018; The World Bank, 2012). Certain regions have made progress towards that end; most notably, a number of countries in Latin America have grown into exporting agricultural economies over the last decades (OECD/FAO, 2019). Africa is on the cusp of a free trade area intended to promote intra-continental cooperation (Muchanga, 2019). The critical role of food supply chains is becoming clear during the COVID-19 pandemic (Reardon et al., 2020). Twenty-eight countries representing 67% of agricultural exports and 60% of imports have committed to maintain fair and predictable standards in order to mitigate the impact of COVID-19 on agricultural trade and food security and avoid the price spikes, volatility, and food shortages associated with restrictive and retaliatory measures (Bouët and Laborde Debucquet, 2012; World Trade Organization, 2020).

For any combination of livestock expansion, intensification, and globalization that is necessary for food security and nutrition, there is a correlated set of public health risks (Mehrabi et al., 2020). Improved nutrition from consumption of animal products can improve health at both an individual and population level (Rohr et al., 2019), but there is also an increment on the risk for the emergence and reemergence of zoonotic and foodborne disease (Daszak, 2007; HLPE, 2016). Around 60% of all human diseases are zoonotic (Taylor et al., 2001), and nearly 50% of zoonotic diseases that emerged in humans since 1940 were associated with agricultural drivers (Rohr et al., 2019). Furthermore, a highly connected world, including the movement of people and goods, facilitates the rapid global spread of pathogens (Fèvre et al., 2006). The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the causative agent of COVID-19, emerged in China in December 2019 and soon reached pandemic proportions. In 2013, two other coronaviruses responsible for highly infectious swine disease (porcine epidemic diarrhea virus (PEDv) and porcine deltacoronavirus) caused a devastating epidemic in North America. PEDv is credited for the death of 10% of US domestic pigs and losses upwards of $1 billion in one year (Hou and Wang, 2019). The viruses likely spread through the movement of feed (Niederwerder and Hesse, 2018). Recent food supply disruptions associated with the global spread of pathogens are not limited to coronaviruses or swine. African Swine Fever (ASF) has since 2007 spread through Asia and Europe and resulted in major losses to the global domestic pig population: China reported a 40% decrease in pig inventory and near doubling of pork prices during the first year of their epidemic (Haley and Gale, 2020). Likewise, highly pathogenic avian influenza (HPAI) and infectious salmon anemia (ISA) are contagious viral diseases that traveled rapidly and wreaked havoc on farmers and countries that produce poultry and salmon, respectively (Barr, 2017; Mardones et al., 2013). Epidemics of COVID-19, PED, ASF, HPAI, and ISA illustrate the extent to which systems that produce and distribute food are, at the same time, potential sources and vulnerable targets of emerging disease events.

Considering the complex dynamics between food systems and environmental, economic, and social phenomena, there will inevitably be future events that shake local and global food supply chains. A review published in 2007 stated that a large reservoir of SARS CoV-like viruses in combination with cultural practices in southern China was “a time bomb”, suggesting the possible reemergence of SARS and other novel viruses (Cheng et al., 2007). Though the potential threat was identified, the precise event of COVID-19 was neither predicted nor prevented. In this sense, many epidemics may be considered black swan (low probability, high impact) events (Paté-Cornell, 2012; Taleb, 2007).

Acknowledging that such events will occur but without knowing precisely what, when, or where (Plowright et al., 2017), we emphasize the importance of well-equipped food and public health systems (Paté-Cornell, 2012). A connected and resilient food system, which is crucial to support the nutrition and health needs of a thriving global population, depends on the ability of all countries to detect and respond to such events. The capacity for risk analysis is a lever to promote participation in global markets, improve domestic animal health and food safety, and develop institutional capacity to respond to anticipated but unknown future developments. It follows that a response to the COVID-19 pandemic should be to strengthen the capacity for risk analysis within the Veterinary Services globally. This is a potentially high-reward lever to affect both food security and global health: by mitigating the impact of future infectious disease outbreaks (through rapid, local, effective response); by promoting each country's capacity to participate in the international trade of animal products while reducing the opportunity for disease transmission through that activity; and by reducing the probability of future events as structural and systemic food production and animal disease policies will be built on sound understanding and appreciation of local risks and tradeoffs.

In the first section of this article, we review the World Trade Organization's (WTO) provisions to promote free trade while protecting public and animal health. The second section describes the role of risk analysis in international trade and in building resilient food systems. The third section addresses whether trade bans would more effectively lower risks associated with movement of goods and animals, concluding that more restrictions may result in greater risk for pathogen introduction. In the final section, we highlight the need for integrated understanding of these complex systems to support both research and policy for resilience.

Section 1: Trade, public health risks, and the SPS Agreement

The Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement) is one of the foundational pillars of the WTO (World Trade Organization, n.d.). The SPS Agreement operates on the idea of "appropriate level of sanitary protection", which is the level of protection that each member country determines is appropriate—or, conversely, the maximum level of risk that a country is willing to tolerate. Governments have the right to take trade-related measures to protect human, animal, and plant health, as long as they can demonstrate that the measures are based on science, are necessary, do not discriminate, and are not more restrictive than regulations applied within their own country. These measures take many forms including mandatory screening or processing protocols, or only accepting products from disease-free regions.

Five provisions in the SPS Agreement lay the groundwork for fair and consistent application of such measures. Harmonization and equivalence urge member countries to follow standards set by the relevant international bodies and to objectively recognize the value of other countries' measures when they differ. The World Organization for Animal Health (OIE), Codex Alimentarius, and International Plant Protection Convention are the recognized standard-setting bodies for animal health, food safety, and plant health, respectively. Transparency stipulates that countries provide sufficient and timely information regarding sanitary situations. Under regionalization, sanitary measures are to be relevant to a product's zone of origin, accounting for geographical and epidemiologic factors. Finally, risk analysis establishes that restrictive measures must be based on an assessment of risks, using systematic techniques and considering available scientific evidence. Through the WTO dispute settlement process, one country may challenge a restrictive measure imposed by another on the grounds of violating these terms.

In reality, these provisions are not as flawless in practice as on paper. WTO members differ in interpretation and implementation of the rules. Countries and individuals at times attempt to navigate the system to advance their own political and economic advantage (Conconi et al., 2017; Worsnop, 2017). The SPS Agreement was established in part because of widespread barriers maintained in the name of risk protection with no effective mechanism for challenging the basis of such measures. The new framework created a structure of expectation and accountability, but there is still work to be done to redistribute power and transform motivations of players involved. Even so, there is evidence that the SPS Agreement and WTO system have helped to facilitate healthy trading relationships. Of over 450 specific trade concerns raised in the SPS Committee meetings since 1995, only 14 have reached the substantive second stage of the formal process (OECD, 2019). The outcome of several disputes has been revised policies better aligned with the standards above. For example, in DS447, Argentina accused the US of, among other things, failing to adapt import regulations to reflect the epidemiologic characteristics of beef exporting regions (World Trade Organization, 2015). The dispute panel found that US policies were inconsistent with the provision of regionalization, and the policy was updated to allow imports and reflect risk measures specific to the regions with and without vaccination for FMD ("Importation of Beef From a Region in Argentina," 2015). In another example, Canada filed a complaint against the Republic of Korea for failing to align their policies with the OIE recommendations (harmonization) after the OIE had classified Canada as a country with "controlled risk" for Bovine Spongiform Encephalopathy (BSE) and defined appropriate measures under which exports could occur ("Korea- Measures Affecting the Importation of Bovine Meat and Meat Products from Canada," 2012). Before the panel delivered a ruling, Canada and Korea reached a mutually acceptable policy revision and Korea lifted its BSE prohibition on the import of Canadian beef. One may subsequently argue that although the current system is not perfect, it represents progress compared to its predecessors.

A remaining challenge is that market access is unevenly distributed, as less developed economies are typically unable to achieve the level of risk that is deemed "acceptable" by wealthier regions. For example, only four of the 47 UN-listed least developed countries have been designated disease-free for trade purposes by the OIE for any of the eligible animal diseases (United Nations Department of Economic and Social Affairs, n.d.; World Organization for Animal Health (Office International des Epizooties), n.d.). Food safety is challenged by fragmented food systems and poor capacity to enforce regulation (Grace, 2015). Some surveys for antimicrobial residues in African countries report residues detected in greater than 20% of meat and milk samples (Mensah et al., 2014). This situation sets up a challenging dynamic: countries with few resources and high disease challenges to start with are unable to access the premium markets that would provide resources and incentive to further develop their agricultural economy and health infrastructure (Unnevehr and Ronchi, 2014). In an attempt to mitigate those challenges, the Standards and Trade Development Facility (STDF) was established in 2001 to support developing markets to gain and maintain market access through compliance with sanitary and phytosanitary standards (Standards and Trade Development Facility, 2019; World Trade Organization, n.d.).

Section 2: Risk analysis and resilient local and global food systems

The SPS Agreement formalized the role of risk analysis in food trade policy (World Trade Organization, n.d.). Risk analysis is a systematic approach for characterizing the expected outcome and impact of an event, considering the variability in the system and uncertainty in our knowledge (Kaplan and Garrick, 1981). The OIE approach consists of four interwoven steps: hazard identification (what could go wrong?), risk assessment (what is the probability and consequence if it happens?), risk management (how to mitigate that risk?), and risk communication (what should we say about it, how, to whom?) (World Organization for Animal Health (OIE), 2019). An analysis may be carried out by an importing country (to guide decisions about a particular product or following a change in a region's sanitary status) or by an exporting country (to demonstrate that a product or region does not present substantial risk).

When there is not enough evidence to assess risk, the SPS Agreement allows for precautionary measures. Examples include disease outbreaks with an evolving and uncertain epidemiologic situation or the use of new technology for which the risks are unclear. Decisions based on uncertainty are inherently provisional and need updating as new information is available (Foster, 2009; Hansson, 2016). Uncertainty-based restrictions can tread the line between precaution and opportunism – e.g., bans on North American swine exports during the 2009 H1N1 outbreak, following the unfortunate designation of the disease in the media as "swine flu" and despite WHO and OIE recommendations that deemed such measures unnecessary (Worsnop, 2017). Further friction arises from differences in interpretation (how much uncertainty is enough to exercise precaution?). Trade disputes involving these issues have stalled in various stages of negotiation(World Trade Organization, n.d., n.d.) and have generated debate around what it means to exercise science-based precaution and the role of public opinion (Epps, 2008; Goldstein and Carruth, 2004). In several cases these disputes have reflected or escalated highly politicized interests, such as bans by the European Union regarding beef raised with hormones, poultry processing methods, and biotechnology (Johnson, 2015, 2014; Orden and Roberts, 2007).

The ability to execute and communicate risk analyses is therefore vital for countries to participate and self-advocate in international trade while minimizing their exposure to hazards. Furthermore, the capacity for risk analysis strengthens within-country public health systems in their prevention, detection, and response to threats (Bastiaensen et al., 2017; Hoffmann, 2010a). Equipping each country and region in this way will strengthen trade relationships, local food and public health systems, and global resilience in the face of a future pandemic or shock to the food system.

The OIE specifies the application of risk analysis as a required competency for members of a country's veterinary authority (World Organization for Animal Health (Office International des Epizooties), 2012). Official veterinary services manage animal health and food safety, carry out surveillance activities, and inform risk-based policy and planning (Zepeda et al., 2005). A review of OIE-conducted evaluations of the Performance of Veterinary Services (PVS) in 44 African countries found that all except three countries lacked the technical capability to conduct risk assessments in compliance with OIE standards (Bastiaensen et al., 2017), and the report suggests that developing and in-transition countries globally lack risk analysis capacity. Building such capacity can encourage a virtuous cycle that begins with using information available, albeit unrepresentative data or expert opinion, to identify and prioritize areas of focus to both mitigate and better understand sources of risk. That process facilitates the concentration of resources, including opportunities such as the STDF, to expand and strengthen infrastructure for data collection, diagnostic testing, and communication among stakeholders. Once a country has developed the capacity to minimize, monitor, and mitigate known risks in food systems, then they are also equipped to detect and respond to the unexpected.

Epidemics are black swan (low probability, high impact) events that cannot be precisely predicted and therefore prevented. Rather, the ability to weather such events depends on a resilient system (Cox, 2020). In this context, resilience includes the readiness to anticipate and mitigate the impact of epidemic events that are expected to happen without knowledge of when or where they will occur. A resilient global food system will be characterized by redundant layers of vigilance and all regions outfitted to respond to and mitigate the impact of novel threats.

Section 3: Counterproductive impact of trade bans on disease spread

Some argue, particularly in a crisis as painful as the COVID-19 pandemic, that it would be prudent to minimize rather than encourage the movement of animals and products between regions (Goodhart, 2020; Legrain, 2020). However, restrictive measures such as trade and movement bans may lead to more underground, and therefore unregulated, movement of goods. For example, public health authorities encouraged the closure of live bird markets during the H7N9 epidemic in China in 2013-14, attempting to limit human cases. That decision prompted altered and unauthorized poultry trading that spread the virus to previously uninfected areas (Li et al., 2018). A given volume of activity will pose a greater risk of transporting and introducing biological hazards when it is unregulated. In other words, permitted and formal avenues for trade can foster a lower total likelihood of disease spread than measures that divert the movement of goods into underground channels (Kwan et al., 2017; Marcos and Perez, 2019).

The illegal movement of animals and animal products has an established role in the spread of infectious disease (Fèvre et al., 2006; van den Berg, 2009). There are intrinsically few data on the volume of smuggled goods, but regular impound events imply extensive activity. The Animal and Plant Health Inspection Service of the US Department of Agriculture reports that 8000 pork products are confiscated annually (Jurado et al., 2019). In spring 2019, a 1 million-pound shipment of illegal pork from China was confiscated in Newark, NJ (during the period that the ASF epidemic was decimating the Chinese swine industry) (Nieto-Munoz, 2019). Several countries, upon testing seized pork products, have found them to be carriers of ASF (Jurado et al., 2019), and there are several past ASF outbreaks attributed to illegally imported goods (Costard et al., 2013). Foot and mouth disease and classical swine fever outbreaks have also been linked to illegal entry of meat or meat products (Costard et al., 2013). Unregulated animal movements can have direct public health impacts as well. The high prevalence of human brucellosis in Saudi Arabia has been attributed to unregulated livestock imports from Africa (Fèvre et al., 2006); 21 people in France required post-exposure prophylaxis for rabies after contact with an illegally imported rabid dog (Fèvre et al., 2006).

Section 4: integrated understanding for effective applications

The goal of risk analysis is to characterize variable and uncertain events in order to plan and implement strategies for a desirable outcome (Kaplan and Garrick, 1981). Those events take place in the context of dynamic, complex systems. Failing to understand or account for that complexity can lead to policy resistance (the tendency for interventions to be defeated by the response of the system to the intervention itself) and unintended consequences (Sterman, 2000).

Conversely, the drivers of system behavior comprise a palette of policy levers for risk management that include social, cultural, and economic incentives (Rich and Perry, 2011a). Models by design require simplification, but awareness of simplifying assumptions helps users to appropriately interpret and contextualize model output (Brisson and Edmunds, 2006). We want to draw attention to two types of assumptions and their implications for designing and interpreting risk analyses.

First, risk is a function of human choices and behaviors (Hoffmann, 2010b; Perrings et al., 2018). In livestock systems, such behaviors include decisions to implement biosecurity measures, report a notifiable disease when suspected, and use pharmaceuticals as regulated. These actions results from socioeconomic factors that may be laborious to include in risk assessment but nonetheless should be explored. Insights can be used to identify behaviors that can be modified, and incentives that may be implemented, to mitigate public health risks (Perrings et al., 2014; Rich and Perry, 2011a; Wolf, 2017).

Second, relationships between variables may be non-linear and/or bi-directional (e.g. there may be threshold effects or feedback loops). Models that fail to capture these dynamics may inaccurately estimate baseline risk, risk reduction, or the value of costs and benefits associated with proposed measures (Brisson and Edmunds, 2003; Williams and Thompson, 2004). In livestock value chains, such relationships include those between incentive structures, foodborne disease, and producer and consumer actions (Rich, 2007; Williams and Thompson, 2004).

Integrated and simulation models can incorporate behavioral drivers and dynamic complexity directly into assessments of risk (Duintjer Tebbens et al., 2015; Ford et al., 2019; Hayashi et al., 2019; Rich et al., 2013). Complex quantitative models are not always practical or appropriate. That said, mental models (on the part of modelers and decision makers) that look for the complexity in the system and wonder about its impact on an assessment's output will produce more productive discussion and effective policy conclusions than those which blindly assume simplicity (Sterman, 2001).

Such mental models – our understanding of the system we are navigating – can be informed by field research and formal modeling studies that elucidate livestock food systems. Food security, infectious disease, ecosystem services, economic development, and the movement of people and animals are all linked through the type of dynamic complexity described above (Carter and Barrett, 2006; Grace et al., 2017; Rohr et al., 2019). By studying these dynamic relationships as an integrated and tangled whole rather than individual silos (Ingram, 2011; Restif et al., 2012), we can learn to better recognize self-reinforcing behaviors and underlying mechanisms (that contribute to policy resistance and frustrated outcomes) as well as levers for effective and sustainable change.

Conclusion:

Food production and distribution systems, including open and global trade, are critical for meeting the twin goals of food security and global health in the 21st century. In this highly connected and evolving world, unpredictable yet impactful events will continue to emerge. The COVID-19 pandemic has highlighted the need to detect, report, and implement effective response measures globally: in importing and exporting countries and at the origin and destination of potential epidemics. The capacity and use of risk analysis coupled with sound understanding of underlying system dynamics will contribute to resilient and enduring food systems. By being both proactive and reactive at local and global scales, the world should progress toward the ultimate objective of promoting societal growth and food security by handling risk with awareness rather than fear, and with innovation and solidarity rather than isolation.

Acknowledgements: This work was supported in part by the Bill and Melinda Gates Foundation and by USDA National Needs grant 2014-38413-21825.

Chapter 3: Partnership with East African veterinarians to characterize the risk of FMD among cattle at slaughter

Two manuscripts included in this chapter:

- One coin, two sides: eliciting expert knowledge from training participants in a capacity-building program for veterinary professionals

- Self-reporting of risk pathways and parameter values for foot and mouth disease in slaughter cattle from alternative production systems by Kenyan and Ugandan veterinarians

One coin, two sides: eliciting expert knowledge from training participants in a capacity-building program for veterinary professionals

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Submitted to Frontiers in Veterinary Medicine, June 2021

Abstract: Scientific research may include the elicitation of judgment from non-academic subject-matter experts in order to improve the quality and/or impact of research studies. Elicitation of expert knowledge or judgment is used when data are missing, incomplete, or not representative for the specific setting and processes being studied. Rigorous methods are crucial to ensure robust study results, and yet the quality of the elicitation can be affected by a number of practical constraints, including the understanding that subject-matter experts have of the elicitation process itself. In this paper, we present a case of expert elicitation embedded within an extended training course for veterinary professionals as an example of overcoming these constraints. The coupling of the two activities enabled extended opportunities for training and a relationship of mutual respect to be the foundation for the elicitation process. In addition, the participatory research activities reinforced knowledge synthesis objectives of the educational program. Finally, the synergy between the two concurrent objectives may produce benefits which transcend either independent activity: solutions and ideas built by local professionals, evolving collaborative research and training approaches, and a network of diverse academic and practicing professionals. This approach has the versatility to be adapted to many training and research opportunities.

Introduction

Scientific research may include non-academic participants in the research process to improve the quality and impact of studies (Balazs and Morello-Frosch, 2013; Knol et al., 2010; Lang et al., 2012). There are many paradigms, methodologies, and purposes for utilizing such approaches. This paper focuses on the elicitation of knowledge from subject matter experts, whose estimation or judgment of fact-based matters is used to answer the research question (Hanea et al., 2021; Knol et al., 2010). This approach is utilized when available data are scarce, unrepresentative, or inadequate to describe the processes and systems being studied. “Expert" in this usage refers to a person who can provide information about the question based on their experience with the subject matter of interest (M. Burgman et al., 2011; M. A. Burgman et al., 2011).

Expert elicitation is increasingly common within veterinary science, although used less frequently than in other fields. A search on Web of Science for “expert knowledge” OR “expert elicitation” OR “expert judgment” returned 60 articles (out of 708,779) within the category of Veterinary Sciences, 30 of which were published since 2017. When accounting for the total number of articles in each Web of Science category, the same search string occurred ten times more frequently within Environmental Sciences (1232 / 1,489,989) and twelve times more frequently for Ecology (599 / 591,636). The purposes of expert knowledge in veterinary publications include estimation of parameter values (Beck-Johnson et al., 2019; Verdugo et al., 2020), ranking of risk factors or criteria (Brookes and Ward, 2017; McEachran et al., 2020; Muellner et al., 2018), enhancing or interpreting available data (Faverjon et al., 2019; Sharifi et al., 2017; Squarzoni-Diaw et al., 2020), or developing an instrument for use by practitioners (Comin et al., 2019; Patyk et al., 2015). Many applications are in data-scarce environments, but there are also cases where expertise is used to make sense of or add rigor to abundant or heterogeneous data sources (Faverjon et al., 2019; Grant et al., 2016).

When expert knowledge is utilized as a source of information, there are limitations and potential pitfalls (Sutherland and Burgman, 2015). People have restricted mental models, poor causal reasoning, and are prone to a litany of biases (Hanea et al., 2021; Vennix, 1996). Estimating probabilities and quantifying uncertainty require training distinct from subject matter expertise (Hanea et al., 2021). Rigorous and structured procedures for participant selection, knowledge elicitation and interpretation, and study validation are crucial to ensure the quality of study conclusions (Gustafson et al., 2013; Hanea et al., 2021; Knol et al., 2010).

Structured procedures and training of participants can help to alleviate bias but may be inconvenient or impractical, especially when working with subject matter experts from outside of academia. Elicitations may be carried out in a restricted time period (e.g., embedded within a workshop or conference) or through long-distance interactions. Including participants who are "boots on the ground" practitioners or community members can be challenging if they have limited time available for the activity and a steeper learning curve with respect to the research and elicitation methods. Subject matter experts may not have an academic understanding of the techniques being used, which can impede effective communication and impact the quality of the results if adequate training is not provided.

In this paper, we present a case of expert elicitation embedded within an extended training course for veterinary professionals as an example of overcoming some of these constraints. The coupling of the two activities may create a synergy between research and training which enriches the outcomes and expands the impact of each component, creating a whole greater than the sum of the parts. First, we give a brief overview of the training program, research objectives, and expert elicitation activities performed. Then, we describe the observed outcomes and character of this approach, perceived to be beneficial and synergistic. Finally, we discuss considerations for future opportunities.

Research and training overview

The research objective was to quantify and analyze the risk for transmission of foot and mouth disease (FMD) associated with the export of beef produced in Kenyan and Ugandan cattle systems. FMD is a highly infectious transboundary disease of cattle and other livestock and wildlife species (Brito et al., 2017) and is endemic to East African countries (Mwiine et al., 2019; Nthiwa et al., 2020). In order to model that risk, it was necessary to understand the underlying processes and the values of key variables. Most of those data are not published; people who work in those beef cattle systems provided expertise and guidance to build, quantify, and validate the risk assessment model.

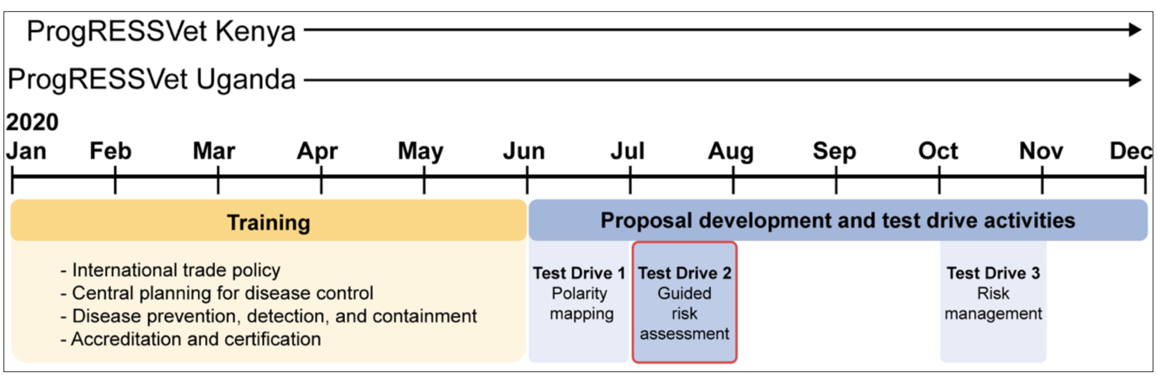
The elicitation was carried out within 2 concurrent cohorts of ProgRESSVet: a systematic education program for building professional capacity of veterinarians in Kenya and Uganda delivered by the University of Minnesota Center for Animal Health and Food Safety (CAHFS) (O'Brien et al., 2019). Participants for the program in each country were required to have a degree in veterinary medicine and experience in the field. There were 13 veterinarians from Kenya, with an average of 13 (range of 2-29) years of experience working in animal health and/or production. The Ugandan cohort had 10 participants, with an average of seven years of experience (range 2-15 years).

ProgRESSVet training programs are tailored to address gaps identified in the OIE (World Organization for Animal Health) Performance of Veterinary Services Pathway (OIE (World

Organisation for Animal Health), n.d.) for each country or region of implementation. The programs are designed per Fink (Fink, 2013) to build individual capacity to generate lasting change in participants, thereby building the technical, collaborative, and systems-thinking capacity of the Veterinary Services (VS) to ultimately improve the health and wellbeing of the communities and countries where they work (O'Brien et al., 2019). ProgRESSVet was first offered in 2017 and in 2018 in the Latin American region. ProgRESSVet Uganda and ProgRESSVet Kenya were launched in 2020, incorporating new educational elements based on results of formative and summative education evaluation from the previous Latin America program.

The guided risk assessment and elicitation was one of three activities integrated into the curriculum, which we called Test Drives (Figure 3-1). The Test Drives included participants in the process of data collection and synthesis about questions relevant to their own communities without requiring them to autonomously direct their own analyses. These activities were conceptualized to achieve research objectives during the challenges of covid-19 restrictions and were then recognized as an opportunity to support knowledge application.

Figure 3-1: Research and training activities were carried out within 2 concurrent cohorts of ProgRESSVet: one in Kenya and one in Uganda. Participants completed 5 months of online coursework followed by six months developing proposals to support the trade of animals and animal products. The guided risk assessment was one of three "Test Drive" activities integrated into the curriculum which included participants in the process of data collection and synthesis about questions relevant to their own communities. The Test Drives, including the guided risk assessment, were part of the training program; participants could opt in for their contributions to be used for research purposes. All training and research activities were carried out separately in each country.



Prior to the Test Drives, including the guided risk assessment, participants had completed five months of online coursework (Figure 3-1), including modules on risk analysis applied to animal health, food safety, and international trade. For the next six months, participants would develop proposals to support the trade of animals and animal products. Each portion of the training was structured and delivered by the same team of researchers and faculty. The guided risk assessment was part of the training program; participants could opt in for their contributions to be used for research purposes and 100% of enrolled individuals in each country chose to do so.

The details of the elicitation procedures and results are described elsewhere (not yet published). The approach followed a modified version of the Delphi method, a technique for obtaining the consensus of a group of experts (Okoli and Pawlowski, 2004), and was carried out independently with the participants from Uganda and from Kenya (n=10 and n=13, respectively). First, participants individually worked through a series of open-ended questions in which they described the system, identified important variables and relationships, and critiqued a preliminary scenario tree and risk model structure. Next, also individually, they estimated the distributions for key parameter values. Those responses were synthesized and presented in a group discussion with each cohort in order to reach consensus on the meaning and values of key variables. Each participant received a final report with an accessible summary of the discussion and had the opportunity to comment with any additional suggestions or concerns.

Research process and outcomes

The novelty of this approach was the use of an education program to support the elicitation activity and research objectives. Structured protocols recommend training experts in the elicitation approach and rationale being used (Drescher et al., 2013; Knol et al., 2010). Such training is thought to reduce apprehension, increase understanding of the process, provide motivation, identify biases among the experts, and provide guidelines for working between the facilitators and experts (Hanea et al., 2021). However, practical constraints may preclude the incorporation of training into the research activities.

By embedding the elicitation within an extended educational program, several of these objectives were achieved. After six months of partnership (including adaptations on both sides to continue the program through covid-19 uncertainty), the experts (veterinary participants) and researchers (education team) had a collaborative working relationship with established norms and patterns. The researchers supported the participants in developing proposal ideas, which may have helped to convey the team's interest and investment in the individual and institutional impact to result from the program. The participants in each country knew one another through interactive ProgRESSVet activities, including pre-covid in-person workshops and a program discussion thread on the WhatsApp platform.

The education program also provided subject matter training for the exercise. The participants discussed the importance of the problem (the control challenges and trade repercussions of endemic FMD) throughout the courses. The curriculum included five weeks on risk analysis including probability and scenario trees, and the elicitation activities included supplemental training on these topics. The participants were well-versed in both “the how” and “the why” of the research question.

The ongoing engagement (in contrast to a single day or workshop) enabled an iterative process of elicitation, consultation, and consensus. Participants allocated a suggested 6-10 hours per week to the program and were offered continuous professional development credit. This may have increased their motivation and time available to submit thorough and thoughtful responses. And the platform of a training program supported inclusion of expert participants who were on-the-ground practitioners across a variety of regions and roles in Kenyan and Ugandan livestock systems.

The attributes of the data collected -- elicited, analyzed, and evaluated separately for Kenya and Uganda-- reflects the value of this approach. Responses provided extensive descriptions of cattle health, production, and handling relevant to the research question. Candid discussions reflected participant perspectives of how the animal health system does work, not merely how it should work, including contrasts between distinct settings (e.g., feedlot versus pastoralist). They provided insights about causal relationships based on firsthand experience, including the actions, motivations, and incentives of key actors. Participants took the option of responding “no answer” to some questions and/or focusing on specific production systems, suggesting to the researchers that they did not feel pressured to provide information beyond the extent of their experience.

As a result, valuable parameters were quantified by expert knowledge where there otherwise were no available data, and participant expertise improved the structure and specification of the risk model used to represent the system (Grant et al., 2016). Participants contributed information that otherwise may have been neglected and corrected errors in the researchers’ thinking. For example, they highlighted the need to specify both disease diagnosis and appropriate follow-up action to define infected cattle as detected. They described scenarios in which the sale of cattle for meat may be correlated with the probability of having disease, and consequently an additional set of parameters was included to represent disease prevalence among animals which had been sold (rather than assuming animals chosen for sale would be selected at random). Both of these issues were raised by multiple individuals in each country.

Synergistic character

This coupled approach of training and expert elicitation yielded benefits beyond the research results. We would characterize the elicitation in this context as synergistic learning

(Fink, 2013), complementing and enhancing the educational material rather than “stealing time” away from training. The Test Drives are intended to contribute to ProgRESSVet learning objectives by enabling participants to apply the tools presented to their own work, to have an expanded view of food systems and their roles, and to value the critical use of evidence for decision-making.

Participant responses to the end-of-program evaluation (supplied anonymously) support the perceived value of the Test Drive activities in contributing to these objectives. Several respondents said they had already applied the principles and skills from the Test Drives, including for work related to covid-19, animal disease control strategies, enhanced safety of meat, managing animal health challenges with limited resources, and even for embarking on a family project. Others commented on changes in their perspectives, including how to consider stakeholders affected by an issue, new understanding of regional and international trade, the multidimensional nature of livestock health challenges, finding common ground among partners with diverse perspectives, and sharing knowledge with other members of a One Health district task force. (The program evaluation asked about the suite of three Test Drive activities as a whole, so these responses describe skills and perspective garnered from the guided risk assessment as well as two other applied activities whose outputs were not used for research (Figure 3-1)).

We believe the impact of this approach can transcend that of elicitation or training activities alone to produce benefits for the research and training team, the participants and their community, and the network of both (Figure 3-2). The experience and insights have contributed to the evolving culture of practice and specifically the education and training model at CAHFS: reinforcing and clarifying the ProgRESSVet approach as a collaborative engagement with peers from a diverse set of background experiences, cultures, and knowledge, focused on meeting local needs through building local capacity. The hope and intention is that participants were empowered by generating and synthesizing shared knowledge about the problems and processes studied, building individual and institutional capacity to address specific and unknown future challenges. Finally, the engagement helped create a network of professionals from both the university and Veterinary Services who can continue to work and learn together.

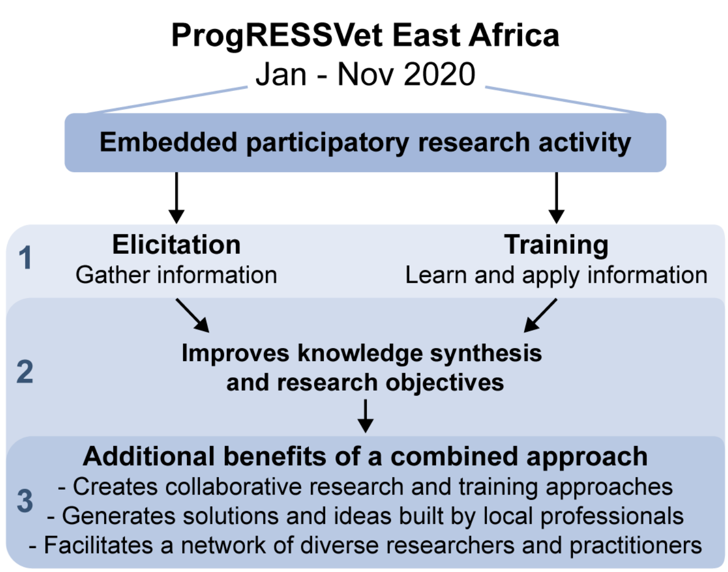
Future offerings of the ProgRESSVet curriculum will maintain the Test Drive approach and the education team will continue reporting related educational modifications and outputs pursuant to a robust understanding of the method’s potential.

Discussion

The coupling of research activities with capacity-building of health professionals has been applied previously (Motta et al., 2019; Ramsay et al., 2014), though we have not seen a model in which the same individuals occupy the role of both trainees and contributors of expert knowledge. The ProgRESSVet and Test Drive approach is unique in that expert elicitation activities are embedded and structurally scaffolded within a broader training program, serving to complement the capacity-building objectives while eliciting and activating the expertise of the participants.

We believe this is a valuable approach with flexibility to adapt to particular settings and constraints. However, it is important to be aware of limitations or potential pitfalls. For example, in our case the experts were all veterinarians and nearly all employed in the public sector. A wider diversity of value chain actors would have provided more perspectives contributing to the research and to the discussion of local issues among participants (M. Burgman et al., 2011). Our structured elicitation and consensus process was heavily facilitated; a constructivist approach with a more open-ended, participant-driven dialogue would favor a different paradigm of research themes and shared learning (Balazs and Morello-Frosch, 2013; Schwandt, 2011).

Figure 3-2: Benefits of combined elicitation and training activity embedded within an education program. *Level 1:* Both objectives (elicitation and education) can be achieved within a single activity. *Level 2:* Each attribute (elicitation and education) of the activity enhances the other, contributing to improved achievement of each. For example, the coupling of the two activities enabled extended opportunities for subject-matter training and a relationship of mutual respect to be the foundation for the elicitation process. The participatory research activities reinforced knowledge synthesis objectives of the educational program. *Level 3:* The synergy between the two concurrent objectives may produce benefits which transcend either independent activity: solutions and ideas built by local professionals, evolving collaborative research and training approaches, and a network of diverse academic and practicing professionals.



The design and implementation of a similar program will require evaluation of the components (the participants, training, and research or elicitation activities) and how they fit together. Practitioners should weigh the value and tradeoffs of possible program designs, considering available resources, existing infrastructure, and their highest priority objectives. The research requiring participant input needs to be carefully aligned with participant expertise and experience. The type and scope of participatory research activity should be guided by the educational approach in order to complement other training elements. The research activity must be realistic given the duration of the training program and the relationships that will be established before launching the elicitation exercises. Time and effort required (of the participants and of the academic team) should be considered, including sequential or iterative steps for the research process.

As with any research method, it is critical to use systematic and robust methods for expert elicitation in order to obtain results that can withstand "close interrogation" and "independent validation", two facets of reproducibility (Begley and Ioannidis, 2015; Bello and Renter, 2018). Rigorous approaches emphasize the inclusion of multiple and diverse experts and the use of a structured protocol for the phases of knowledge elicitation, aggregation, and validation (M. A. Burgman et al., 2011; Drescher et al., 2013); the specific character of those methods may be situation-specific (Drescher and Edwards, 2019; Iglesias et al., 2016). There is much yet to be studied about the nature of expert elicitation approaches that alleviate bias to obtain accurate and well-calibrated results (Hanea et al., 2021).

Research studies that embed expert elicitation into a training program as described here should be designed to produce rigorous results, and may have opportunities to validate those results through repetition over multiple training cohorts. In addition, it may be possible to assess the impact of the coupled approach on the quality of research outputs, furthering the field’s understanding of the practice and methodology of expert elicitation (Hanea et al., 2021). For example, the impact on quantitative parameter estimates could be studied in the future by eliciting the parameterization from each participant before and after the training program. Another area of research could be to assess the relationship between responses and certain features of the participants (e.g., gender, age, years of experience). It may be expected that the training approach results in less variation in the responses, compared to gathering data in the absence of a training program, and may be less biased by external factors.

We have demonstrated the opportunity to gather information from subject matter experts in a way that enhances the research process and outputs while at the same time educating and training participants. In our experience, combining both objectives in a single set of activities served to reinforce each component. The participants, before their formal role as “experts”, were trained in the methods and rationale of risk analysis and had developed a relationship of mutual respect with the academic team members. Conversely, the experience of switching roles and interacting (with the subject matter and with each other) in a new way provided an opportunity for significant learning for the participants, pushing them beyond consumption of information or hypothetical scenarios into a a realm of application to their actual communities and challenges, while able to sit in the seat of expertise to “test drive” research and analytic methodologies without the full expectation of designing and managing a project on their own. This combined approach has the potential to generate benefits for the academic team as well as the participants and their communities that transcend what any individual activity or institution would produce alone.

Funding This project has been supported in part by the Bill & Melinda Gates Foundation (grant number OPP1211169). Under the grant conditions of the Foundation, a Creative Commons Attribution 4.0 Generic License has already been assigned to the Author Accepted Manuscript version that might arise from this submission. Additional support was received from the USDA National Needs (grant 2014-38413-21825) and from the MnDRIVE Global Food Ventures Graduate Student Professional Development award.

Acknowledgments The authors would like to acknowledge and thank the veterinarians who participated in the 2020 cohorts of ProgRESSVet Uganda and ProgRESSVet Kenya for their partnership and contributions to the activities described.

Self-reporting of risk pathways and parameter values for foot and mouth disease in slaughter cattle from alternative production systems by Kenyan and Ugandan veterinarians

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Submitted for publication to Viruses special edition: Global foot and mouth disease control; August 2021

Abstract: Countries in which foot and mouth disease (FMD) is endemic may face bans on the export of FMD-susceptible livestock and products because of the associated risk for transmission of FMD virus. Risk assessment is an essential tool for demonstrating the fitness of one’s goods for the international marketplace and for improving animal health. However, it is difficult to obtain the necessary data for such risk assessments in many countries where FMD is present. This study bridged the gaps of traditional participatory and expert elicitation approaches by partnering with veterinarians from the National Veterinary Services of Kenya (n=13) and Uganda (n=10) enrolled in an extended capacity-building program to systematically collect rich, local knowledge in a format appropriate for formal quantitative analysis. Participants mapped risk pathways and quantified variables that determine the risk of infection among cattle at slaughter originating from each of four beef production systems in each country. Findings highlighted that risk processes differ between management systems, that disease and sale are not always independent events, and that events on the risk pathway are influenced by the actions and motivations of value chain actors. The results provide necessary information for evaluating the risk of FMD among cattle pre-harvest in Kenya and Uganda and provide a framework for similar evaluation in other endemic settings.

1. Introduction

Foot and mouth disease (FMD) is a highly contagious disease of livestock with massive global impact (Knight-Jones et al., 2017; Perry and Rich, 2007). FMD costs billions of dollars annually due to endemic losses and outbreaks (Knight-Jones and Rushton, 2013); control measures such as vaccination, biosecurity, and stamping out when outbreaks occur are also costly (Compston et al., 2021; Perry et al., 2020). Despite global efforts for FMD control (European Commission for the Control of Foot and Mouth Disease, 2018; Rweyemamu et al., 2008), FMD remains endemic in many regions (Brito et al., 2017).

The Agreement on Sanitary and Phytosanitary Standards adopted by World Trade Organization Member States (World Trade Organization, n.d.) specifies that trade restrictions based on health hazards associated with the trade of goods should align with the guidance of international standard setting bodies (the World Organization for Animal Health (OIE) in the case of transboundary animal diseases such as FMD). Actions should be based on the level of risk presented by the trade of goods, as evaluated through objective risk assessment. According to the principle of equivalence countries are to recognize the actions taken by exporting partners according to the reduction in risk achieved rather than requiring a specific set of protocols (though actual practice is often murkier (Adamchick and Perez, 2020)). For this reason, risk assessments are an essential tool for demonstrating the fitness of one's goods for the international marketplace as well as for understanding and improving animal and public health domestically (Adamchick and Perez, 2020; Bastiaensen et al., 2017).

Import risk assessment is typically used to inform risk management from the defensive standpoint of an importing country: how to reduce and mitigate the risk of importing a threatening bug or substance based on the probability and consequence of the event occurring. Countries that want to export are evaluated by potential importers using this approach and criteria. In order to export products that could potentially transmit FMD virus, a country has traditionally been required to demonstrate that FMD is not present in the region where cattle (or other source livestock or wildlife) are produced and processed. This requirement is costly, comes with tradeoffs and externalities, and has not been achievable for most of Africa (Mogotsi et al., 2016; Paton et al., 2009). Recent alternatives, which include disease-free compartments and commodity-based trade, encourage the examination of more nuanced, strategic approaches to the development of production and processing systems for export (Rich and Perry, 2011b; Thomson et al., 2013b). In this context, import risk assessment can be used by the exporting country to evaluate the risk (probability of FMD transmission) experienced by a potential importer under various production and processing scenarios. That analysis could then be used to lobby for access to external markets, or, if unacceptably high, to evaluate the potential value of interventions to reduce risk compared with net benefits from other markets with less stringent entry requirements.

However, in many countries where FMD is present, it is challenging to obtain the necessary data for such assessments, due in part to the small scale and non-standardized value chains that often operate with a mix of formal and informal processes and incomplete documentation of transactions (Grace et al., 2008). In this study, we used a hybrid between participatory and expert elicitation techniques to overcome this gap. This novel approach, in which we partnered with local veterinary professionals to characterize risk pathways and parameter values, captured some of the richness and quality of data collected through participatory methods while maintaining the quantitative rigor required to utilize the data in formal risk assessment models.

There is a history in animal and public health fields of using participatory methods to overcome data scarcity challenges for epidemiological surveillance, research, and outreach (Allepuz et al., 2017; Jost et al., 2007). A participatory approach to risk assessment has been developed and implemented for many studies of food safety in African markets and value chains (Grace et al., 2012, 2008; Oguttu et al., 2014) and more recently to qualitatively assess the risk of disease introduction and spread (Squarzoni-Diaw et al., 2020). Efforts to marry value chain analysis with risk assessment have also attempted to connect participant knowledge of value chain dynamics with the assessment and management of risks related to animal and public health (FAO, 2011; Indrawan et al., 2018; Taylor and Hinrichs, 2012). Participatory approaches promote both efficiency and impact by including populations who are affected by decisions made based on study findings (Grace et al., 2008). Specifically relating to risk assessment, an advantage over conventional approaches is the chance to capture relevant aspects of human behavior as well as technical causal mechanisms contributing to risk pathways and probabilities (Barker et al., 2010). However, a challenge encountered in participatory risk assessments is the need to generate robust evidence of the type that can be used for formal, quantitative risk assessment (Grace et al., 2008).

The elicitation of expert knowledge from subject matter experts is another approach utilized when data are scarce, unrepresentative, or inadequate to describe the process being studied (Hanea et al., 2021; Knol et al., 2010). “Expert” in this usage can refer to a person who can provide information about the question based on their experience with the subject matter of interest (M. Burgman et al., 2011; M. A. Burgman et al., 2011). This approach has been used within veterinary science to estimate parameter values or prioritize risk factors (Beck-Johnson et al., 2019; Brookes and Ward, 2017; Gustafson et al., 2013; McEachran et al., 2020; Muellner et al., 2018; Verdugo et al., 2020). However, when trying to collect information about local systems or informal pathways, a challenge is that those familiar with the subject may not have an academic understanding of the techniques being used. This can impede effective communication and impact the quality of the results if adequate training is not provided (Hanea et al., 2021; Knol et al., 2010).

The hybrid approach employed here relied on partnership with Kenyan and Ugandan mid-career veterinary professionals who were enrolled in a capacity-building course that covered topics including international trade, transboundary diseases, and risk analysis. Their participation and contribution to the research generated credible data about the risk pathways and parameter values that can be used in a quantitative, probabilistic risk assessment to inform decisions about disease management based on local conditions and priorities. The richness of the data collected gave insight into causal relationships that can help inform appropriate model structure (Grant et al., 2016) and risk management strategies, including correlations between events in time and space and the influence of actors’ incentives on events that contribute to risk.

The objective of this study was to characterize the risk pathways for FMD among cattle at the time of slaughter in Kenya and Uganda through partnership with practicing veterinarians. That objective has been achieved through a) describing the risk pathways and events, b) defining the populations of cattle, based on the production system of origin, expected to have distinct FMD risks associated with baseline conditions and processes, and c) specifying parameter values to characterize events that require knowledge of the local sale and inspection processes (i.e., what happens between the farm and the abattoir). These results can be used to perform risk assessments, modeling exercises, and economic analyses regarding the expected value of investments based on empirical understanding of the local system. This framework may be used for similar analyses in other endemic settings, ultimately contributing to analysis and design of targeted interventions for development of risk-based export markets.

2. Materials and Methods

2.1 Risk question

The question to be answered for each of four cattle production systems in two countries was *what is the risk that cattle sold for meat are slaughtered while infected with FMD?* Mapping and quantifying that risk required system-specific knowledge of the events that occur prior to slaughter for cattle originating from local production systems. Expert knowledge was elicited from practicing veterinarians in Kenya and Uganda, separately, to describe the risk pathways, define populations of relevance, and quantify parameter values for key variables related to sale, transportation, and inspection of cattle.

2.2 Participant selection

The subject-matter experts for this study were defined as veterinary professionals living and working in their respective country (Kenya, Uganda) with at least two years of experience related to livestock production, and training in risk assessment for animal health and international trade. Experts were identified and contacted in the context of an online capacity-building course for mid-career Veterinary Service (VS) professionals (progressvet.umn.edu) in which they were trainees (Adamchick et al., 2021a). The procedures for recruitment and selection of participants in the training course differed between Kenya and Uganda. In Kenya, participants were nominated for the course by the national Directorate of Veterinary Services for the country; in Uganda, participants were self-selected with facilitation through Makerere University and the national Ministry of Agriculture, Animal Industry and Fisheries. The training was done in parallel for both countries (i.e., the instructors, materials, and procedures were the same but there was no interaction between participants in Kenya with those in Uganda). At the time of the research study, which was five months into the program, they had completed five weeks of training on risk analysis applied to animal health and food safety. Thirteen Kenyan and ten Ugandan participants were in the program at the time when the study was conducted and comprised the pool of available subject matter experts.

The elicitation activity-- a guided exercise of building and quantifying a risk assessment model based on participant knowledge and experience-- was part of the training program. This facilitated an approach that was a hybrid between traditional participatory and expert elicitation techniques. The participants—already experts on the subject matter of local cattle production and disease management systems—were recently trained as a cohort in topics related to the research question, methodology, and context. The context of the training program facilitated data collection through a prolonged, iterative process of gathering descriptive, qualitative information as well as quantitative parameter values, first at the level of individual responses followed by group discussion. The specific steps of data collection are outlined below. Further discussion of the duality of the training and research activities can be found elsewhere (Adamchick et al., 2021a).

Participants were given the opportunity to opt in for their input during the training exercise to be used for research purposes, with the explanation that their choice would not have any impact on their standing or relationships in the training program. All individuals (n=13 Kenya, n=10 Uganda) chose to do so. The University of Minnesota Institutional Review Board for research involving human participants reviewed the study protocol and determined that it met the criteria for exemption from review.

2.3 Knowledge elicitation and integration

The elicitation activities took place in three stages, referred to as Part A, Part B, and Part C, over a three-week period. All activities were conducted separately for each country. The three stages comprised a variation of the Delphi method (Okoli and Pawlowski, 2004), an iterative process of eliciting individual responses and group discussion to reach consensus. Parts A and B were completed individually, helping to avoid dominance of any one opinion in the information gathered (M. Burgman et al., 2011). Part A was 18 open-ended, short answer questions. In Part B, participants provided quantitative estimates for parameter value distributions, and were asked to only respond for the management systems with which they felt most comfortable. Part C was a group discussion to reach consensus regarding the values of key variables for all management systems; the aggregated values from Part B were provided as a starting point and all participants were encouraged to comment on how they felt those distributions should be altered to best represent the range and distribution of values in each system.

2.3.1 Part A

The instructions, background material, and questionnaire for Part A were distributed in a similar manner as all previous assignments in the training program: via email as well as through an online learning platform (Canvas LMS, Instructure, Salt Lake City, UT, USA). Participants were able to fill out and return the questionnaire through either route. This was completed individually by each participant. The questionnaire consisted of four sections with 18 open-ended, short answer questions (Supplementary Material Document S1) interwoven with educational material related to the process of risk assessment and the role of expert opinion. This context-gathering phase, not often included in expert elicitation protocols, provided insight into correlational and causal relationships between events that otherwise may have been overlooked by the modeling team.

The first section contained seven questions about the sale, transportation, and inspection of cattle sold for slaughter in their country, including two questions that asked about possible correlations between events. In the second section, participants walked through the steps and logic of building a fault tree and event tree for a simple example risk model (the risk of sleeping through one's alarm). They were then presented with preliminary outputs (a fault tree and event tree) of the same process applied to the combination of events that would lead to the outcome of cattle infected with FMD at the time of slaughter. They were asked whether the pathways presented made sense, whether they agreed, and whether they could identify any additional pathways. The preliminary model structure was built by the research team after a review of available literature.

In the third section, participants were asked to consider how the risk could differ among animals originating from distinct production systems. Kenya and Uganda each have diverse cattle production systems including pastoralism, smallholder agropastoralism, and confined extensive and intensive farms. Beef cattle systems in each country have been classified by the FAO through a process that engaged key national stakeholders and synthesized sources of cattle distribution and production data (Gikonyo et al., 2018a; Mubiru et al., 2018). The participants reviewed these classifications for their country, were asked for each of 11 variables whether they believed the value would be the same or different in each system, and were asked if they would recommend a different way of dividing and identifying subpopulations.

The fourth section was four open-ended questions reflecting on the processes that create and mitigate risk and the role of Veterinary Services.

The anonymized individual responses were reviewed separately by three researchers, whose review was guided by the question: Do participant responses support, expand, or contradict the preliminary model structure (variables, relationships, and populations)? After reviewing the responses individually, the researchers discussed in which areas the responses indicated a consistent action to be taken and in which areas there was contradiction or ambiguity in their responses, requiring further clarification in later stages. As a result of that discussion, they had a list of aspects of the model structure to be accepted as is, modifications to the model structure, and additional information to be elicited during parts B and C.

2.3.2 Part B

Part B was a questionnaire intended to elicit quantitative and qualitative information about key parameter values for the risk model (Supplementary Material Document S2). The questionnaire was completed individually using web-based survey software (Qualtrics, Provo, UT, USA) by each participant. Instructions and background information were distributed through email and on Canvas.

The questionnaire opened by presenting the sub-populations (production systems) for the cattle industry in the respective country, and participants were asked to select those for which they had experience and/or felt comfortable giving opinions about FMD risk and the farm-to-market process. For each production system they selected, participants were asked to estimate the minimum, maximum, and most likely value, and explain their reasoning, for 16 variables related to beef cattle production, sale, and inspection processes. They were instructed to reply "no answer" for any question if they did not feel they could provide a useful estimate.

Results were anonymized and aggregated for a selection of variables to be discussed by the whole group in part C. Variables were prioritized based on those which the population of veterinarians were well equipped to answer and for which there was little other information available.

A noteworthy point of the elicitation process is that each participant provided both a point estimate (most likely value) and a distribution of uncertainty around that value (minimum and maximum possible). This is considered a better measure of uncertainty than simply taking the variability among several individuals' point estimates (Hanea et al., 2021). Thus, our sample of 10 or 13 experts in each country yielded that many distinct distributions of the point estimate and uncertainty interval for each variable.

The distributions of each individual (specified as PERT distributions) were then combined into a single mixed distribution, weighting each one equally. This approach is outlined in risk assessment textbooks (Vose, 2000) and has been used elsewhere (Cabezas et al., 2018; Jemberu et al., 2016). In our study, we used that mixed distribution as a starting place for group discussion, so that participants engaged with each others' judgments of the range and most likely values to ultimately reach a consensus on the characteristics of a final appropriate distribution. This aligns with the recommended best practices for expert elicitation: including multiple experts, using a structured protocol for the phases of knowledge elicitation and aggregation, and providing the opportunity to interact and cross-examine reasoning within the group (M. A. Burgman et al., 2011; Hanea et al., 2021).

Answers were excluded from the aggregation if the respondent's rationale indicated that they were estimating something other than what the question was asking. If the distributions and reasoning were similar across the four production systems, then they were merged into a single distribution; otherwise, they were kept distinct for each production system. Some variables were conceptually summarized or manipulated to form a new variable, related but distinct from that which had been asked in the questionnaire, in order to be better formulated for input to a risk assessment model. More specific information about the aggregation approach for each variable is described below.

- Duration in days between sale and slaughter: direct mathematical aggregation for discussion
- Probability of not commingling: The questionnaire asked about the probability of mixing with animals from other herds. The estimates given by each participant were subtracted from 1 to yield the probability of not mixing with animals from other herds. This complementary probability was aggregated into a composite distribution for each production system and presented for discussion in Part C.
- Number of animals mixed with, when commingling does occur: direct mathematical aggregation for discussion
- Number and probability of inspections: The questionnaire asked participants to estimate the number of times an animal would be inspected for FMD and then to describe each inspection and to estimate certain attributes: the percent of animals that would be inspected, the sensitivity of the inspection to detect clinical FMD, and the percent of positive diagnoses that would be ignored or compromised. The number of inspections was summarized as a range of point values to initiate discussion in Part C. The probability of inspection was handled differently in each country based on the flow of conversation in Part C. In Uganda, the discussion about the number of inspections included the proportion of animals for which that number would be zero. In Kenya, the most likely value for the percent of animals who undergo each inspection was used to calculate the complementary portion of animals who do not get each inspection, which was then combined across all inspections reported by an individual to calculate the proportion of animals that would not receive any inspection. These values were

presented to the group in Part C as the starting point for discussion about the probability of bypassing inspection for animals from each production system.

- Effectiveness and type of inspections: For each inspection described by each participant, a distribution for "effectiveness" was calculated by multiplying the minimum, maximum, and most likely values of the sensitivity multiplied by the most likely value of the reporting rate (defined as the complement of the most likely value for the proportion of positive results ignored or compromised). The effectiveness therefore described the percent of animals that would be detected and detained by each inspection. If no answer was given for the proportion of results ignored, the sensitivity was assumed to functionally represent the effectiveness. In each country, the inspections and corresponding effectiveness estimates were categorized into two types that emerged from the comments and descriptions in parts A and B. The effectiveness distributions for all inspections of each type were aggregated as described above into a single composite distribution of effectiveness for each type of inspection in each country. The inspection descriptions were used to quantify how frequently each type occurred at each location (checkpoints, farm, market, slaughter, or unspecified / blended) and what rate of inspections in each production system took place at each location. This was used to compute the relative frequency (weight) of type 1 and type 2 inspections for each production system.

2.3.3 Part C

Part C was a structured group discussion held using a web conferencing system with the participants of each country (conducted separately for Kenya and Uganda). The purpose of the discussion was to reach group consensus on the distribution of values for key parameters for each production system.

For each variable to discuss, the facilitator presented a summary of the related question/s asked in Parts A and B and representative comments pertaining to the interpretation and estimation of the variable. Then the most likely, minimum, and maximum values specified by each respondent along with the density plot and summary statistics of the composite distribution were presented. Participants were asked whether the summary presented was an accurate description of the distribution for a particular management system or for all management systems. If they agreed or disagreed, they were asked to provide their reasoning and, where relevant, to propose how they would modify the distribution presented. There was limited use of the poll function in the web conferencing system to gather participant opinions; most of the discussion occurred as direct conversation among participants and through the chat. To close the discussion of each variable, the facilitator summarized the consensus of the discussion up to that point and asked if there was any further comment. Once all participants expressed agreement or no objection, the discussion moved on to the next variable.

There was one variable presented in Part C for which no information was collected in Part B (included after reviewing the responses to Part A). For this variable, participants were asked to estimate, out of 10 animals infected with FMD, how many would experience each of four distinct outcomes. Participants gave their answers in the chat (Uganda) or in a poll (Kenya) and then discussed with each other the reasons for variation in their responses.

Responses to Part B were unevenly distributed among management systems in each country. Where there were no responses for a certain variable in a certain management system, the group was asked which system they thought it would be most similar to, and then to explain how they would modify the values for that similar system in order to represent the one for which no Part B data had been provided.

The discussion was recorded and distributed via email so that participants who were unable to attend would be able to view it and were encouraged to submit any comments they had regarding the discussion.

2.3.4 Final steps

For the few variables designated as important to quantify by VS opinion but without time to discuss in Part C, the individual descriptions in Part A and B were used to thematically classify the responses into relevant summary variables as described above, and the quantitative estimates were then mathematically aggregated to represent the composite distribution described by all of the responses for each variable.

Following Part C, the modified distribution for each variable (based on group consensus or mathematical aggregation) was summarized as a probability distribution that could be used for input into a probabilistic risk assessment model. Values that were VS opinion of a probability were summarized as PERT distributions. Values that were estimates of a scalar (number of animals, inspections, or days) or test characteristics (inspection effectiveness) were summarized as a common probability distribution with appropriate theoretical characteristics. Where multiple distributions were considered, the one with the lowest AIC was chosen. Distributions were fit using maximum likelihood estimation (package “fitdistrplus” (Delignette-Muller and Dutang, 2015), R software version 4.0.2 (R Core Team, 2020)).

The distributions were presented back to each group for final comment, along with the consensus of the discussion and reasons supporting that consensus. Each distribution was described with accessible summary statistics. The report was distributed to the participants via email, and they were asked to review it and respond via email or in a virtual forum with any questions or comments.

3. Results

In Kenya, there were 12/13 responses to Part A, 13/13 responses to Part B, and 6/13 active participants in Part C. In Uganda, there were 10/10 responses to Part A, 10/10 responses to Part B, and 9/10 active participants in Part C.

The veterinarians in both Kenya and Uganda unanimously confirmed that there was value in evaluating risk separately for distinct cattle production systems. Most respondents (9/10 Uganda, 11/12 Kenya) indicated that the management systems presented were appropriate classifications of beef cattle production systems in their country.

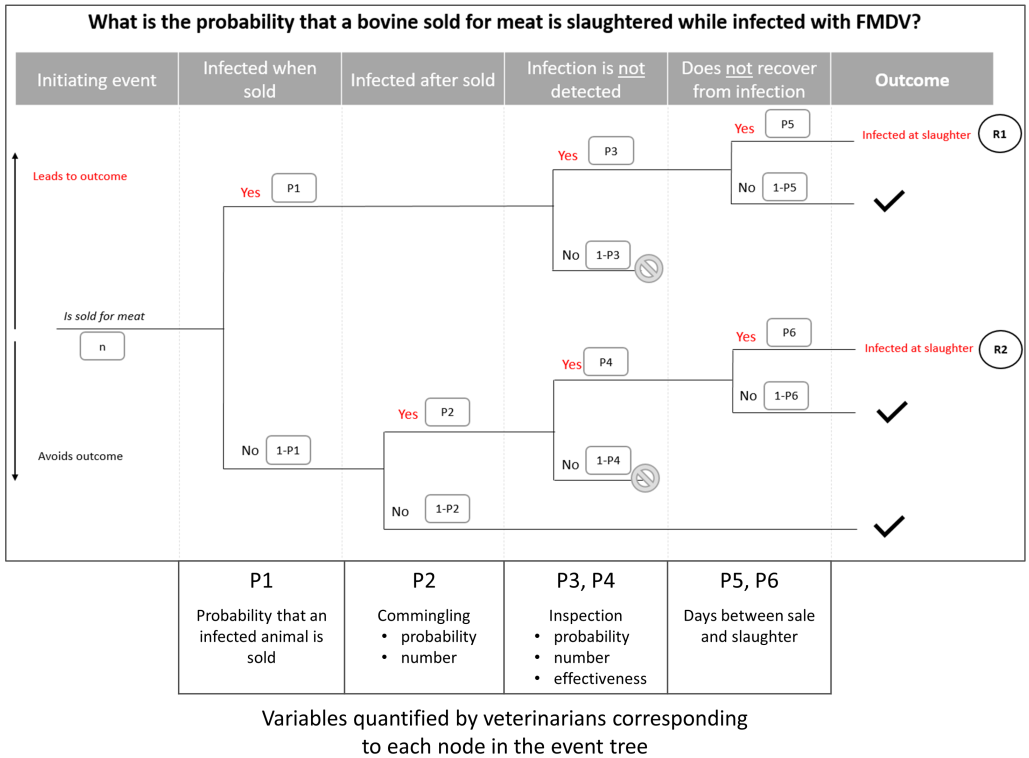
3.1. Pathways

3.1.1. Additional event added to the proposed risk pathways

Most participants (8/10 Uganda, 12/12 Kenya) concurred with the risk pathways presented in the preliminary model of Part A. Two individuals in Uganda and three individuals in Kenya proposed an additional event be included on the pathway to represent the inspector’s decision to appropriately report and act on an FMD-infected animal. “We assume the right action will be taken but that isn’t always the case,” explained one Kenyan response.

Following these responses, the event tree and risk pathways were updated similarly for each country. The event tree (Figure 3-3) was included in the final report back to the participants for review; it includes the steps from the preliminary model that participants supported and the additional step for the probability that appropriate action is taken by inspectors when an infection is suspected. There was no objection from any participant with the formulation of the resulting pathway.

Figure 3-3: Event tree with risk pathways and variables characterized by veterinarians in Kenya and Uganda



3.1.2 Correlations exist between events

Four Ugandan and three Kenyan participants indicated that points exist where an animal with FMD would be more likely to be sold for meat than an FMD-free animal. The Ugandan participants described that farmers at times want to dispose of animals that are sick, that farmers may sell animals when there is an outbreak in the area but quarantine is weakly enforced, and that during an outbreak farmers may want to dispose of affected animals to avoid losses. They also indicated that there may be temporal (seasonal) correlations between disease incidence and sales volume due to factors related to both demand (e.g., festivals) and supply (e.g., need for income at beginning of school year, decreased forage available during dry season). Kenyan responses described circumstances when farmers want to dispose of sick animals and traders to buy animals at a cheaper rate.

In contrast, three Kenyan and two Ugandan individuals indicated that there was no point at which an animal with FMD would be more likely to be sold for meat compared to a healthy animal. Several responses (six in Kenya and four in Uganda) discussed the possibility of selling FMD-infected cattle but did not address the question of correlation or comparison between sick and healthy animals.

3.2 Parameter values

Participants estimated the minimum, maximum, and most likely value of variables for any/all production systems for which they felt comfortable responding. For Uganda, there were the following number of responses for each production system: Semi-intensive- 7; Agropastoral- 6; Ranching- 2; Pastoral- 1. For Kenya, there were the following number of responses for each production system: Pastoral- 10; Agropastoral- 3; Feedlot- 1; Ranching- 0.

Individual responses were aggregated into a composite distribution which was presented and discussed with the cohort to reach consensus on the characteristics of an appropriate distribution for each variable and each production system. The consensus, final parameters, and summary statistics for each are reported in Tables 3-A1 and 3-A2 for Kenya and Uganda, respectively.

3.2.1 Probability that an infected animal is sold while infected

A discussion question was added to Part C following the responses about a possible correlation between the probability that an animal is infected with FMD and the probability that an animal was sold. The group was asked, out of 10 infected animals at random (throughout the year), how many would experience various outcomes including that the animal sold from the farm without reporting infection. In Uganda, the group consensus was that two to four out of every 10 infected animals are sold, for all production systems. The participants reasoned that it is hard for a farmer to report to the authorities that an animal is infected unless discovered by a professional because there is no form of compensation, and that when farmers realize disease is in their region, they tend to sell animals to make sure their farms are empty. In Kenya, the group consensus was that two to three out of every 10 infected animals are sold on average across all production systems.

3.2.2 Duration of time (days) between sale and slaughter

The duration in days between when a cow leaves the herd and slaughter was described qualitatively in Part A, estimated in Part B, and discussed in Part C. The group consensus in Uganda was that the distribution for the duration of the process was similar for all production systems and that sources of variation, primarily the distance between origin and destination, could vary within any of the systems. They specified that this range does not include scenarios in which the purchased animals are held by a trader or butcher for extended lengths of time prior to slaughter. The Kenyan cohort concluded that the duration is different between production systems: pastoral and agropastoral systems had longer maximum durations and a larger variation, with pastoral having the longest most likely value (eight days) due to the distances the animals typically travel to reach the final destination. Feedlot and ranching systems had much shorter described durations, maxing out at two and three days respectively, due to the shorter distance to travel and vertical integration in some systems.

3.2.3 Commingling with animals from other herds: probability, number

Situations in which commingling occurs were described qualitatively in Part A. In Part B, participants estimated the proportion of animals from each management system which do not commingle with animals from other herds before slaughter, and then, for those which are exposed to animals from other herds, the number of animals with which they are mixed. In both countries, it was agreed that the probability of commingling would vary by management system, and the distribution for number of animals mixed with when commingling does occur was the same for all cattle regardless of origin. The Ugandan group discussed that the probability of avoiding commingling was highest for animals from ranching systems (most likely value of 40%), and lowest (0%) for animals from pastoral systems. Participants commented on the general trend that in systems where farms have fewer animals, there would be more mixing on the way to market. In Kenya, individual and group discussions highlighted a distinction in the probability of avoiding commingling between systems that trek cattle to market on foot (identified as pastoral, agropastoral) and those that transport animals on trucks directly to a slaughterhouse premise (feedlot, ranching). This was attributed to the length of the journey, opportunities to congregate with other animals at markets or stops, and the number of animals sold at once from a single herd (e.g., enough to fill a truck with animals from the same origin).

3.2.4 Inspection: probability, number

Participants described inspection points and procedures from farm to slaughter. The Uganda responses highlighted differences in the probability of inspection between systems based on the availability of veterinary services and the motivation of producers to maintain credibility and follow regulations. In the Part C discussion, participants reinforced that it was not uncommon for animals from any system, and especially the three systems other than ranching, to completely bypass inspection before slaughter. They pointed to the current (at the time) movement restrictions in place in one district because of an FMD outbreak and that cattle were, regardless, being moved and slaughtered through unofficial channels. The consensus after some discussion was that the probability that an animal is never inspected (number of inspections = 0) was influenced most heavily by the destination for slaughter: if at designated slaughter points, they will be inspected; those that miss inspection are those going to undesignated slaughter points ("local slabs"). Animals from ranching systems were more likely than those from other systems to go to a designated slaughter facility and therefore had a lower likelihood of receiving 0 inspections.

Five Kenyan participants indicated in Part A that they expected the probability of bypassing inspection completely (i.e., for whom the number of inspections is zero) to be higher among cattle from pastoral or agropastoral systems than those from feedlots and ranches. Individual estimates posited that 1% of animals originating from a feedlot were expected to bypass inspection completely, while up to 20% of agropastoral and 70% of pastoral cattle could potentially reach slaughter without being inspected. They reasoned that pastoral systems include vast areas that are poorly covered by all services including veterinary services, though others pointed out that inspection and permits are mandatory for all animals transported from one point to another. Others commented that buyers are motivated to perform their own inspections and check animals for indications of poor health that may cause losses; they want to "avoid being duped." In the group discussion, the Kenyan cohort concluded that the probability of bypassing inspection differs by management system, with the lowest probabilities for animals from feedlot and ranching systems and a higher frequency and broader distribution of occurrence for animals from agropastoral and pastoral systems. The broad range for pastoral and agropastoral systems included acknowledgment that some of those inspections would be performed by community health workers or other non-veterinarians. The group emphasized that the percent would be very low for cattle sourced from feedlots, since the animals and systems are closely monitored.

3.2.5 Inspection: effectiveness

Participants described potential inspection points and estimated the sensitivity as well as non-reporting rate for each.

Among Ugandan responses, there were 27 inspection points described in total (2 pastoral, 10 agropastoral, 4 ranching, 11 semi-intensive). The inspection descriptions and distributions were similar for all production systems, so they were aggregated into a single distribution of effectiveness. Both the descriptions and the distribution indicated there were multiple "types" of inspection being lumped together. Based on the descriptions, inspections were categorized into two types:

- Rigorous (type 1): qualified and experienced personnel conducting exams, thorough inspection, "clinical signs are very clear";
- Lesser (type 2): Any of the following: personnel less qualified (different incentives/stakes), less experienced, or less thorough (rushed, poor conditions/facilities, etc.), "clinical signs not always distinctive".

There were 15 inspection points classified as type 1. All 15 individual distributions had a most likely value of 0.70 or greater, and the median value for the combined distribution was 0.83. There were 12 inspections classified as type 2. Ten of the twelve had a most likely value of 60 or lower, and the median value for the combined distribution was 0.52.

Kenyan responses described 21 inspection points (2 feedlot, 6 agropastoral, 13 pastoral). Descriptions and reasoning for each inspection delineated two types based on the occasion for inspection and who was performing it.

- Formal (type 1): any inspection performed by veterinary or animal health professionals before movement to the next stage (e.g., a movement permit before transportation or antemortem inspection before slaughter). Results from formal inspections were unlikely, but possible in some instances, to be ignored or falsified;
- Informal (type 2): performed by a trader, owner, butcher, or other middleman before sale takes place. Results from these inspections were more likely to be compromised or ignored in the opinion of some VS members.

There were 16 inspections classified as type 1. Fifty percent of type 1inspections had a most likely value of effectiveness greater than 0.90, and the median value for the combined distribution was 0.71. There were five type 2 inspections, four of which had a most likely value of 0.60 or lower. All inspections for feedlot cattle were described to be formal inspections; this was attributed to ranching systems as well based on the descriptions in Part A.

Discussion

In this study, we partnered with veterinarians in Kenya and Uganda to characterize the pathways and events leading to FMD infection at the time of slaughter among distinct populations of cattle in Kenya and Uganda. We then estimated values for key variables along those pathways from farm to slaughter based on expert knowledge of veterinarians in each country. We found that risk processes differ between management systems, that disease and sale are not always independent events, and that events on the risk pathway are influenced by the actions and motivations of value chain actors including the decision of inspectors to report or to ignore an animal they suspect to be positive for FMD. The findings provide necessary information for evaluating the risk of infection among cattle at the time of slaughter in Kenya and Uganda and provide a framework for similar evaluation in other endemic settings. This knowledge can be used to guide exporter decisions for development of risk-based export markets.

The results describe differences in the risk processes among animals from distinct production systems. In the Kenyan systems, a trend emerged with clear delineation between pastoral/agropastoral and ranching/feedlot systems for several variables including the time from farm to slaughter, the probability of commingling en route, and the probability of bypassing inspection. The clustering of production systems whose characteristics extend beyond the farm gate is supported by other studies of Kenyan value chains (Alarcon et al., 2017; Otieno et al., 2012). The delineation between types of systems for factors contributing to the risk of acquiring a new infection en route to slaughter (in particular the probability of commingling with cattle from other herds) may be a strong indicator of which systems have the capacity to most easily adapt to an approach that involves direct transport and completely eliminates opportunities for exposure to other animals.

The events of FMD infection and sale for slaughter are not always independent for cattle in Kenya and Uganda, due to both causal and correlational factors described by veterinarians in each country. Temporal and spatial patterns in FMD incidence, animal movements, and meat supply and demand have been described elsewhere (Alarcon et al., 2017; Ayebazibwe et al., 2010; Munsey et al., 2019). Three participants (two Kenya, one Uganda) described the beginning of the school year as another time when producers would be more likely to sell cattle because of the need to pay school fees. The seasonal patterns may cause correlations between disease incidence and likelihood of being sold such that the prevalence of FMD infection among animals sold is different than the disease prevalence in a herd or region when expressed as the annual average. Furthermore, responses indicated that the presence of FMD in a region, herd, or individual could impact the probability of sale through various mechanisms. Other sources have reported the practice of informal sales continuing in Uganda even when an FMD quarantine is in place (Mpairwe et al., 2015; Okurut, 2012) and that the implementation of formal control measures such as ring vaccination may not be implemented for weeks after the initial outbreak event (Muleme et al., 2012; Munsey et al., 2019).

If disease and sale are not independent of one another, it may not be appropriate for a risk assessment to assume that animals sold are chosen at random from a herd and therefore the risk of infection for that animal is represented by the average risk of infection for any animal in the herd. This assumption is common in risk assessments performed in the field of animal health and is often appropriate for a particular question and context (Asseged et al., 2012; Marcos and Perez, 2019; Meyer et al., 2017). However, for risk assessments examining the movement or sale of animals in endemic environments (Avila et al., 2018; Makungu and Mwacalimba, 2014; Wongsathapornchai et al., 2008; Woube et al., 2015), our findings suggest it would be judicious to characterize the relationship between sale and disease of cattle in the population of study and to interpret the results of the risk assessment accordingly. While there are many studies on livestock marketing (Baldwin et al., 2008; Onono et al., 2015; Ruhangawebare, 2010) and many on FMD epidemiology (Kibore et al., 2013; Mwiine et al., 2019), this gap highlights the opportunity for further research on the relationships and mechanisms connecting the two. Such insight would contribute to a fuller understanding and more accurate assessment of risk among animals originating from distinct production systems in FMD-endemic areas.

The decisions of value chain actors influence the ultimate risk level in the product. The role of such decisions was highlighted and exemplified by the suggestion, made independently by multiple individuals in each country, to include a variable that accounts for the action taken by the inspector after diagnosing an animal as positive or suspect for FMD. Corruption is a barrier to health care access in many countries (MacKey and Liang, 2012), has been described during regulatory inspection of pharmacies in Uganda (Bagonza et al., 2020), and may be incentivized among livestock producers by quarantine measures and disease control policies that restrict access to markets (Barrett et al., 2003). Actor motivations and incentives to make a decision in a given situation should be considered when building the structure of a model for risk assessment or economic analysis, especially where there may be feedback loops that could qualitatively change the conclusions of an analysis (Adamchick and Perez, 2020; Brisson and Edmunds, 2006; Hoffmann, 2011). Utilizing risk analyses for identifying opportunities and designing effective policies requires understanding and acknowledging the role of motivation and incentives (Wolf, 2017) including how they will change over time and the expected changes in actions taken (Rich and Perry, 2011a; Sterman, 2001).

The approach used here, a partnership with local professionals in a hybrid between participatory and expert elicitation techniques, is a novel contribution to import risk assessments particularly in disease endemic and data scarce settings. Participatory mapping and characterization of the risk pathways and value chains gathered valuable information about the processes and relationships at work, as described above. By utilizing local veterinary expertise to guide the model structure, this approach elicited information to help achieve the purpose of evaluating risk from the perspective of the importer but for the purposes of the exporter -- giving insight into causal relationships to help inform an appropriate model structure (Grant et al., 2016) and risk management strategies (Paté-Cornell and Cox, 2014). Earlier uses of participatory methods for risk assessment have faced the challenges of “coupling” the beliefs of participating stakeholders with technical contributors when they differ (Barker et al., 2010). In this case, since we considered our participants to be subject matter experts, we deferred to their beliefs in the realm of information discussed and in fact the procedures were designed so that participants would update and improve the research team's preliminary drafts and impressions of the systems obtained from generic or external sources. Robust and systematic procedures for training, eliciting, and reviewing participant knowledge helped to minimize bias and generate risk pathways and parameter estimates suitable for use in a formal model. At the same time, it is the hope and intention that the veterinarians and their communities also benefited from their involvement (Adamchick et al., 2021a). As professionals who are invested in improving animal health and livestock systems, their planning and decisions impact the outcome being discussed. It is reasonable to expect that the participatory exercise of mapping and interrogating the system, risk factors, and relationships from many professional viewpoints contributed to an updated understanding of their own role related to FMD and trade (Lie et al., 2017).

The primary limitations of this study are related to the use of expert knowledge as a surrogate for empirical data (Drescher et al., 2013). Rigorous methods must be utilized to obtain accurate and reproducible study results in the face of motivational, behavioral, and cognitive biases (Sutherland and Burgman, 2015). This study included many of the core tenets associated with rigorous protocols (Hanea et al., 2021), including: multiple experts with diverse backgrounds, training of experts with the necessary vocabulary and concepts, following a structured elicitation protocol that privately recorded individual judgments before encouraging discussion among participants, and quantifying uncertainty around parameter estimates (Drescher and Edwards, 2019; Gustafson et al., 2013; Iglesias et al., 2016). One limitation is potential bias of the perspective of expertise by including veterinarians as the only profession represented, though they did come from diverse regional and personal backgrounds.

It may be perceived that the sample size here (number of participants) may be relatively small, compared to the population of field experts. The definition of sample size when consulting experts is subjective and, in many cases, a sample size of even one single expert has been used to parameterize distributions (Collineau et al., 2020); see also the discussion of sample size in (Drescher et al., 2013). Rather than numbers, we focused on giving our population the required training to help them understand what we wanted to estimate, and then relied on their expertise and consensus-building to arrive at the best representation of each value. That said, results should be interpreted in light of the relatively few responses in Part B for the feedlot and ranching systems in Kenya and pastoral systems in Uganda. It is desirable to have several experts contributing knowledge because each tends to be overconfident in their own judgment (i.e., they specify bounds for a parameter that are too narrow), and the aggregation of uncertainty across several experts, as well as interaction and discussion among them, increases the consistency of expert knowledge with reality (M. Burgman et al., 2011; Drescher et al., 2013). Because fewer individuals contributed to the aggregate distribution, there may be less uncertainty expressed for the parameter values than would have been covered with a greater number of contributors with expertise in these systems. Even so, the values of the estimates reported by our participants are generally supported: they are plausible compared to known values, supported by the consensus of the group, and align with trends shown in other literature.

Finally, the risk model structure and parameters were handled and influenced by the primary researcher and discussion facilitator, who is not from East Africa. This researcher built the preliminary model structure and questionnaires based on a literature review, reviewed and aggregated the individual results, facilitated the group discussion, and was involved in all decisions regarding data analysis and interpretation. The participants were invited to review and discuss the conclusions from each stage of the research process, including the report summarizing the process, final risk tree, and parameter distributions. It is possible that misinterpretation (Brugnach et al., 2008; Drescher et al., 2013) could have occurred in both directions during communication between the researcher and the participants and is certain that the lens of the primary researcher has been incorporated into the final risk mapping outputs.

Conclusion

The results of this study fill the gap of identifying risk pathways and quantifying key variables for which published data are not available that are representative of the East African cattle management systems and value chains. This information could be combined with other available data to perform systematic risk assessment to estimate the baseline and relative risk for FMD transmission associated with beef products and to identify key variables for intervention including populations of focus, design of risk mitigation measures, and evaluation of what level of risk is reasonably achievable and at what cost. The novel approach builds on prior participatory and expert elicitation approaches to risk assessment to generate credible data appropriate for use in formal risk assessment models from local veterinary professionals.

Appendix

Table 3-A1: Group consensus and final distribution for each variable for cattle production systems in Kenya.

Variable description	System	Consensus†	Final distribution	Distribution median (5%-95% range)
Probability that cattle infected with FMD are sold for slaughter	Agropastoral Pastoral Ranching Feedlot	0.20 (0.1-0.3)	~PERT ()	0.2 (0.14-0.26)
Days from sale/leaving the herd until slaughter	Agropastoral	3 (0.5 – 30)	~Gamma (1.8, 0.28)	5 (1-15)
	Pastoral	8 (0.5 – 21)	~Gamma (4.5, 0.5)	8 (3-17)
	Ranching	1 (0.5 – 3)	~Gamma (8.5, 6.8)	1.2 (0.6-2)
	Feedlot	1 (0.5 – 2)	~Gamma (15.1, 14.0)	1 (0.7-1.6)
Probability that cattle sold do not commingle with cattle from other herds	Agropastoral	0.1	0.1	NA
	Pastoral	0.05	0.05	NA
	Ranching	0.95	0.95	NA
	Feedlot	0.95	0.95	NA
Number of cattle mixed with when commingling does occur	Agropastoral Pastoral Ranching Feedlot	*Individual estimates: median= 19; 90% range = 3-75*	~Nbinom (1.2, 26.2)	19 (1-75)
Probability that cattle bypass all inspection before slaughter	Agropastoral	0.2 (0.1-0.3)	~PERT ()	0.2 (0.14-0.26)
	Pastoral	0.4 (0.2-0.6)	~PERT ()	0.4 (0.28-0.52)
	Ranching	0.02 (0.01-0.05)	~PERT ()	0.02 (0.01-0.04)
	Feedlot	0.01 (0.01-0.05)	~PERT ()	0.02(0.01-0.03)
Number of inspections when cattle are inspected at least once	Agropastoral Pastoral	1 (1-3)	({1,2,3}, {0.5, 0.33, 0.17})	1 (1-3)
	Ranching Feedlot	2 (1-2)	({1,2}, {0.25, 0.75})	1 (1-2)

Effectiveness for type 1 inspection to detect and report/remove clinically infected cattle	Agropastoral Pastoral Ranching Feedlot	*Individual estimates: median = 0.71 range = 0.15-1.0*	~Beta (1.9, 0.8)	0.75 (0.23-0.99)
Effectiveness for type 2 inspection to detect and report/remove clinically infected cattle	Agropastoral Pastoral Ranching Feedlot	*Individual estimates: median = 0.56; range = 0.05-0.98;*	~Beta (1.6, 1.5)	0.52 (0.12-0.91)
Relative frequency of each type of inspection	Agropastoral	*Calculated from individual estimates*	0.86, 0.14	NA
	Pastoral		0.66, 0.34	NA
	Ranching		1.0, 0	NA
	Feedlot		1.0, 0	NA

† Represents consensus from the group discussion unless otherwise indicated.

Table 3-A2: Group consensus and final distribution for each variable for cattle production systems in Uganda.

Variable description	System	Consensus†	Final distribution	Distribution median (5%-95% range)
Probability that cattle infected with FMD are sold for slaughter	Agropastoral Pastoral Ranching Semi-intensive	0.3 (0.2-0.4)	~PERT ()	0.3 (0.24-0.36)
Days from sale/leaving the herd until slaughter	Agropastoral Pastoral Ranching Semi-intensive	2 (0-7)	~Lognormal (0.84, 0.49)	2.3 (1-5)
Probability that cattle sold do not commingle with cattle from other herds	Agropastoral	0.2 (0-0.5)	~ PERT ()	0.21 (0.07-0.38)
	Pastoral	0 (0-0)	~ PERT ()	0
	Ranching	0.4 (0.3-0.5)	~ PERT ()	0.4 (0.34- 0.46)
	Semi-intensive	0.25 (0-0.7)	~ PERT ()	0.28 (0.08- 0.51)

Number of cattle mixed with when commingling does occur	Agropastoral Pastoral Ranching Semi-intensive	15 (1-50)	~Nbinom (5.0, 18.4)	17 (6-35)
Probability that cattle bypass all inspection before slaughter	Agropastoral	0.4 (0.35-0.45)	~PERT ()	0.4 (0.37-0.43)
	Pastoral	0.5 (0.4-0.6)	~PERT ()	0.5 (0.44, 0.56)
	Ranching	0.3 (0.25-0.35)	~PERT ()	0.3 (0.27-0.33)
	Semi-intensive	0.25 (0.1-0.4)	~PERT ()	0.25 (0.16, 0.34)
Number of inspections when cattle are inspected at least once	Agropastoral Pastoral Ranching Semi-intensive	1(1-3)	({1,2,3}, {0.5, 0.33, 0.17})	1 (1-3)
Effectiveness for type 1 inspection to detect and report/remove clinically infected cattle	Agropastoral Pastoral Ranching Semi-intensive	*Individual estimates: median = 0.83; range = 0.5-1.0*	~Beta (8.9, 1.7)	0.86 (0.63-0.97)
Effectiveness for type 2 inspection to detect and report/remove clinically infected cattle	Agropastoral Pastoral Ranching Semi-intensive	*Individual estimates: median = 0.52; range = 0.2-0.9;*	~Beta (6.6, 5.7)	0.54 (0.31-0.76)
Relative frequency of each type of inspection	Agropastoral	*Calculated from individual estimates*	0.48, 0.52	NA
	Pastoral		0.60, 0.40	NA
	Ranching		0.54, 0.46	NA
	Semi-intensive		0.53, 0.47	NA

† Represents consensus from the group discussion unless otherwise indicated.

Chapter 4 Assessment of the risk of foot and mouth disease among beef cattle at slaughter from East African production systems

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Submitted for publication to Viruses, special issue: Global foot and mouth disease control, August 2021

Abstract: Endemic foot and mouth disease (FMD) in East African cattle systems is one factor that limits access to export markets. The probability of FMD transmission associated with export from such systems have never been quantified and there is a need for data and analyses to guide strategies for livestock exports from regions where FMD remains endemic. The probability of infection among animals at slaughter is an important contributor to the risk of FMD transmission associated with the final beef product. In this study, we built a stochastic model to estimate the probability that beef cattle reach slaughter while infected with FMD virus for four production systems in two East African countries (Kenya and Uganda). Input values were derived from the primary literature and expert opinion. We found that the risk that FMD-infected animals reach slaughter under current conditions is high in both countries (median annual probability ranging from 0.05 among cattle from Kenyan feedlots to 0.62 from Ugandan semi-intensive systems). Cattle originating from feedlot and ranching systems in Kenya had the lowest overall probabilities of the eight systems evaluated. The final probabilities among cattle from all systems were sensitive to the likelihood of acquiring new infections en route to slaughter and especially the probability and extent of commingling with other cattle. These results give insight into factors that could be leveraged by potential interventions to lower the probability of FMD among beef cattle at slaughter. Such interventions should be evaluated considering the cost, logistics, and tradeoffs of each, ultimately guiding resource investment that is grounded in the values and capacity of each country.

1. Introduction

Livestock and animal products comprise a large portion of the economy for East African countries, including Kenya and Uganda. The livestock sector of Kenya contributes 12% of national gross domestic product and employs approximately 10 million people; sixty percent of households in Kenya own livestock (Kenya Markets Trust, 2019). In Uganda, livestock accounts for 4.3% of national GDP, 58% of households own livestock, and 92% of those are subsistence farmers (FAO, 2019a). The vast majority of livestock revenue is from domestic sales with a small fraction sold to neighboring countries through formal and informal channels. If each country were able to expand into international markets and increase the sales volume and margins received for animal-source goods, these countries could improve livelihoods for participants in the agricultural sector and strengthen the infrastructure which supports animal health, production, and food safety. For these reasons, market access can be viewed as a tool toward economic growth as well as improved public health and food security (Bennett and Rich, 2019).

Several challenges hinder the profitable and sustainable supply of East African livestock to premium international markets. One barrier is that countries will not import animal-source goods which could carry diseases that threaten their own animal or public health. Foot and mouth disease (FMD) is a highly contagious disease of cattle and other livestock and wildlife species that has been eradicated from many parts of the world but remains endemic in much of Africa and Asia (Brito et al., 2017; Knight-Jones et al., 2017). There is a tremendous economic cost associated with outbreaks of FMD in naïve populations of agricultural animals (cost estimates for past outbreaks range from 0.5 – 10 billion US dollars) because of impacts on animal health and productivity, costs to control the disease, and knock-on repercussions for the affected country's participation in international trade (Knight-Jones and Rushton, 2013).

In regions where FMD remains endemic, local conditions make it very difficult to eliminate. Many countries lack robust veterinary infrastructure and institutions (Knight-Jones et al., 2016b; Maree et al., 2014; McLachlan et al., 2019); systemic issues are compounded by the difficulties of animal surveillance and vaccination in remote areas (Belsham, 2020). The challenges described as most significant to the control of FMD in Africa in 2016 (Tekleghiorghis et al., 2016) are largely unchanged from those identified in 1982 (Compston et al., 2021). In contrast to South America, where FMD control efforts have been largely successful and vaccine coverage is roughly 146% (i.e., all cattle are vaccinated more than once a year on average), it is estimated that only 5.5% of African cattle are vaccinated annually (Knight-Jones and Rushton, 2013).

Kenya and Uganda have both tried unsuccessfully to establish disease-free zones in which FMD and other transboundary diseases of livestock would be controlled, monitored, and eventually eliminated for the sake of enabling international exports. The areas designated by Uganda as Disease Control Zones in 2011 (Chrisostom et al., 2013; Rich et al., 2012) are still the foci of beef development projects, but have since pivoted to emphasize production efficiency, environmental sustainability, and value addition rather than achieving freedom from disease (Uganda Ministry of Agriculture Animal Industries and Fisheries (MAAIF), n.d.). In Kenya's

Vision2030 (Republic of Kenya, 2013), one of the goals for economic development through agriculture was to establish four disease-free zones for export, hoping to expand disease freedom to include a large swath of the country by 2022. To date, some progress has been made toward individual export zones which would function more as quarantine stations than disease-free regions (Mamo, 2019), though construction on the most advanced was called off in June 2020 due to apparent lack of progress by the contractor (Kenya News Agency, 2020).

OIE standards, which underpin transactions between World Trade Organization Member Countries related to animal health (World Trade Organization, n.d.), provide strategies for trade from regions infected with FMD. Options include establishing disease-free compartments, processing goods such that the virus would be destroyed, or demonstrating that the risk of transmission via the product to be traded is reduced to an acceptable level (according to international standards and/or the requirements of the importing country) (World Organization for Animal Health (OIE), 2019). In the latter case, known as commodity-based trade, established protocols for commodity-based trade recognized by OIE countries in practice have not yet been established. The risk of transmission associated with the final product is influenced by the geographic presence of FMD in the region but is also impacted by actions pre- and post-harvest to detect, eliminate, and prevent contamination with FMD virus, together with a well-documented and traceable process (Paton et al., 2010). Scientific risk assessment of the threat posed by a product is the method recognized by the OIE to justify protective trade measures by importing countries (Adamchick and Perez, 2020). Risk assessments are an essential tool for demonstrating the fitness of one's goods for the international marketplace as well as for understanding and improving animal and public health domestically (Bastiaensen et al., 2017).

There is little information available to complete a risk assessment for beef produced from East African cattle systems. The risk reduction achieved by post-harvest steps of inspection, processing, and storage of deboned beef according to OIE specifications has been extensively reviewed and assessed (Paton et al., 2010). Their analysis, starting from the assumption that 100% of animals arriving to the facility were infected with FMD, was that the risk of FMD transmission associated with the movement of beef produced under such conditions was low but not negligible. However, it is also true that the FMD risk for animals arriving at slaughter is likely (1) less than 100%, even in endemic settings, (2) varies across regions and production systems, and (3) may be mitigated by certain measures. A first objective of exporting markets may be to sufficiently decrease the risk at slaughter, so that deboning and processing would result in negligible levels of risk. For that reason, in order to achieve and demonstrate a level of risk acceptable to many trade partners, it is necessary to extend that post-harvest risk assessment

(Paton et al., 2010) to consider the risk of infection among animals arriving at slaughter from local systems. The relative risk of FMD infection among livestock exported from Somalia has been modeled for several scenarios to compare the impact of risk reduction strategies (Knight-Jones et al., 2014b). They found that cattle held in 21-day quarantine at the point of export and inspected daily had 4% of the risk of being exported while infected with FMD compared to cattle exported with no control measures implemented.

Although previous studies have assessed the epidemiology (Casey-Bryars et al., 2018; Kibore et al., 2013; Mwiine et al., 2019), risk factors (Ayebazibwe et al., 2010; Munsey et al., 2019; Nthiwa et al., 2020), and challenges of FMD control (Compston et al., 2021; Maree et al., 2014; Tekleghiorghis et al., 2016) in Kenya and Uganda, the risks for FMD in cattle and deboned beef originating from both countries have not been quantified. Infection risk among animals at slaughter is dependent on the events that occur between the farm and abattoir in addition to the herd-level disease risk (Paton et al., 2010), especially considering the important risk presented by animals in the early incubation phase of disease (Sutmoller, 2001). Kenya and Uganda each have several beef cattle production systems (Cecchi et al., 2010; Gikonyo et al., 2018a; Mubiru et al., 2018) and complex ruminant value chains (Alarcon et al., 2017). In order to complete a risk assessment that can usefully guide each country toward steps to reduce risk, it is important to include information about the distinct risk factors associated with the production, sale, and transport of beef cattle from each management system.

Risk is a concept that incorporates both the probability of occurrence of an event and the magnitude of the consequence if the event does occur. In this publication, the terms risk and probability are used interchangeably unless otherwise specified, always referring to the probability that a given event takes place without evaluation of consequence. A complete import risk analysis, from the importer perspective, would consider the magnitude of the consequences if the event occurs in order to guide decisions. Exporters consider what it would take (what measures and at what cost) to appease potential importers, and, given those concessions or investments, if the product would be competitive in that market, profitable for local producers, and a worthwhile pursuit for public and private resources.

The objective of this study was to estimate the probability of FMD among cattle at the time of slaughter originating from eight total production systems in Kenya and Uganda. Results showed a wide gap in Kenya between systems at high (pastoral, semi-intensive) and low (feedlot, ranching) risk. By contrast, in Uganda, all systems had similar values for total probability despite differences in individual inputs and nodes. Model results indicate that this probability could be reduced by varying degrees in all systems by eliminating or even reducing commingling with other cattle between sale and slaughter. The next step in contextualizing these results is to consider specific interventions that may reduce that probability to a level acceptable to trading partners and the cost, logistics, and tradeoffs of each. The potential costs and benefits of pursuing those interventions to participate in international trade can then be weighed in light of the opportunities and capacity of each country.

2. Materials and Methods

2.1 Model overview

2.1.1 Setting and production systems

Beef cattle production systems in Kenya and Uganda have been classified by the FAO through a process that engaged key national stakeholders and synthesized sources of cattle distribution and production data (Gikonyo et al., 2018a; Mubiru et al., 2018). These classifications were reviewed by Veterinary Services members for their country and evaluated as appropriate to use for classifying risk assessment inputs and assessing results (Adamchick et al., 2021b). The four production systems in Kenya are: feedlot (1% of beef cattle), pastoral (34%), ranching (11%), and semi-intensive / agropastoral (54%). The four production systems in Uganda are: agropastoral (49%), pastoral (41%), ranching (8%), and semi-intensive (2%).

2.1.2 Risk question and model formulation

A quantitative and stochastic risk model was developed to estimate the baseline risk of the slaughter of FMD-infected cattle from distinct production systems in Uganda and Kenya. The question to be answered for each of four cattle production systems in two countries was: What is the probability that cattle sold for meat are slaughtered while infected with FMD virus? Specifically, the outputs of interest for the model were:

- the probability for any cattle sold for meat to be slaughtered while infected;
- the annual probability that at least one infected bovine is slaughtered.

The major events and pathways resulting in the possible slaughter of an FMD-infected animal are depicted in Figure 4-1. The inputs and probabilities are described in the following section and summarized in Table 4-A1. The input variables and relationships described were used to construct a stochastic risk assessment model. The model structure was the same for each production system and country; distinctions were represented through differences in input variable distributions.

Two pathways were identified through which the event of slaughtering an FMD-infected animal may occur—in which the animal is infected in the herd of origin (already infected at the time of sale) or through contact with infected animals between the farm and slaughter. The probability that a single animal sold is slaughtered while infected with FMD virus through each of the respective pathways is given by:

R1: Infected on farm before sale, not detected and does not recover: *P1 * P3 * P5*

R2: Infected after sale, not detected and does not recover: *(1-P1) * P2 * P4 * P6*

Where *Pi* is the conditional probability associated with step *i*.

The probability that cattle sold for meat are slaughtered while infected with FMDV (*Ptot*) via either pathway is the sum of *R1* and *R2*:

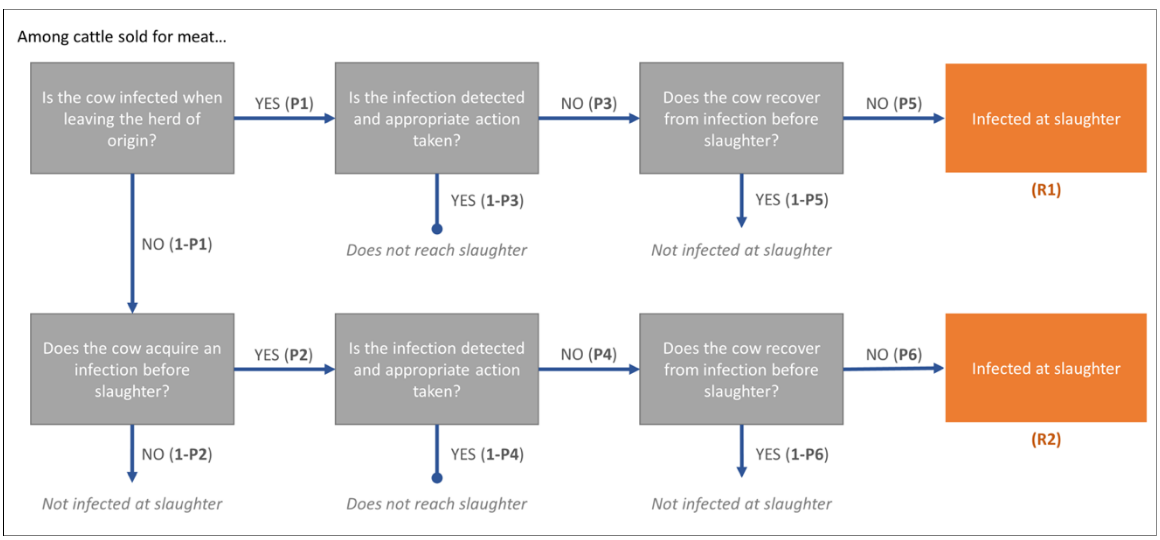
Ptot = R1 + R2

The probability that at least 1 bovine sold for meat reaches slaughter while infected can be calculated as a binomial process:

$$Pany = 1 - (1 - Ptot)^{N}$$

Where *Pany* represents the probability of at least 1 event occurring.

Figure 4-1: Risk pathways for the probability of FMD infection at slaughter among cattle sold for meat in Kenya and Uganda. *R1* represents cattle infected at the time of leaving the source herd. *R2* represents cattle that acquire new infections between the herd and the time of slaughter. The total probability, *Ptot*, is the sum of *R1* + *R2*.



2.2 Evidence gathering and parameter estimation

The populations and key processes, variables, and relationships were identified in partnership with mid-career veterinarians in Kenya and Uganda. The elicitation process and outputs have been described elsewhere (Adamchick et al., 2021b, 2021a). A probability distribution for each input variable for each population was described using information available through scientific literature, country reports, and the opinion of professional veterinarians in each country.

2.2.1 Are cattle infected when leaving the herd of origin? (P1)

The prevalence of FMD among cattle sold from each management system was calculated as the annual probability of infection per head times the probability that an infected animal would be sold divided by the probability that any animal (infected or uninfected) would be sold. This formulation was used because VS members indicated that the probability of infection among animals sold should not be assumed to be the same as the probability of an animal chosen at random from the source population, and so prevalence in the population is not an appropriate proxy for prevalence among cattle sold.

Because all values used the same denominator (total population times 365 days/year), the calculation was simplified to:

$P1 = C * Si / S,$

where C is the number of infections in the population per year, Si is the probability that an infected animal is sold while infected, and S is the number of sales from the population per year.

The annual number of FMD infections in each management system (C) was estimated from cross-sectional seroprevalence data collected in each country as well as the mean age and total population of cattle in each system.

Distributions of annual incidence in Uganda were based on data reported elsewhere (Munsey et al., 2019; Mwiine et al., 2019). A total of 14,439 cattle from 211 herds were tested for antibodies to non-structural FMDV proteins using a PrioCHECK ELISA test kit (Thermo Fisher Scientific, USA). The data used for this analysis was limited to animals chosen as part of random sampling (not purposively targeted) and with age at time of sampling between 6 months and 3 years of age (n = 3468 individuals from 111 herds). The mean and standard error for the proportion of positive animals, accounting for clustering within herd and regional-level sampling weights (Dohoo et al., 2009), were used to construct a beta distribution of the prevalence of antibodies against FMD virus (Pr) within each of the four production systems in Uganda. Because a positive ELISA result represents at least one seroconversion event within the animal's lifetime, the prevalence was divided by the mean age of the respective population (A) to reach an estimate of the incidence of new infections per year in each production system. The distribution of mean age for each management system was built by bootstrapping from the ages of cattle sampled within each system, sampling with replacement at the herd level and calculating the mean age of each bootstrapped sample.

Two alternative approaches to estimating the incidence of FMD in Uganda were evaluated for impact on the overall risk. In the default scenario, described above, all cattle with positive ELISA results for NSP antibodies were classified as having experienced an FMD infection. In the first alternate approach, cattle that were positive for antibodies and had a record of vaccination within six months of the date of testing were classified as FMD negative (evaluating the possibility that such animals had a vaccine-induced antibody response). All subsequent steps for estimating *P1* using these data were the same as described above. In the second alternate approach, virus isolation (VI) results from probang (oropharyngeal) samples taken on a subset of the cattle surveyed were used instead of ELISA testing. This dataset, limited to cattle of any age from randomly chosen herds, contained 488 cattle from 29 herds from only the Eastern and Northern regions of Uganda (region classification and more information on sample collection and processing available elsewhere (Mwiine et al., 2019)). The mean and standard error for the proportion of VI-positive animals, accounting for clustering within herd and regional-level sampling weights, were used to construct a beta distribution of the prevalence of virus in probang samples from each production system (semi-intensive and ranching systems were combined into one due to limited data). The annual incidence was calculated as the prevalence divided by the average duration of infection in days times 365 days per year. The average duration of infection was specified as a function of the probability that an infection was acute or persistent and the associated duration of an acute infection (*D*) or persistent infection (Pert distribution with minimum of six months, maximum of 24 months, and most likely value of 13 months (Bertram et al., 2020; Hayer et al., 2018a, 2018b)).

Distributions of annual incidence in Kenya were based on data reported elsewhere (Kibore, 2013; Kibore et al., 2013). Serum samples from 2908 cattle in 39 counties in Kenya were ELISA-tested for antibodies to non-structural FMD virus proteins. The management system was not recorded, so prevalence for pastoral, semi-intensive, and ranching production systems was estimated by restricting analysis to counties with at least 80% of cattle in pastoral systems (n=10 counties), at least 80% of cattle in semi-intensive systems (n=14 counties), and at least 50% of cattle in commercial ranching systems (n=2 counties). Given the low sample size, an alternative parameterization was evaluated with a range between 0 and 1 and most likely value 0.47 (the mean of the prevalence in those two counties); there was no notable impact on the model output so the default parameterization was retained. Because feedlot operations make up a small portion of total beef cattle and operations, the prevalence was given a range between 0 and 1 and results from a survey of 31 feedlots in Ethiopia (Alemayehu et al., 2014) used to define the most likely value. The mean and standard error for the proportion of positive animals, accounting for sampling weights and stratification by county, were used to construct a beta distribution of the prevalence of antibodies against FMD virus (*Pr*) within each of the four production systems in Kenya, which was divided by the mean age of the respective population (*A*) to estimate the incidence of new infections per year. The distributions of mean age were based on the reported age of animals sampled (Kibore, 2013) in counties with predominantly pastoral or semi-intensive animals and on reports relevant to ranching, pastoral, and feedlot systems (Alemayehu et al., 2014; Mwangi et al., 2020).

The cattle population for each production system was calculated as the percent of cattle in each system (*Mg*) reported by the FAO classifications described above (Gikonyo et al., 2018a; Mubiru et al., 2018) times the national beef cattle population (*Np*). The national population in Kenya was estimated from descriptions ranging from 14.1 million to 16 million cattle raised for meat (FAO, 2019c; Gikonyo et al., 2018a; Mamo, 2019). The national population in Uganda was estimated from descriptions that ranged from 12.1 million to 15.9 million head (FAO, 2019c; Uganda Bureau of Statistics, 2018, 2020).

The probability of sale among infected animals (*Si*) was estimated by the VS participants as described elsewhere.

The number of cattle sold per year from each system (*S*) was calculated as the offtake rate times the cattle population. Estimates for annual offtake rate (*O*) within each production system were based on ranges reported by studies in Uganda, Kenya and Ethiopia (Behnke and Muthami, 2011; Mwangi et al., 2020; Nyariki and Amwata, 2019; Ruhangawebare, 2010; Teklebrhan and Urge, 2013). Feedlots were estimated to have one to four cycles of fattening per year with complete turnover of their population for each cycle, i.e., an offtake rate ranging from 100-400%. In Kenya, these estimates in each population amount to a mean national offtake rate of 17.2% per year, in alignment with the range of 15-20% calculated using FAOSTAT estimates. In Uganda, they add up to a mean national rate of 11.5%, compared to an estimated 12% reported in 1998 (Mbabazi and Ahmed, 2012).

2.2.2 Do cattle acquire a new infection before slaughter? (P2)

The probability of acquiring a new infection en route to slaughter was calculated based on the probability of mixing with cattle from other herds (*1-Pn*) and subsequent effective contact with an infectious animal (*Ic*):

$P2 = (1 - Pn) * Ic.$

The probability of commingling was estimated through discussion with VS participants, in which they estimated the proportion of animals from each management system which do not commingle with cattle from any other herds before slaughter (*Pn*).

The probability of effective contact (*Ic*) was formulated as a binomial process. Commingling was assumed to result in effective transmission if the animal mixed with was infectious with FMD virus. Therefore, the probability of at least one infectious contact among cattle that mix with other animals was defined as:

$Ic = 1 - (1 - Pa * Pi)^{Nm},$

where *Pa* was the overall prevalence of FMD among animals sold (all management systems combined), *Pi* the probability that an infected animal is infectious, and *Nm* the number of cattle mixed with when commingling occurs.

The probability that an infected animal is infectious (*Pi*) was based on the ratio of the latent (preinfectious) period (*L*) to the total duration of an acute infection (*D*). Distributions for the phase durations for the latent, incubation, and infectious periods of an acute FMD infection were each constructed by sampling from ten equally-weighted distributions: two from meta-analyses of experimental studies (Mardones et al., 2010; Yadav et al., 2019) and eight from a single study with distributions constructed from the input of 11-15 experts for scenarios combining high or low virulence, high or low virus dose, and airborne or direct contact transmission (Cabezas et al., 2018).

We assumed that all animals who are not infected upon leaving the herd are susceptible to new infections.

2.2.3 Is the infection detected and appropriate action taken, among cattle infected on the herd of origin? (P3)

P3 is the probability that cattle infected with FMD at the time they leave their herd of origin are not effectively detected and acted upon. Effective detection and action requires that cattle are inspected (*In*), are displaying clinical signs at the time of inspection (*Cl*), and that the inspection identifies and reports the clinical inspection (*De*). Therefore, *P3* was defined as:

$P3 = 1 - In * Cl * De.$

The probability that cattle are inspected at least once (*In*) was defined as one minus the probability that cattle completely bypass inspection as estimated by the VS participants of each country.

The probability of displaying clinical signs at the time of inspection (*Cl*) was equal to the probability of being in a clinical phase of infection on a random day between sale and slaughter: defined as the ratio of the days of clinical infection remaining after the animal is sold from the herd to the duration of the whole process from herd to slaughter (*Dp*). Any values greater than one or less than zero were set to one and zero, respectively. Conceptually, there were three categories of values: cattle in which clinical signs start before the time of sale (*Cl* is equal to one); cattle in which clinical signs don't begin until after the herd-slaughter process is over (*Cl* is equal to zero); and cattle in which clinical signs develop sometime during the process (*Cl* is between zero and one).

The probability that an inspected, clinically-infected animal is effectively detected and reported (*De*) was specified as a binomial process based on the effectiveness of each inspection and the number of inspections received. The effectiveness of inspection was defined by VS responses and discussion as described (Adamchick et al., 2021b). Briefly, it was based on the sensitivity of inspection, the reporting rate of positive animals, and the ratio of two different levels of inspection quality (*W1, W2*). The number of inspections (*Ni*) was also described by VS participants.

2.2.4 Is the infection detected and appropriate action taken, among cattle that acquire new infections en route? (P4)

P4 is similar to *P3*, with a different value for the probability that an infected animal is displaying clinical signs at the time of inspection (*Cn*). *Cn* was defined as the ratio of days during which newly infected cattle are in a clinical phase of infection compared to the duration of the whole process from herd to slaughter (*Dp*). It was assumed that a new infection could be acquired with equal probability on any day during the process. *Cn* was adjusted to be bounded at zero and one as described for *Cl*.

$$P4 = 1 - In * Cn * De.$$

2.2.5 Do cattle infected on the herd of origin recover from infection before slaughter? (P5)

Cattle infected on-farm were assumed to recover before slaughter if they had acute infections and the duration of infection remaining when leaving the herd was less than the duration of the herd-to-slaughter process:

$P5 = 1 - Pa * Re,$

where Pa is the probability that an infection is acute and Re the probability of recovery from an acute infection.

The probability that an infection persisted beyond the acute stage was described with parameters from the literature. A review of the carrier state for FMD (Stenfeldt and Arzt, 2020) described from 20% to over 50% of cattle likely to be carriers. In a short communication of animals slaughtered in Uganda (Balinda et al., 2010), nine out of 12 animals slaughtered had viral RNA in the oropharyngeal tissue at slaughter three months after the lifting of quarantine measures. Therefore, the probability of acute infection was described as the complement of a PERT distribution with a minimum of 0.2, maximum of 0.75, and most likely value of 0.5.

The recovery from an acute infection (*Re*) was specified as a Poisson process. The rate (*Rr*) was defined as the reciprocal of (one over) the duration of infection (*D*) and the exposure time (*Ro*) defined as the sum of the process duration (*Dp*) and the days of infection prior to the day of sale (*Ts*). Therefore, the probability of not recovering before slaughter among cattle with acute infections was defined as the probability that the event does not occur during that period of time, *exp(-Rr*Ro).*

2.2.6 Do cattle infected en route recover from infection before slaughter? (P6)

P6 is similar to *P5*, with the exception that the exposure time for recovery (*On*) was defined as the difference between the duration of the herd-to-slaughter process (*Dp*) and the day of that process on which infection occurred (*Tn*).

$P6 = 1 - Pa * Rn.$

2.2.7 Number of cattle exported annually (N)

The number of cattle that would be exported annually was hypothetically assigned to be 20% of the total current production (*S*) from a given management system.

Quantities *P1-P6* and *N* were combined to simulate distributions for *R1, R2, Ptot*, and *Pany* for each of the four management systems for Kenya and Uganda.

2.3 Sensitivity analysis

Sensitivity analysis was performed to identify the most influential nodes and input parameters and evaluate the impact of their uncertainty on the overall risk estimate, *Ptot*, within each production system. Each node value was divided into percentiles (1, 5, 25, 50, 75, 95, 99) and the conditional mean value of *Ptot* was calculated when the node was held fixed within each percentile interval while all others varied randomly (similar to the Change in Output Mean function of @Risk (Palisade Corporation, Ithaca, NY, USA)). For production systems with a median total risk less than 0.5, the input variables were also plotted and examined similarly.

2.4 Model environment

All Monte Carlo simulations were performed using RStudio (RStudio Team, 2020) and R software version 4.0.2 (R Core Team, 2020) to estimate the outcome distributions by computing 30,000 iterations of each model. Stata (version 16, College Station, TX, USA) was used to calculate the mean and standard error of the prevalence estimate in each management system while accounting for clustering, stratification, and sampling weights (Dohoo et al., 2009).

3. Results

3.1 Total probability

The probabilities of FMD infection at slaughter, estimated for cattle from eight total production systems in Kenya and in Uganda are reported in Table A2. Plots of the cumulative distribution function and probability density function for overall probability (*Ptot*) are shown in Figures 4-2 and 4-3.

Figure 4-2: Total risk, Kenya. The cumulative distribution functions (left) and probability density functions (right) for the probability of cattle sold for meat arriving at slaughter while infected with FMD from each of four production systems in Kenya. The vertical gray line represents the median value. Distributions are based on 30,000 iterations of the stochastic model. Ptot is the sum of R1 and R2 depicted in Figure 4-1.

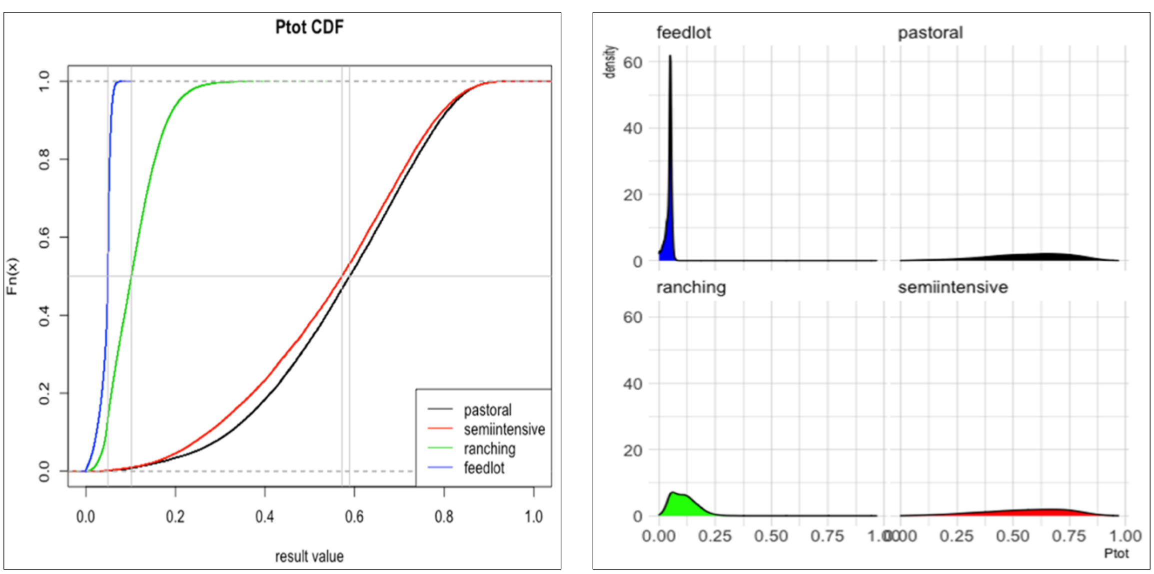
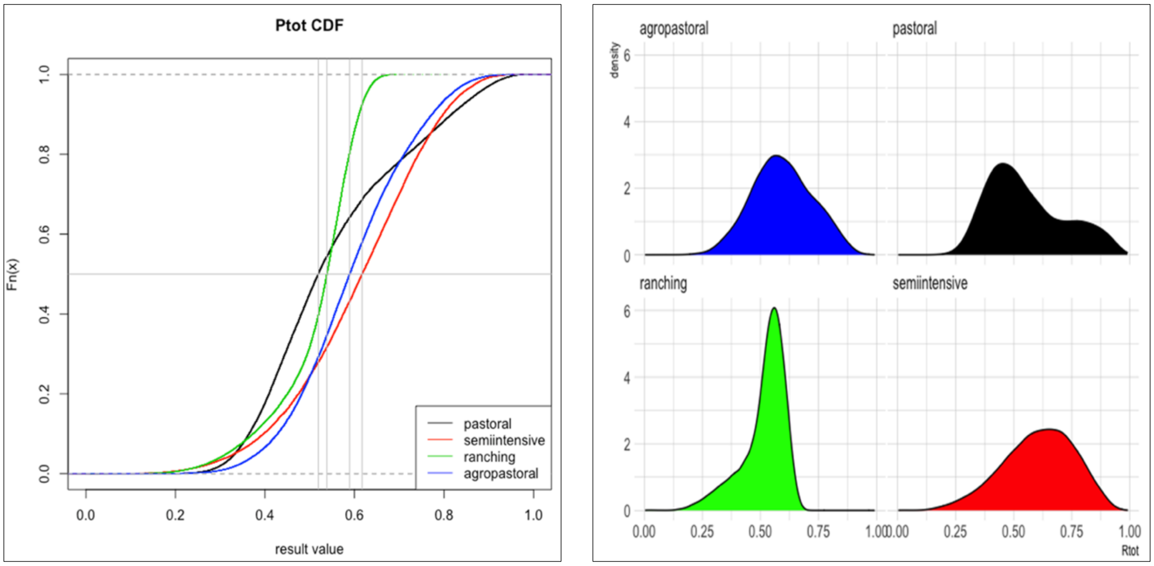


Figure 4-3: Total risk, Uganda. The cumulative distribution functions (a) and probability density functions (b) for the probability of cattle sold for meat arriving at slaughter while infected with FMD from each of four production systems in Uganda. The vertical gray line represents the median value. Distributions are based on 30,000 iterations of the stochastic model. *Ptot* is the sum of *R1* and *R2* depicted in Figure 4-1.



In Uganda, the overall probability that cattle arrive at slaughter while infected was similar across all four production systems (despite substantial variation between systems in the values for the pathways of being sold while infected, *R1*, and acquiring a new infection en route to sale, *R2*). Ranching had the lowest mean *Ptot* at 0.52 (95% interval: .27-.64), followed by pastoral with mean 0.55 (.31-.91). The mean probability (95% interval) for agropastoral and semi-intensive systems was 0.59 (.35-.85) and 0.61 (.28-.87), respectively.

In Kenya, there was a sharp demarcation between two groups of systems (in contrast to Uganda). Those with lower *R1* also had lower *R2* values, so the sum of those, *Ptot*, compounded the gap. Feedlots (mean 0.04, 95% interval 0.01-0.06) and ranching systems (mean 0.11, 95% interval 0.03-0.23) had a relatively low overall risk. Pastoral and semi-intensive systems had high *Ptot* values, with mean values of 0.57 (0.17-0.85) and 0.55 (0.16-0.85), respectively.

The probability of at least one infected animal slaughtered per year (*Pany*) had a 95% interval spanning from 1 to 1 for each of the systems evaluated, given the estimated exports volume of 20% of total sales from a given system. In other words, there is 95% confidence of the occurrence of at least one infected animal at slaughter in a given year under current conditions from each of the production systems modeled.

3.2 Influential variables and nodes

The analysis highlighted two groups of production systems according to which pathway contributed most to the overall risk. Most management systems (Kenya: pastoral, ranching, semi-intensive; Uganda: agropastoral, ranching, semi-intensive) were *R2*-dominant: the expected value of the *R2* pathway was higher than *R1*, and correspondingly the value for the node *P2* (probability of acquiring a new infection en route) was greater than P1 (probability of being infected at the time of sale). In other words, the greatest contribution to the total risk of infection at the time of slaughter was through new infections acquired between sale and slaughter. The other two systems – ranching in Kenya, and pastoral in Uganda – had a higher value for *R1* than for *R2* (and for *P1* than for *P2*).

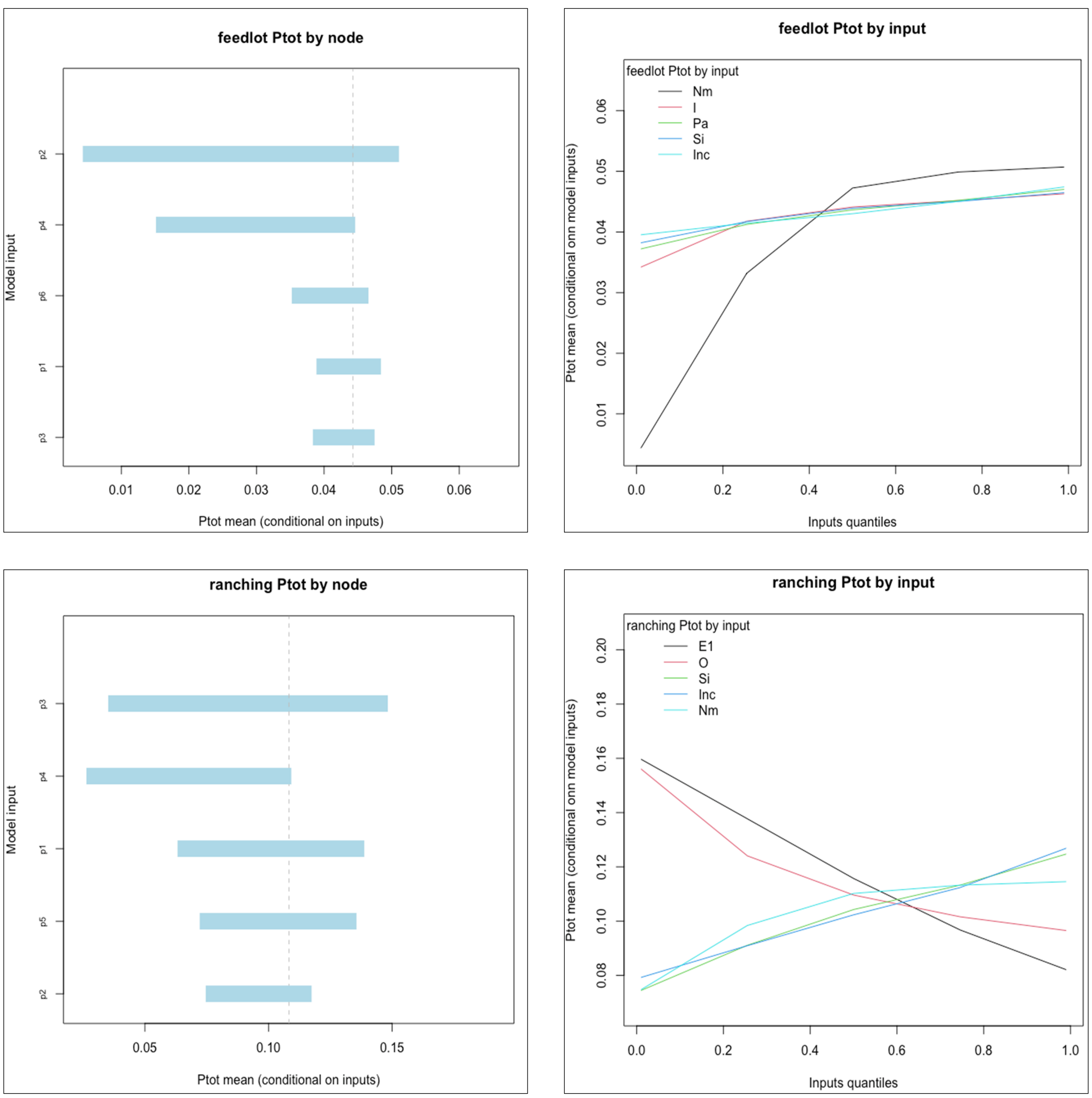
For systems below a threshold risk (median *Ptot* less than 0.50), the relationships of input values to conditional mean output were evaluated in order to identify candidate variables for interventions that may reduce total risk into a range likely to be acceptable to potential trade partners. The two systems which met the criteria were feedlot and ranching systems in Kenya (see Figure 4-4). In feedlot systems, *P2* (probability of acquiring a new infection en route) and *P4* (probability that a new infection is not detected) were the most influential nodes. The number of cattle mixed with (*Nm*) was the single most influential input variable: mean *Ptot* ranged from .004 to .05 as *Nm* increased from the 1st to 99th percentile values (0 to 112 animals mixed with). In ranching systems, *P3* and *P4* (probability of not detecting an infection that originated on-farm and en route, respectively) were the nodes associated with the largest range of conditional mean values for *Ptot* (from 0.03 to 0.15 as *P3* increased from 1st to 99th percentile values). Efficacy of inspection (*E1*) was the most influential input variable.

3.3 Alternative approaches

Two alternative approaches for the estimation of FMD prevalence among Uganda cattle populations were evaluated (Figure 4-A1). Under the first approach, where antibodies of recently vaccinated animals were assumed to indicate vaccination rather than infection, the agropastoral system had the largest decrease in prevalence of all systems and resulted in a reduction in the median value of *R1* (probability of infection at slaughter due to cattle infected when leaving the source herd) to 0.14 (from 0.22). An increase in *R2* (new infections acquired en route, due to more animals eligible for infection) "compensated" for the lower *R1*, and the mean *Ptot* was slightly higher (0.62 vs. 0.59 in the default) in the alternative scenario despite the lower prevalence. Where viral isolation data were used rather than serology to estimate the annual incidence of disease, the pastoral system had the largest decrease in prevalence of all systems, causing the median *P1* value to drop to 0.40 (from 1.0 in the default scenario). The lower prevalence reduced the median value of *R1* from 0.43 to 0.20. The resulting increase in *R2* "compensated" for the lower *R1*, and the mean *Rtot* was actually higher in the alternative scenario (0.7 vs. 0.55 in the default) due to the impact of new infections acquired during the sale process, despite the lower estimated occurrence of disease in the source population.

In both cases, any large change to the estimation of disease occurrence and thereby *P1* led to a decrease in the value of *R1*. However, since *R2* includes the value *(1-P1)*, there was a compensatory effect (smaller *P1* values resulted in larger *R2* values) and even a paradoxical increase in the overall risk, *Ptot*.

Figure 4-4: Influential nodes (a) and input variables (b) for feedlot and ranching systems in Kenya. Each node (*P1-P6*) or input value was divided into percentiles (1, 5, 25, 50, 75, 95, 99) and the conditional mean value of *Ptot* was calculated when the node was held fixed within each percentile interval while all others varied randomly. Only the top five most influential nodes or inputs were included for each plot. Note that the axes vary for each.



4. Discussion

In this study, we modeled the risk of FMD infection among cattle at the time of slaughter for cattle originating from four different management systems under current conditions in Kenya and in Uganda. These values and relationships provide an essential input for further evaluation of marketing and risk management considerations, although a full analysis requires more than the probability of occurrence. The first step in contextualizing these results will be to consider interventions that may reduce that probability to a level acceptable to trading partners along with the cost, logistics, and tradeoffs involved in each. The risk estimates and sensitivity analyses produced here provide insight about influential factors that could be leveraged to effectively lower the probability of FMD among beef cattle at slaughter from select populations.

Our results highlight the heterogeneity between countries and even between production systems of risk for FMD among cattle at slaughter. In Kenya, a wide gap emerged in the total risk between systems at high (pastoral, semi-intensive) and low (feedlot, ranching) risk. By contrast, in Uganda, all systems had similar values for total risk despite differences in individual inputs and nodes. This distinction between countries was driven in part by the wide gap in P2 values (new infections en route) among Kenyan systems, due to the probability of completely avoiding mixing with other animals as described by Veterinary Service professionals -- 0.95 for feedlot and ranching, 0.05 for pastoral and 0.10 for semi-intensive. In Uganda, all systems had a fairly low probability, or a wide range that included low probabilities, of avoiding commingling. Therefore, P2 values were modestly high (mean value greater than 0.5) for all systems in Uganda. In both countries, *P3* through *P6* (the probability of non-detection and recovery for cattle infected on-farm or en route) were similar between systems (mean value within 0.10 range) and the distinction of total risk between systems was driven by the diversity of *P1* and *P2* values. Thus, the differences in commingling probability played a key role in separating the Kenyan systems (and, likewise, failing to separate those in Uganda). The variation between regions and systems is important because of the possibility to focus investments and interventions in targeted populations for which exporting beef is a feasible and favorable opportunity.

Feedlots in Kenya had the lowest risk among all production systems assessed in both countries, driven by low values for both infections among animals sold (*P1*) and new infections acquired en route (*P2*). Feedlots are finishing systems where cattle from ranches or pastoral systems spend between three months and a year for fattening and are sold through formal channels to prime or niche markets. There are very few feedlots in Kenya (1% of cattle farms (Gikonyo et al., 2018a)). Feedlots require high levels of input (capital and labor) and typically invest in relatively robust biosecurity and animal health practices. The feedlot model requires a market that will pay a high price in order to be profitable, and has been historically limited by the low availability and high cost of feed inputs in Kenya (Agriterra, 2012; Kahi et al., 2006). If such a market could be secured / established and the feeds issue solved, feedlots could be an option to increase the quality and consistency of beef produced from pastoralist and ranching value chains. Feedlots have been suggested as one strategy to mitigate the volatility of rainfall and temperature associated with climate change in the semi-arid areas of northern Kenya (Ndiritu, 2020).There are few data on the prevalence of FMD at feedlots in Kenya, so the range of possible values specified for the model (ranging from 0 to 1) reflected a great deal of uncertainty about disease occurrence. Regardless, the high rate of sales (assumed 100-400% turnover rate annually) diluted the impact of positive cases on the probability that any individual animal would be infected at the time of sale. The high offtake rate combined with the low probability of commingling as described by VS created the low overall probability of infection at slaughter as calculated by the model. While the low result may partially be a product of the dilution impact of such a high rate of sales and turnover, it is also true that such systems enable concentrated use of resources for disease prevention, surveillance, and documentation. The companion question is whether the beef produced from such high-input systems could be competitive and profitable on the international market.

Further reduction of FMD prevalence at slaughter for cattle originating from feedlots could be most effectively achieved by targeting nodes *P2* (new infections) and *P4* (detection of new infections), and specifically the number of animals mixed with when commingling occurs (*Nm*), according to our sensitivity analysis. Theoretical interventions that target these nodes are similar to measures already being discussed and implemented for some systems in Kenya (Alarcon et al., 2017; Mamo, 2019): direct shipment of cattle from their herd of origin to the point of slaughter and holding cattle in quarantine or holding areas where they are not exposed to cattle from other sources. If these measures were consistently implemented so that the risk of acquiring new infections en route was reduced or even eliminated, then additional biosecurity and animal health investments for disease prevention and control at the source herd could directly translate to lower probability of infection among cattle at the time of slaughter.

These principles apply generally to many of the other, “higher-risk” management systems in our analysis, though the probability level achieved would not be as low as that predicted for feedlots. Elimination or reduction of the *R2* pathway (infected slaughter cattle due to new infections en route) would be very effective to lower the prevalence of FMD-infected animals at slaughter, especially among cattle coming from a source population with a relatively low rate of infection. Most remarkably, if the *R2* pathway were eliminated for ranching and semi-intensive systems in Uganda, the remaining *R1* pathway (through cattle infected at the time of sale) would have a median total risk of 0.02. The most impactful strategy for any *R2*-dominant system would be to eliminate commingling completely; our model showed that even incremental decreases in exposure to other animals en route (fewer animals mixed with, or lower proportion of cattle who mix with other animals) can powerfully influence the prevalence of disease among animals at slaughter. Where that is not possible, an increase in the total length of the process from herd to slaughter could allow time for detection and/or recovery from infection (nodes *P3* through *P6*), but would also allow ongoing transmission of disease between animals if groups are not separated. Incubating, early stage infections among animals at the time of slaughter are especially concerning (Paton et al., 2010), as they are able to evade detection if not yet showing clinical signs, and viremia present at this stage is associated with viral particles in the skeletal muscle (Alexandersen et al., 2003; Sutmoller, 2001). The international standards of the OIE for cattle originating from FMD-endemic regions recommends at least 30 days of holding animals in a quarantine station or FMD-free facility followed by direct transport to the abattoir for slaughter (World Organization for Animal Health (OIE), 2019). A risk analysis in Somalia (Knight-Jones et al., 2014b) identified outbreaks within holding areas as an important source of infection among cattle who may have been disease-free when leaving their herd of origin.

Cattle from Kenyan ranching systems were the second-lowest in terms of infection probability at slaughter (median *Ptot* = 0.10). This was one of only two systems (along with Ugandan pastoral) in which probability associated with the *R1* pathway (infected at the time of sale) was greater than *R2* (acquired en route). Effective detection (*P3, P4*) were the nodes with greatest impact on mean risk (see Figure 4-4). Efficacy of inspection (*Eff1*) was the single most influential input variable for ranching systems in Kenya. Inspection quality is connected with other dynamic factors including volume of animals sold, availability of inspectors, and incentives for human actors to avoid corrupt behavior (Adamchick et al., 2021b; Rich et al., 2013). Our results indicate that ranching systems are capable of achieving a relatively low probability of infection at slaughter among cattle sold, and further study into the factors that could improve the consistency and quality of inspection within the existing value chains and infrastructure may elucidate ways to further reduce that level of risk. However, even at the highest values of *Eff1* evaluated (inspection efficacy of 0.999), the mean risk (*Ptot*) was estimated to be 0.076. A similar risk reduction could be achieved if the *R2* pathway was eliminated, as discussed for the systems above. (Median *R1* value was 0.07; therefore an *R2* value of 0 would yield a median *Ptot* of 0.07).

Another observation of note is that prevalence of disease in the source population (*Pr*) had relatively little influence in determining the mean value of overall probability of infection at slaughter (*Ptot*) for any production system. (The maximum impact was in Kenyan ranching systems, where the conditional mean *Ptot* associated with the lowest percentile of annual cases per animal (.099) was a 27% reduction of the overall mean- see Figure 4-4). In fact, the analysis of alternative approaches demonstrated the futility of lowering prevalence in systems with opportunity for transmission of new infections before reaching slaughter (see Figure 4-A1). This underscores the need to understand the specific goal (e.g., freedom from disease in a population versus risk reduction in a commodity) and the value of achieving that goal in a given system before investing scarce resources in the pursuit of development and health.

Results and conclusions of this study should be interpreted in light of a number of limitations and assumptions. The management systems with the lowest risk were also the least common systems in each country (feedlot and ranching in Kenya, ranching and semi-intensive in Uganda). Consequently, there were fewer available data -- published and VS experience -- for these systems. Additional work to describe the production, health, and value chain dynamics of specific systems can confirm and clarify findings from this study about opportunities for impactful intervention and the level of achievable risk.

Assumptions in the risk model structure are also important to consider. It was assumed that all cattle who were not infected at the time of sale were eligible to be infected en route (i.e., no resistance). This is a conservative assumption as some cattle may have protection due to natural infection or vaccination. However, delivering a vaccine of adequate quality that is matched to circulating strains with appropriate frequency (recommended twice annually) is challenging. There are at least four serotypes of circulating FMD identified in East Africa with no cross-protection (Mwiine et al., 2019), such that infection with one may not confer resistance to other FMD viruses. In 179 serotype O viral isolates recovered from 48 herds of cattle in Uganda, only 1.1% were within the same topotype as the serotype O vaccine strain used in Uganda (topotype EA-1) (Mwiine et al., 2019). Studies of vaccine coverage and efficacy in target populations could be integrated into the analysis to evaluate the impact of vaccination or assumptions about natural resistance. However, it is established that currently available FMD vaccines do not prevent subclinical infections (Stenfeldt and Arzt, 2020) and an analysis integrating vaccination should also account for impacts on the probability of displaying clinical signs and of transmission to other cattle.

The input values for cases (*C*), sales (*S*), and probability of sale given infection (*Si*) resulted in impossible values of *P1* (i.e., >1) for some iterations in some systems (most notably pastoral systems in Uganda). These values were forced to 1 for the model. The inputs were obtained from distinct sources and the tension highlights that the absolute value of *Si* may be less important than the relationship between the probability of sale for an animal that is infected and the probability of sale for any other animal (e.g. two times more likely to be sold? Or maybe only one third as likely to be sold?). The explicit relationship between the probability of sale in the two populations, and/or obtaining estimates for the probability of sale for each from a common source, would be useful in future analyses. Furthermore, this analysis did not incorporate temporal or spatial trends in events such as infection, sale, or movement of cattle that could potentially influence the range and shape of output distributions.

In summary, cattle from the Kenyan systems of feedlots and ranches had the lowest risk of being infected with FMD at the time of slaughter out of all eight systems evaluated. Model results indicate that this probability could be reduced by eliminating the commingling with other cattle between sale and slaughter; improved detection of infected animals was also indicated for ranching systems. For ranching and semi-intensive systems in Uganda, the risk of acquiring new infections en route raised the probability of infection at slaughter from a similarly low level (median risk less than 0.05) to approximately ten times higher; a reduction or elimination of that pathway could have substantial impact. Both Kenya and Uganda have published intentions to construct holding grounds and quarantine stations that would facilitate the export of livestock, meat, and leather from a consistent and high-quality cattle supply (Mamo, 2019; Uganda Ministry of Agriculture Animal Industries and Fisheries (MAAIF), n.d.). Our analysis indicates that such an approach -- utilizing cattle from existing ranches in a feedlot/finishing type system with high biosecurity measures and following strict isolation from other cattle populations until slaughter -- would capture the most effective risk reduction strategies from the viewpoint of reducing the probability of FMD infection among cattle at slaughter.

However, such ambitious plans can be challenging to implement in reality. The insights from this analysis can contribute to formulating steps that may help move specific populations toward production of beef with a lower probability of FMD transmission through trade. These results need to be contextualized further, including understanding how low of a probability would be necessary to achieve certain trade benefits, what else would need to be done for market success once that level is achieved (is FMD the true bottleneck?), and the cost of implementation for risk management interventions and other measures needed to achieve those risk reduction targets and benefits. An important alternative to evaluate would be participation in markets where FMD is not an automatic barrier to trade, including livestock deficit countries within the COMESA preferential trade area of which Kenya and Uganda already participate (Mamo, 2019).

In that scenario, FMD would be managed as an obstacle to health and productivity but without the extreme measures required for entry to more premium markets. In several assessments of other African countries, the expected benefits of removing the FMD barrier to entry to premium international beef markets, through either disease-free compartments or commodity-based trade, have not automatically justified the investment required (Naziri et al., 2015; Queenan et al., 2017; Rich et al., 2009). Pressure to achieve disease freedom and control in Africa for trade purposes has historically been driven by European interests (Compston et al., 2021; Rodeia, 2008) and it is important that analyses to guide the investment of scarce resources for health and development are grounded in the values and capacity of each country even if the resulting steps forward are more modest.

Funding: This project has been supported in part by the Bill & Melinda Gates Foundation (grant number OPP1211169). Under the grant conditions of the Foundation, a Creative Commons Attribution 4.0 Generic License has already been assigned to the Author Accepted Manuscript version that might arise from this submission. Additional support was received from the USDA National Needs (grant 2014-38413-21825) and from the MnDRIVE Global Food Ventures Graduate Student Professional Development award.
Acknowledgments: The authors would like to thank the veterinarians of the ProgRESSVet Kenya and ProgRESSVet Uganda programs for their participation and contributions to this work, Silver Ochwo and Anna Munsey for assistance in locating and interpreting available data, and the EpiX Analytics team for sharing code used to develop and visualize the sensitivity analyses.

Appendix

Table 4-A1: Input variables, values, and references for the stochastic risk assessment model to evaluate the risk of FMD infection among cattle at the time of slaughter for animals sourced from four different production systems in each of two countries (Kenya and Uganda).

Input	Variab le	Distribution or Estimate	Reference
Probability that a cow is infected when leaving the herd of origin	**P1**	$\frac{C*Si}{S}$ Adjusted for all values to be < 1	**NA**
Number of FMD cases per year in source population	C	${}^{Pr}/_{A} * (Mg * Np)$	NA
Probability that FMD-infected cattle are sold while infected	Si	Kenya: ~Pert (.1, .2, .3) Uganda: ~ Pert (.2, .3, .4)	VS Estimates[†]
Number of cattle sold for meat annually from the source population	S	$O * Np * Mg$	NA
Prevalence of antibodies against FMD non-structural proteins	Pr	Kenya, *~Beta (mean, sd):* F: Mode=.145, 95^{th} pct = 0.9 P: (.55, .01) R: (.47, .06)	(Alemayehu et al., 2014; Kibore,

		S: (.63, .02)	2013; Kibore et al., 2013)
		Uganda, ~*Beta (mean, sd):* AP: (.29, .05) P: (.72, .09) R: (.09, .02) S: (.09, .02)	(Munsey et al., 2019; Mwiine et al., 2019)
Mean age of cattle surveyed for prevalence data	A	Kenya, ~*Pert (min, mode, max):* F: (2, 4, 5) P: (2, 3, 5) R: (2, 2.5, 5) S: (2, 2.5, 5)	(Alemayehu et al., 2014; Kibore, 2013; Mwangi et al., 2020)
		Uganda, *Empirical distributions of mean age (mean, sd):* AP: (2.0, .04) P: (2.2, .06) R: (2.0, .06) S: (2.0, .06)	(Munsey et al., 2019)
Proportion of total cattle population in each management system	Mg	Kenya, F: .01 P: .34 R: .11 S: .54	(Gikonyo et al., 2018a)
		Uganda, AP: .49 P: .41 R: .08 S: .02	(Mubiru et al., 2018)
National population of beef cattle	Np	Kenya: ~Pert (14100000, 14500000, 16000000) Uganda: ~Pert (12112000, 14189000, 15855000)	(FAO, 2019c; Gikonyo et al., 2018a; Mamo, 2019; Uganda Bureau of Statistics, 2018, 2020)
Percent of source population sold annually for meat	O	Kenya, ~*Pert (min, mode, max):* F: (1, 3, 4) P: (0, .125, .25) R: (.1, .24, .3) S: (0, .15, .25)	(Behnke and Muthami, 2011; Mwangi et al., 2020; Nyariki and Amwata, 2019; Ruhangawebare,

			2010; Teklebrhan and Urge, 2013)
		Uganda, AP: (.05, .1, .15) P: (.05, .1, .15) R: (.2, .25, .3) S: (.2, .25, .3)	*Same as Kenya*
Probability that non-infected cattle acquire a new infection before slaughter	**P2**	**(1-Pn)*Ic**	**NA**
Probability that cattle sold for meat do not mix animals from other herds before slaughter	Pn	Kenya, F: .95 P: .05 R: .95 S: .1	VS Estimates†
		Uganda, ~*Pert (min, mode, max):* AP: (0, .2, .5) P: (0, 0, 0) R: (.3, .4, .5) S: 0, .25, .7)	VS Estimates†
Probability that cattle who mix with others will experience at least one effective contact with an infected bovine	Ic	$1-(1-Pa*Pi)^{Nm}$	NA
Prevalence of FMD infection among all cattle sold	Pa	*Mixture distribution, unique for each country:* Mix(values=P1, probs=Mg)	NA
Probability that infected cattle are infectious on any day	Pi	$1-{}^{L}/_{D}$	NA
Duration of latent phase (days pre-infectious)	L	*Equally weighted mixture of 10 distributions described in literature* Mean = 3.1, IQR = 1.4-4.1	(Cabezas et al., 2018; Mardones et al., 2010; Yadav et al., 2019)
Duration of total acute infection in days	D	L + I	NA
Duration of infectious phase	I	*Equally weighted mixture of 10 distributions described in literature* Mean = 8.6, IQR = 3.9-9.9	(Cabezas et al., 2018; Mardones et al., 2010; Yadav et al., 2019)

Number of animals from other herds commingled with, when mixing occurs	Nm	*~Nbinom (mean, IQR)* Kenya: (26.4, 9-36) Uganda: (18.4, 12-24)	VS Estimates[†]
Probability that cattle infected at the time of sale are not detected and reported	**P3**	$1 - In * Cl * De$	**NA**
Probability that cattle are inspected at least once between the source herd and slaughter	In	Kenya, *1 – Pert(min, mode, max):* F: (.01, .01, .05) P: (.2, .4, .6) R: (.01, .02, .05) S: (.1, .2, .3)	VS Estimates[†]
		Uganda, AP: (.35, .4, .45) P: (.4, .5, .6) R: (.25, .3, .35) S: (.1, .25, .4)	VS Estimates[†]
Probability that cattle infected at the time of sale display clinical signs on a random day when inspection could occur	Cl	$\frac{Dp-Tc-Ts}{Dp}$ Adjusted for all values to be between 0,1	NA
Duration in days of the process from leaving the source herd until slaughter	Dp	Kenya, *~Gamma (mean, IQR):* F: (1.1, 0.88-1.3) P: (9.0, 5.9-11.4) R: (1.2, 0.94-1.5) S: (6.5, 2.9-8.7)	VS Estimates[†]
		Uganda, *~Lognormal (mean, IQR):* All: (2.5, 1.6-3.1)	VS Estimates[†]
Day of infection on which cattle show clinical signs (Poisson process, time to first event)	Tc	*Exponential* $(\frac{1}{Pc})$	NA
Day of infection on which cattle are sold	Ts	*Uniform* (0:D)	NA
Duration of incubation phase of infection (days pre-clinical)	Pc	*Equally weighted mixture of 10 distributions described in literature* Mean = 4.4, IQR = 2.5-5.7 Adjusted for all values to be ≤ D	(Cabezas et al., 2018; Mardones et al., 2010; Yadav et al., 2019)
Probability that inspected cattle showing clinical signs are detected and reported	De	$1 - \left(1 - (W1 * E1 + W2 * E2)\right)^{Ni}$	NA
Probability that a "high quality" inspection detects and reports clinically-infected cattle	E1	*~Beta (mean, IQR)* Kenya: .70, .55-.91 Uganda: .84, .78-.92	VS Estimates[†]
Probability that a "low quality" inspection detects and reports clinically-infected cattle	E2	*~Beta (mean, IQR)* Kenya: .52, .32-.72 Uganda: .53, .44-.63	VS Estimates[†]

Proportion of high and low quality inspections experienced by cattle in each population	W1, W2	Kenya, F: 1, 0 P: .66, .34 R: 1, 0 S: .86, .14	VS Estimates†
		Uganda, AP: .48, .52 P: .6, .4 R: .54, .46 S: .53, .47	VS Estimates†
Number of times cattle are inspected between sale and slaughter, when inspected at least once	Ni	Kenya, *~Mixture(values, probs):* F: (1, 2) (.25, .75) P: (1,2,3) (.5, .33, .17) R: (1, 2) (.25, .75) S: (1,2,3) (.5, .33, .17)	VS Estimates†
		Uganda, All: (1,2,3) (.5, .33, .17)	VS Estimates†
Probability that cattle infected between sale and slaughter are not detected and reported	**P4**	$\mathbf{1 - In * Cn * De}$	**NA**
Probability that newly-infected cattle display clinical signs on a random day when inspection could occur	Cn	$\frac{Dp-Tn-Tc}{Dp}$ Adjusted for all values to be between 0,1	NA
Day of sale-to-slaughter process on which cattle acquire new infection	Tn	$Uniform(0{:}\,Dp)$	NA
Probability that cattle infected at the time of sale do not recover before slaughter	**P5**	$\mathbf{1 - Pa * Re}$	**NA**
Probability that infected cattle have an acute infection (not persistent)	Pa	1 – *Pert* (0.2, 0.5, 0.75)	(Balinda et al., 2010; Stenfeldt and Arzt, 2020)
Probability that acutely-infected cattle recover before slaughter	Re	$1 - Exp(-Rr * Ro)$	NA
Rate of recovery from acute infections (/day)	Rr	$1/D$	NA
Duration during which acutely infected cattle have opportunity to recover before slaughter (days)	Ro	$Dp + Ts$	NA
Probability that cattle infected between sale and slaughter do not recover before slaughter	**P6**	$\mathbf{1 - Pa * Rn}$	**NA**
Probability that newly-infected cattle recover before slaughter	Rn	$1 - Exp(-Rr * On)$	NA
Duration during which acutely infected cattle with new infections have opportunity to recover before slaughter	On	$Dp - Tn$	NA

Number of cattle sold for export per year from each source population	N	0.2*S

†Full description and discussion of obtaining VS estimates available elsewhere (Adamchick et al., 2021b)

Table 4-A2: The median (25th , 75th percentile) values for each node (*P1-P6*), route (*R1, R2*) and total probability (*Ptot*) for each of four production systems in Uganda and in Kenya. The nodes correspond to events on the risk pathway as described in Figure 1. *R1 = P1*P3*P5. R2 = (1-P1)*P2*P4*P6. Ptot = R1 + R2.* The distributions have the mathematical relationships as described even though point values shown do not all show the same relationships.

Median values (25th, 75th percentiles), Kenya

	P1	P2	P3	P4	P5	P6	R1	R2	Ptot
Feedlot	.01 (.00, .01)	.05 (.04, .05)	.66 (.28, 1.0)	1.0 (1, 1)	.78 (.70, .85)	.98 (.96, .99)	0.0 (.00, .01)	.05 (.04, .05)	.05 (.04, .05)
Pastoral	.29 (.21, .41)	.94 (.80, .95)	.74 (.62, .88)	.98 (.88, 1.0)	.63 (.55, .71)	.85 (.74, .93)	.13 (.09, .20)	.43 (.27, .56)	.59 (.45, .71)
Ranching	.15 (.12, .19)	.05 (.04, .05)	.65 (.28, 1.0)	1.0 (1, 1)	.77 (.70, .84)	.97 (.95, .99)	.07 (.03, .11)	.04 (.03, .04)	.10 (.06, .14)
Semiintensive	.32 (.24, .44)	.89 (.75, .90)	.63 (.43, .87)	1.0 (.88, 1.0)	.67 (.59, .75)	.90 (.80, .96)	.13 (.08, .20)	.41 (.25, .53)	.57 (.41, .70)

Median values (25th, 75th percentiles), Uganda

	P1	P2	P3	P4	P5	P6	R1	R2	Ptot
Agro-pastoral	.44 (.36, .53)	.77 (.70, .85)	.59 (.48, .88)	1.0 (.97, 1.0)	.74 (.66, .81)	.95 (.91, .98)	.19 (.14, .28)	.37 (.29, .45)	.59 (.50, .68)
Pastoral	1.0 (.83, 1.0)	1.0 (.99, 1.0)	.64 (.56, .89)	1.0 (.97, 1.0)			.43 (.35, .57)	0.0 (.00, .14)	.52 (.43, .67)
Ranching	.05 (.04, .06)	.59 (.56, .62)	.51 (.38, .85)	1.0 (.96, 1.0)			.02 (.01, .03)	.51 (.45, .55)	.54 (.48, .58)
Semi-intensive	.04 (.04, .06)	.71 (.61, .80)	.48 (.35, .84)	1.0 (.96, 1.0)			.02 (.01, .03)	.48 (.59, .70)	.62 (.50, .72)

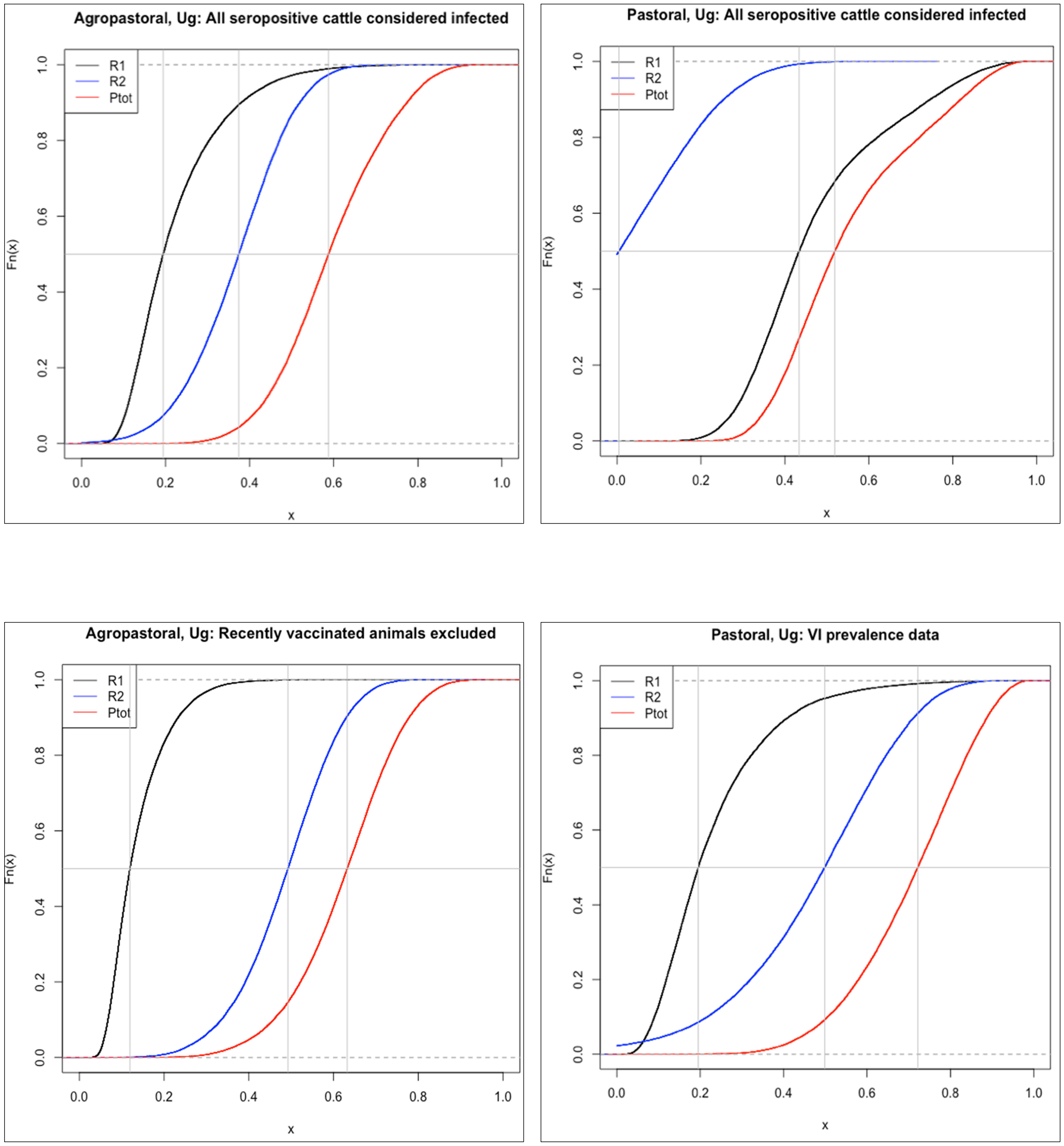


Figure 4-A1: Sensitivity analysis: Reductions in *P1* result in "paradoxical" increases in total risk.

Cumulative distribution functions for *R1* (cattle infected in the source herd), *R2* (cattle infected en route to slaughter), and *Ptot* (overall probability of infection at slaughter) for two production systems in Uganda under the default and alternative approaches to estimating FMD incidence. Top left: agropastoral, default. Bottom left: agropastoral, animals seropositive with record of vaccination within 6 months of sampling are called FMD-negative. Top right: pastoral, default. Bottom right: pastoral, viral isolation from probang samples used rather than serology. Vertical gray lines indicate the median value of each curve.

Left: Under the scenario where antibodies of recently vaccinated animals are assumed to indicate vaccination rather than infection (bottom panel), the agropastoral system has the largest decrease in prevalence of all systems. This resulted in a reduction in the median value of *R1* to 0.14 (from 0.22 in the default scenario (top, black curve)). An increase in *R2* (due to more animals eligible for infection) "compensated" for the lower *R1*, and the median *Ptot* was slightly higher in the alternative scenario despite the lower prevalence.

Right: Where viral isolation data were used rather than serology to estimate the annual incidence of disease, the pastoral system had the largest decrease in prevalence of all systems, causing the median *P1* value (not shown) to drop to 0.40 (from 1.0 in the default scenario). The lower prevalence reduced the median value of *R1* from 0.43 to 0.20. The resulting increase in *R2* "compensated" for the lower *R1*, and the median *Rtot* was higher in the alternative scenario due to the impact of new infections acquired during the sale process, despite the lower estimated occurrence of disease in the source population.

Chapter 5: Cost-effectiveness of livestock identification and vaccination interventions to reduce foot and mouth disease prevalence among East African cattle at slaughter

Introduction

Increased market access through control of transboundary diseases such as foot and mouth disease (FMD) has been suggested as a pathway out of poverty for livestock producers and economies (Perry et al., 2002; Perry and Rich, 2007). FMD, a highly contagious viral disease of livestock and wildlife species, is an important reason for restrictions on the import of livestock products from endemic regions to places that are free from the disease. Namibia and Botswana in southern Africa have controlled the FMD well enough to develop consistent export markets, achieved through mass vaccination and regionalization (Bennett and Rich, 2019). However, most African countries have been unable to follow in this success, due to challenges including the co-existence of livestock and wildlife in integrated ecosystems, presence of multiple FMD serotypes and evolving strains with no cross-protection, the low perceived benefits for producers to invest or buy into control efforts, and the fragmented and poorly resourced infrastructure for animal health service delivery (Compston et al., 2021; Maree et al., 2014). In an attempt to aid endemic countries to control the disease, the intergovernmental organizations have promoted the use of a framework for FMD control, known as the Progressive Control Pathway (PCP), which outlines a series of steps to guide countries in advancing toward improved FMD awareness and control, intended to provide a template for forward motion regardless of a country's starting place (Ismayilova, 2017; Rweyemamu et al., 2008). However, the steps emphasize geographically-based disease control and have been elusive for some countries to achieve.

An alternative is to focus on reducing and documenting a low level of FMD transmission risk in the product to be exported, for example deboned beef. Commodity-based trade (CBT) has been regarded as an alternative pathway to market access for countries with persistent, endemic FMD (Thomson et al., 2013b), though this approach has not been widely accepted in practice. Regardless of which approach is used, a successful export economy depends on being able to overcome barriers to market entry (e.g., elimination or risk management of trade-sensitive diseases) and to offer a product that is competitive in that market. Some have pointed out that production of beef that meets requirements for FMD may not be economically competitive in target markets, especially if the acceptance of CBT opens a flood of supply from countries currently restricted from participation in those markets (Naziri et al., 2015; Rich et al., 2009; Rich and Perry, 2011b). Even so, a focus on reduction of risk associated with the product (e.g., beef) that internalizes the progressive and gradual mindset of the PCP could support countries to implement foundational programs for disease control, institutional SPS capacity, and product traceability, setting the stage for longer term market opportunities while deriving more immediate domestic benefits. This objective could be reached in a manner that is within the means of the country and the interests of value chain participants, improving local animal health and production efficiency while making movement toward market participation.

The risk reduction achieved by post-harvest steps of inspection, processing, and storage of deboned beef according to OIE specifications has been extensively reviewed (Paton et al., 2010). A recent assessment quantified the probability of FMD infection among cattle at slaughter in Kenya and Uganda, a key contributor to the risk for FMD transmission associated with beef produced from these systems (Chapter Four). Briefly, the risk assessment considered two pathways by which infected cattle could arrive at slaughter-- by infection at the herd of origin, and by acquiring a new infection en route or at the abattoir-- and examined the probability and influential factors for cattle originating from eight production systems across Kenya and Uganda. Results suggested that most Kenyan and Ugandan systems would be unable to reduce risk to the point acceptable for premium markets in a single step. However, results also suggest that pre-harvest risk may be substantially reduced considering strategies that could a) provide the foundation for future advancements to build on, b) have more immediate benefits domestically besides/before market returns, and c) are done in a way that can be sustainable and scalable.

Specifically, they found that the probability of FMD infection among cattle at slaughter was expected to be substantially lower for cattle originating from Kenyan feedlots and ranches compared to the other six systems evaluated, and Ugandan ranches and semi-intensive systems had potential to achieve comparable levels. Based on the risk assessment findings, preventive vaccination to provide protective immunity for cattle in these systems could be an effective intervention strategy. By reducing both the prevalence and transmission of disease, FMD vaccination could effectively reduce the probability of infection through both pathways: at the herd of origin or en route to slaughter. Improved quality and probability of inspection at the abattoir, potentially linked with animal identification and traceability, could be another high leverage opportunity for reducing the disease prevalence among cattle that reach the point of slaughter. Therefore vaccination campaigns and systems for livestock identification and traceability are potential interventions to consider but need to be evaluated for the level of risk reduction that could be achieved and at what cost.

Vaccination has been a pillar of disease prevention and control in many countries that have successfully managed and eradicated FMD (Blacksell et al., 2019; Gallego et al., 2007).

Vaccination decreases severity and duration of clinical signs, the transmission of disease from infected to susceptible individuals, and the overall level of disease present in the population. A benefit-cost analysis of FMD vaccination in South Vietnam found that a biannual vaccination strategy for cattle would be profitable for dairy farms based on the financial impact of FMD outbreaks; it was less certain whether vaccination would be a profitable investment for beef farms (Truong et al., 2018). An analysis of bi-annual FMD vaccination in Koch County, South Sudan estimated that the benefit to cost ratio was 11.5 when accounting for both acute and chronic losses caused by FMD (Barasa et al., 2008). Effective vaccination campaigns are expensive and challenging to implement, however, and it is difficult for countries to supply adequate coverage when provided free of cost to producers. Kenya had compulsory vaccination programs in the past, but in recent decades has been unable to control the evolving FMD landscape of both pathogen and production systems, particularly given the challenges of disease control in smallholder and pastoral herds (Compston et al., 2021). Both Uganda and Kenya rely on FMD vaccination primarily as a reactive measure, applying ring vaccination to help control disease in the face of an outbreak; delays in outbreak detection and response compromise the effectiveness of such measures (Muleme et al., 2012; Munsey et al., 2019). Even where vaccines are successfully supplied and administered, there are many factors that can influence the effectiveness of vaccination at protecting against infection and disease spread. Matching the vaccine to circulating strains of virus and monitoring the protective immunity of vaccinated populations can help to understand limitations and improve the efficacy of vaccination programs (Ferrari et al., 2016).

Livestock identification and traceability systems (LITS) are systems of identifying livestock, individually or in batches, such that they can be cross-referenced with information about their past movements, health records, or other relevant information to enable traceability of animals and products (Britt et al., 2013). LITS systems are tools for addressing issues related to animal health, food safety, and zoonoses (World Organization for Animal Health (OIE), 2019), and livestock identification, traceability, and movement control, is a critical component of veterinary technical authority and capability (World Organisation for Animal Health (OIE), 2019). The absence of traceability systems in animal health systems was highlighted as a constraint to the safe export of products from the Horn of Africa to the Arabian Peninsula in a recent consultation (Mtimet et al., 2020). Several countries in eastern Africa have run pilot programs with varying success (ICPALD, 2014). Ethiopia tested a program using tamper-proof visual tags and batch recording of animals on paper forms to track animals entering feedlots and destined for export. South Sudan reported reduced cattle rustling by 95% when they trialed a program in which animals were given tamper-proof tags and logged in a database enabling the verification of animal ownership. Kenya has tested programs including the use of RFID boluses but none that has been sustainable or scalable beyond the initial pilot. Uganda has had little success toward establishing an effective traceability system.

The objective of this study was to evaluate and compare interventions that could be implemented in Kenya and Uganda to reduce the probability of infection among cattle at slaughter. That objective was achieved through a) developing scenarios believed to be productive, technically feasible, and with potential for the buy-in of partners required for implementation, b) estimating the cost and risk reduction (change in probability) for each scenario considering implementation in a specific region of each country, and c) discussing the limitations, trade offs, and benefits of each. The scenarios evaluated were an animal identification and traceability system, preventive vaccination campaign, a combination of both LITS and vaccination, and a herd-level biosecurity approach for feedlots in partnership with an export abattoir. The results can contribute to planning beef export strategies that are aligned with local goals and capacities for East African countries and other regions with endemic FMD.

Methods

Setting

A setting was chosen in Kenya and in Uganda for cost-effectiveness evaluation of interventions that may be implemented to reduce the probability of FMD infection among cattle at slaughter. In each country, a region was chosen with a mix of production systems with some market-oriented producers. The settings were suggested by members of the Veterinary Services as promising sites for piloting of livestock and traceability systems in each country.

Narok County, Kenya is located in the southern part of the country along the Great Rift Valley and shares a border with Tanzania. The county is approximately 18,000 square kilometers with a population of 1.2 million people (narok.go.ke) and is home to the Maasai Mara National Reserve. There are approximately 1,190,700 head of beef cattle in the county, with 70% belonging to pastoralist herds, 20% to agro-pastoral farms, and 10% to extensive ranching systems (Gikonyo et al., 2018a). Land use and FMD epidemiology are influenced by the presence of the Reserve (Nthiwa et al., 2020) and any strategies for disease control or market development should take into account the dependencies between people, wildlife, and livestock in the region (Ferguson et al., 2013).

The Ankole sub-region of Uganda is located in the southwest part of the country and part of the "cattle corridor" that stretches diagonally toward the northeast. Mbarara and surrounding districts in the Ankole include a relatively high concentration of market-oriented cattle systems relative to the rest of the country. Due to the level of granularity of available data, the entire South Western region of Uganda was evaluated for these interventions, which includes the Ankole sub-region and five additional counties in the southwest corner. The South Western region contains approximately 641,000 beef cattle, of which 70% belong to agro-pastoral herds, 20% to commercial ranches and 10% to semi-intensive systems (Mubiru et al., 2018).

Intervention scenarios and cost inputs

Intervention scenarios were developed and refined through consultation with stakeholders and professionals familiar with livestock production and/or economics in one or both settings. The initial interventions under consideration were chosen based on insights from a risk assessment model (Chapter Four) of what types of systems and interventions might be most impactful at reducing FMD risk at slaughter, and from project ideas for improving trade and sanitary capacity related to animal health and food safety proposed by members of the Veterinary Services enrolled in a training and proposal development program (progressvet.umn.edu, (Adamchick et al., 2021a)). The resulting list of interventions to consider included LITS, mass vaccination, enhanced outbreak response and movement controls, and combinations of the above. Next, information was collected from a variety of sources to refine scenarios, identify inputs that would be required for each intervention, and estimate the costs associated with each. Sources included published scientific literature such as cost benefit analyses; project proposals, reports, and guidelines from organizations including IGAD, the FAO, and WTO STDF; virtual meetings with Kenyan and Ugandan veterinarians including team members working on the proposals described above; and written questionnaires soliciting quantitative and qualitative information sent to researchers and practitioners familiar with the setting. The synthesized information was used to develop a list of inputs for each scenario in the simplest form that captured the common elements used in similar examples or described by stakeholders.

Point estimates for the quantity needed and cost of each input were derived from the same reference material. Initially, published estimates for each input from projects in other places were collected to create a range of reported values for each. That range was used as a guideline for the expected value. If a conversation or questionnaire with someone from East Africa had provided a number within or close to that range, then that was the value assigned. If not, a mid-range value was chosen. Where information was provided for either Kenya or Uganda but not both, it was assumed that costs would be similar and quantities could be scaled according to the population of cattle. The inputs used for each scenario are provided in the appendix, tables 5-A1 and 5-A2.

At the end of this process, there were three interventions developed for evaluation in each setting. These were a Livestock Identification and Traceability System (LITS), a mass vaccination program, and a combination of both. There was an additional scenario evaluated in Kenya that focused on feedlots.

The first intervention evaluated was a basic Livestock Identification and Traceability System (LITS) implemented on a voluntary basis for five years in partnership with an export-oriented abattoir. Following the recommendations provided by IGAD and the FAO (FAO, 2016; ICPALD, 2014), the system was assumed to use visual ear tags (in contrast to electronic identification devices such as radio frequency ID tags or rumen boluses); this is the least expensive option and also most practical for situations in which the animals would only have events recorded a few times in their lifetime and/or reading of the tags may need to take place in remote regions. The program would be implemented for willing producers in the region (Narok County, Kenya or Mbarara and surrounding districts, Uganda) in partnership with a participating abattoir equipped to process cattle for export. All cattle would be inspected before slaughter and only accepted by the abattoir if they have the appropriate identification and are registered in the central database. At this same inspection, they would be examined for clinical signs of FMD (or other diseases). Cattle with FMD lesions would not be accepted and the producer would not receive payment for this animal. For all healthy and registered cattle from producers enrolled in the program, producers would receive a premium price per kilogram of carcass weight (established at the beginning of the program). Based on an average carcass weight of 150 kg at slaughter and price of approximately $2.65/kg (Mubiru et al., 2018), a 10% premium was estimated to be $0.27/head. Participation in the program, including ID tags, would be zero cost to the producer. A central database, developed with intention to be able to scale up to include a greater region at the end of the program and/or to integrate with existing components, would house information for all of the animals and premises in the program. Full time staff would be hired for the roles of database development and support, program coordinator, farm/data coordinator, and an inspector at the abattoir. In the first year, animal technicians would be contracted in each sublocation for thirty days to carry out the initial enrollment and registration of animals. Costs per category are provided in Table 5-1 with a complete breakdown in the appendix.

The second intervention evaluated was a compulsory preventive vaccination campaign for all cattle producers in the region. This would involve twice-yearly vaccination with a trivalent vaccine (that which is currently used by each country). Blood samples from a small subset of cattle would be collected and submitted annually for post-vaccination monitoring to evaluate population immunity (Ferrari). The vaccine and administration would be covered at no cost to the producer. Costs per category are provided in Table 5-2 with a complete breakdown in the appendix.

Table 5-1 Costs by category for LITS-only intervention

LITS only	Start up + year 1 costs		Annual costs, years 2-5	
	Uganda	Kenya	Uganda	Kenya
Materials	$ 141,949.45	$ 147,084.00	$ 41,165.34	$ 33,829.32
Database + infrastructure	$ 115,000.00	$ 115,000.00	$ 34,000.00	$ 34,000.00
Human resources	$ 229,200.00	$ 229,200.00	$ 67,200.00	$ 67,200.00
Enrollment + implementation	$ 20,500.00	$ 20,500.00	$ 4,200.00	$ 4,200.00
Abattoir subsidy for producer premium	$ 1,231,735.34	$ 957,216.96	$ 1,231,735.34	$ 957,216.96
Monitoring + evaluation	--	--	$ 3,200.00	$ 3,200.00
Total	*$ 1,741,384.79*	*$ 1,472,000.96*	*$ 1,381,500.68*	*$ 1,099,646.28*

Table 5-2 Costs by category for compulsory vaccination intervention

Vaccination only	Start up costs		Annual costs, years 1-5	
	Uganda	Kenya	Uganda	Kenya
Vaccine storage	$ 12,617.34	$ 23,639.06	$ 2,000.00	$ 4,000.00
Stakeholder engagement	$ 15,000.00	$ 15,000.00	--	--
Vaccine cost			$ 1,794,800.00	$ 2,856,000.00
Vaccine administration			$ 82,410.00	$ 158,100.00
Supplies			$ 13,205.00	$ 24,662.00
Sero-monitoring			$ 6,000.00	$ 6,000.00
Total	*$ 27,617.34*	*$ 38,639.06*	*$ 1,898,415.00*	*$ 3,048,762.00*

The third intervention was a combination program of both LITS and biannual FMD vaccination for voluntary producers. The structure of each component is very similar to that of scenarios one and two, with few modifications. The premium received per kilogram would be 50% of that offered in the LITS-only intervention, with the assumption that receiving FMD vaccine would also provide incentive for participation in the program. The population of cattle enrolled would be much lower than in the compulsory vaccination scenario, and so less labor and storage would be required as well as fewer total doses of vaccine.

The fourth intervention considered the intervention of a herd-level biosecurity package for highly commercial production systems in collaboration with an abattoir and other local partners. It was evaluated for a system of five feedlots, each with three cycles of 1500 head of cattle per year, who would implement farm-level LITS, routine vaccination, ship cattle directly to slaughter at an abattoir equipped to handle batches without commingling between herds. This set-up could ideally incorporate more advanced measures including a certified farm biosecurity program and/or tracking of the carcass all the way through processing and distribution to provide farm-to-fork traceability. As this scenario requires a number of situation-specific inputs and assumptions, costs were not estimated. It could be an opportunity to explore partnerships and cost-sharing between a group of producers, abattoir, Veterinary Services and other interested stakeholders.

Population for each intervention

The level of participation in voluntary programs was estimated by production system within each region. Estimates were based on the expected market orientation of each producer group and on the number of total offtake expected, targeting between 100-150 head for slaughter per working day on average. In Uganda, the participation levels were estimated as 67% of ranches, 67% of semi-intensive herds, and 2% of agro-pastoral producers for an overall enrollment of 21.5% of the cattle population (approximately 137,000 head). The overall offtake rate (percent of the population sold for slaughter) of the enrolled population was 24% each year, calculated as a weighted estimate based on the expected offtake from each production system. In Kenya, it was estimated that 67% of ranches, 7% of pastoralist herds, and 2% of agro-pastoral producers would participate, for an overall enrollment of 12% of the population (approximately 143,000 head). The overall offtake rate was 18%. In each country, it was assumed that the offtake rate would be equal to the rate of new enrollments (births and purchases) per year for a stable population.

The primary outcome of interest was the probability of FMD infection at slaughter among cattle participating in the program for each intervention. For the first and third scenarios, the population evaluated was limited to that enrolled in the program. This is appropriate because those animals would comprise the population supplying the participating abattoir; it should be noted that this is not the same as the probability among all cattle in the region. For the second intervention with compulsory universal participation, the outcome was estimated for the entire population and it was assumed that 20% of the offtake from that population would be or could be destined for export.

We then reduced the proportion of cattle enrolled in each program to explore the tradeoffs between cost and risk reduction.

Estimation of risk

A full description of the model structure and parameters used to estimate risk can be found elsewhere (Chapter Four).

The probability of FMD infection among cattle at slaughter for the baseline scenario was evaluated in each setting (using the total beef cattle population and proportion belonging to each of four management systems). It was assumed that twenty percent of the total population of cattle slaughtered would be intended for export.

Next, the risk model was modified to reflect the parameter values expected to change under each intervention (Table 5-3). For LITS, these were values related to either a) increased detection (due to inspection procedures at slaughter) or b) decreased incentive to sell (producers) or ignore (inspectors) FMD-infected cattle. For vaccination, values were related to the decrease in FMD incidence in the source population, decreased infectiousness of FMD-vaccinated cattle even when infected, and increased rate of subclinical infections among FMD-vaccinated cattle. The feedlot scenario included those same modifications (for LITS and vaccination impacts) as well as a decreased probability of commingling with cattle from other herds before slaughter.

The impact of vaccination on disease occurrence in a population is complex, non-linear and multifactorial and could be modeled in detail to predict the outcome in a specific population of hosts, pathogen, vaccine strategy, and environmental factors including other control measures and contact networks. Because many of those specific data are variable or unknown for these systems, a simplified approach was used and the impact of vaccination was incorporated as the relative risk of infection among vaccinated cattle compared to unvaccinated cattle. A study of cattle exposed to the Asia-1 serotype of FMD in Turkey found that the TUR11 vaccine provided a 63% reduction in infection risk (95% CI: 29-81%) (Knight-Jones et al., 2014a). While the region, serotype, and vaccine are all different from the Kenyan and Ugandan scenarios, it was decided that the estimate and point value were wide enough to capture reasonable variation expected from a moderately effective vaccine. (Though the same study also highlighted that some vaccines can be almost completely ineffective at preventing disease or infection). This estimate was supported by a study of the impact of an FMD vaccination program in India that compared the occurrence of reported outbreaks in states participating in the program compared to those not participating (Gunasekera et al., 2021). While controlling for other factors, they found that participating states reported approximately 50% fewer outbreaks than non-participants.

The risk model was parameterized so that the vaccinated portion of the population (specified as between 50 and 90% with a most likely value of 80%) experienced an incidence of infection equal to (1-VE) times the incidence experienced by the unvaccinated population (which was unchanged from the baseline scenario).

The risk model was a stochastic (probabilistic) model implemented with 10,000 iterations for each scenario in R (R Core Team, 2020).

Table 5-3 Parameters modified for risk reduction scenarios

Variable	**Value in scenario** (median)	**Value at baseline** (median)	**Rationale**
Probability of sale for FMD-infected cattle, Kenya[a]	0.09-0.16, system-dependent[c]	0.2	Traceability increases the incentive to **not** sell an animal known to be infected (i.e., if won't receive payment for infected cattle), so adjusted to be the same probability as any animal at random not showing clinical signs of disease, for the subset of infected animals who appear healthy offtake rate (probability of sale for any animal) x rate of subclinical infections among clinically infected animals
Probability of sale for FMD-infected cattle, Uganda[a]	0.07-.19, system-dependent[d]	0.3	
Efficacy of inspection (type 1; type 2), Kenya[a]	0.86; 0.59	0.76; 0.52	Traceability increases incentives for inspectors to report + act on suspect infections, so removes the probability of detecting but not reporting an infection
Efficacy of inspection (type 1; type 2), Uganda[a]	0.88; 0.55	0.86; 0.53	
Probability of at least 1 inspection, Kenya[a]	95%[e]	0.75-0.99, system dependent	Cattle inspected individually at slaughterhouse for appropriate identification and concurrent health exam
Probability of at least 1 inspection, Uganda[a]	95%	0.6 – 0.75, system dependent	
Proportion of inspections that are "high quality" (type 1), Kenya[a]	0.75-1, system dependent	0.66-1, system dependent	Assuming at least 1 type 1 inspection for 95% of cattle (see above)
Proportion of inspections that are "high quality" (type 1), Uganda[a]	75%	Range from .48-.6, system dependent	
FMD incidence in source population, Kenya[b]	0.004-0.09, system-dependent	0.11-0.23, system-dependent	Assume incidence in vaccinated animals is 0.37 (0.15-0.75) of the incidence in unvaccinated animals (Knight-Jones et al., 2014a)
FMD incidence in source population, Uganda[b]	0.02-0.14, system-dependent	0.05-0.36, system-dependent	
Percent of population vaccinated[b]	74%	NA	Range 50-90%, most likely value 75% (Knight-Jones et al., 2016a)

Percent of vaccinated cattle that have clinical infections, Kenya & Uganda[b]	28%	NA	Range 0-75%, most likely value 25% (Elnekave et al., 2013; OIE, 2018; Stenfeldt et al., 2016)
Probability of infected, vaccinated cattle transmitting infection upon contact[b]	1/9	1 (non-vaccinated cattle)	Based on 1/9 of viral load reported in oral/nasal secretions compared to unvaccinated cattle (Stenfeldt et al., 2016)

[a] Modified from baseline for scenarios 1, 3, 4 (Kenya only)
[b] Modified from baseline for scenarios 2, 3, 4 (Kenya only)
[c] Median values 0.11-0.20 for scenario 3, system-dependent
[d] Median values 0.09-0.22 for scenario 3, system-dependent
[e] Median value 0.99 for scenario 4 (Kenya only)

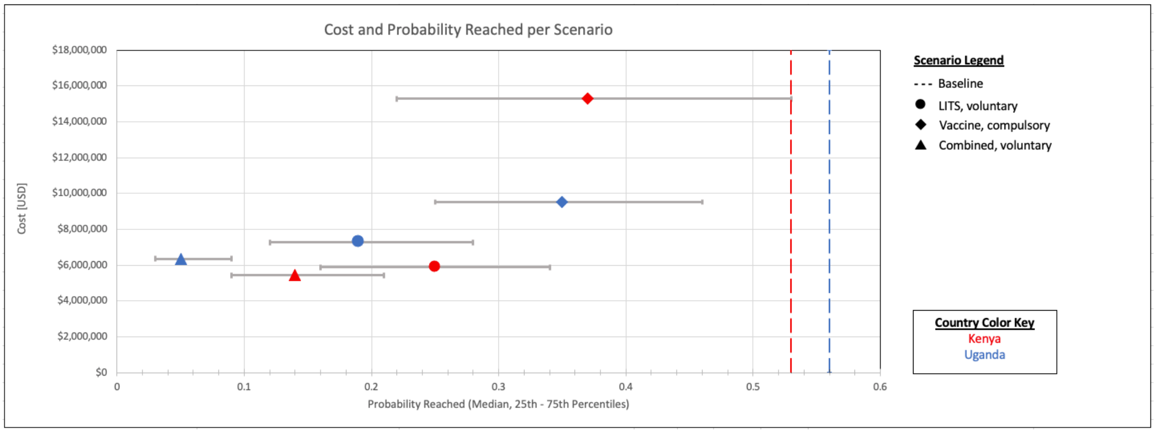
Results

The cost (point estimate) and probability reached (median and 25th - 75th percentile range) for three scenarios in Narok County, Kenya and the South Western region of Uganda are displayed in Figure 5-1. Results for tradeoffs between cost and risk reduction associated with varying population enrollment are in Table 5-4.

Interestingly, there was an inverse relationship between cost and effectiveness for lowering probability as displayed in Figure 5-1. The strategy that most effectively reduced the prevalence of infection among cattle at slaughter, a combined LITS and vaccination program for willing producers, was also the least expensive to implement.

In both countries, compulsory biannual vaccination was the most expensive and least cost-effective intervention at reducing the prevalence of FMD infection among cattle at slaughter. This strategy achieved a 30% and 38% reduction from the baseline probability in Kenya and Uganda, respectively. It was assumed that 75% (possible range of 50-90%) of the target population of cattle in the region would be effectively vaccinated. By reducing the target population to 30% of cattle (from 100% in the default), the cost decreased into a range comparable with other interventions evaluated but barely achieved any reduction in risk of infection at slaughter (Table 5-4). The cost of the vaccine, estimated at $1.20 per dose in Kenya and $1.40 per dose in Uganda, accounted for 82% and 91% of the overall cost of the program in each country.

Figure 5-1: Cost-effectiveness of scenarios to reduce risk of FMD among cattle at slaughter in Narok County, Kenya and the South Western region of Uganda. Vertical lines represent the baseline probability for each setting (with no interventions implemented).



The Livestock Identification and Traceability Systems (LITS) intervention achieved a 53% reduction in probability from baseline in Kenya and 66% reduction in Uganda. This scenario was based on the premise of voluntary enrollment of interested producers based on an incentive system of a premium price per kilogram received at slaughter for healthy cattle registered in the program. The premium, estimated as $0.27 per kilogram, accounted for nearly 85% of the overall program cost. Given the proportion of participating producers expected from each production system, there were expected to be 26,000 cattle per year for slaughter in Kenya and 33,000 per year in Uganda. When participation was restricted in order to keep the overall cost below $3 million, the effectiveness did not change (estimated probability of infection of approximately 24% in Kenya and 20% in Uganda) but the number of slaughter cattle per year dropped to 11,000 and 10,000 respectively.

The combination of an LITS system with biannual vaccination based on voluntary enrollment achieved a synergistic decrease in infection risk while also decreasing cost to be less than either of the other interventions. This strategy achieved a 76% reduction in risk from baseline to a median expected prevalence of infection at slaughter of 0.14 in Kenya, and a 91% reduction to a median expected probability of 0.05 in Uganda. The cost savings were achieved by reducing both the vaccine costs (fewer cattle and therefore fewer doses than in the compulsory vaccination scenarios) and a 50% reduction in the premium per kilogram (lowered on the assumption that receiving FMD vaccine at no cost would also act as an incentive for enrollment). As with the LITS only scenario, costs could be further reduced by restricting participation with no expected change in the prevalence of infection among participating cattle, but at the “cost” of a decreased supply of cattle to the abattoir.

The fourth scenario explored in Kenya was a partnership between an export abattoir and select high volume, intensive herds (modeled as 5 feedlots that do 3 cycles yearly of 1500 head apiece). Given the assumed effects associated with livestock identification and inspection, biannual vaccination, and nearly no commingling before slaughter, this scenario was estimated to achieve a median prevalence of 0.01 (one infected animal per 100 cattle slaughtered).

Table 5-4 Results, Kenya

Cost rounded to nearest thousand

Cost	Intervention	Average head slaughter/day for export[3]	Probability of infection at slaughter	# Infected at slaughter/year (mean)	# for export/year (mean)[4]
$9 million and above					
$15,282,000	Compulsory vaccination, target 100% of population	145	0.37 (0.22 – 0.53)	12,233	33,072
$6 – 9 million					
$9,517,000	Compulsory vaccination, target 60% of population	145	0.50 (0.25 – 0.61)	15,701	33,072
$3-6 million					
$5,871,000	LITS only, voluntary[1]	112	0.25 (0.16 – 0.34)	6,670	26,473
$5,437,000	LITS + vaccination combined, voluntary[1]	112	0.14 (0.09 – 0.21)	4,107	26,117
$5,193,000	Compulsory vaccination, target 30% of population	145	0.53 (0.41 – 0.63)	16,731	33,072
Under $3 million					
$2,938,000	LITS only, reduced voluntary enrollment[2]	47	0.23 (0.15 – 0.31)	2,491	10,882
$2,850,000	LITS + vaccination combined, reduced voluntary enrollment[2]	47	0.13 (0.08-0.19)	1,573	10,882
Not calculated					
Not calculated	Feedlot biosecurity package	98	0.01 (0.01 – 0.02)	336	22,500

[1] Assumed participation by 67% of ranch, 7% of pastoralist, and 2% of agro-pastoral herds
[2] Assumed participation by 30% of ranch, 2% of pastoralist, and 2% of agro-pastoral herds
[3] Assuming 230 working days per year

[4] Assume that in compulsory vaccination scenarios, 20% of cattle offtake from region would be destined for export abattoirs

Table 5-5 Results, Uganda

Cost	Intervention	Average head for slaughter/day for export [3]	Probability of infection at slaughter	# Infected at slaughter/year (mean)	# for export/year (mean) [4]
$9 million and above					
$9,520,000	Compulsory vaccination, target 100% of population	82	0.35 (0.25 – 0.46)	6,520	18,596
$6 – 9 million					
$7,267,000	LITS only, voluntary[1]	146	0.19 (0.12 – 0.28)	6885	33,109
$6,351,000	LITS + vaccination combined, voluntary[1]	146	0.05 (0.03 – 0.09)	2128	33,109
$3-6 million					
$5,901,000	Compulsory vaccination, target 60% of population	82	0.50 (0.40-0.59)	9024	18,596
$3,187,000	Compulsory vaccination, target 30% of population	82	0.55 (0.45-0.62)	9921	18,596
Under $3 million					
$2,735,000	LITS only, reduced voluntary enrollment[2]	44	0.21 (.13-0.30)	2221	10,064
$2,640,000	LITS + vaccination combined, reduced voluntary enrollment[2]	44	0.06 (0.04-0.09)	696	10,064

[1] Assumed participation by 67% of ranch, 67% of semi-intensive, and 2% of agro-pastoral herds
[2] Assumed participation by 30% of ranch, 30% of semi-intensive, and 1% of agro-pastoral herds
[3] Assume 227 working days per year
[4] Assume that in compulsory vaccination scenarios, 20% of cattle offtake from region would be destined for export abattoirs

Discussion and conclusions

The aim of this study was to evaluate the expected costs and impacts of several strategies for risk reduction of FMD prevalence among slaughter cattle in East Africa, with the ultimate objective of identifying promising and/or dead-end paths to guide plans and investments. Preventive mass vaccination was the least cost-effective strategy and would face a number of barriers to successful implementation. Strategies that involved voluntary rather than compulsory participation had more favorable cost-effectiveness ratios. The greatest reduction in risk at the lowest cost was obtained through a voluntary program that combined a Livestock ID and Traceability System with biannual preventive vaccination and a premium price at slaughter for participants. The results can contribute to planning beef export strategies that are aligned with local goals and capacities for East African countries and other regions with endemic FMD.

Mass vaccination of the cattle population in a region has been a successful strategy for FMD control and elimination in some countries but can be an expensive and often cost-prohibitive approach (Jemberu et al., 2016). To be effective, preventive vaccination must achieve a high level of coverage in the susceptible population with a potent vaccine matched to circulating serotypes and strains and must be coupled with other disease control measures (Ferrari et al., 2016). Even when a biannual vaccination schedule is carried out routinely and as planned, 20-40% of the population may have been vaccinated either never or not for a year or more (Knight-Jones et al., 2016a) at the time of the next round. Given the challenges experienced by Kenya and Uganda in expediently delivering ring vaccination or enforcing movement controls in the face of outbreaks (Compston et al., 2021; Muleme et al., 2012; Munsey et al., 2019), it is difficult to expect that the necessary coverage to achieve population-level protection from disease would be achieved. Movement of cattle across borders within and between countries, a common occurrence in both of the pilot areas considered, would add further complications. This intervention would require a relatively high investment for not the best return with many obstacles on the path, and may not be an advisable strategy especially for the purpose of targeting export opportunities.

The most cost-effective strategy was a voluntary program for producers in which cattle would be registered in a LITS system and vaccinated twice a year against FMD. This would be carried out in partnership with an export abattoir that would inspect all cattle at slaughter and only accept healthy, identified cattle who are registered in the system. In return, they would pay a premium price per kilogram which would be subsidized as part of the program design (i.e., incorporated into the estimated costs). The premium increases the implementation cost but can be thought of as an investment in the success of the program, considering that farmers may not be inclined to participate without an incentive and, if a program such as LITS were mandated without a choice, may be suspicious or afraid of losses and therefore find ways to get around the system. A reason for the relative cost-effectiveness of the combination strategy relative to a voluntary LITS-only program is that the premium was reduced by 50% on the assumption that producers would also be incentivized to participate by the opportunity for regular FMD vaccination.

The voluntary nature and partnership with an abattoir sets up other potential benefits of this approach, by giving agency and ownership to producers while building programs that would help veterinary services to do their job of serving the public good, including both those participants and others in the region. An important consideration is how incentives and information would flow between the abattoir and producers. It is common for traders or brokers to serve as a middleman between the farm and the abattoir, but this could disrupt the farmer's ability to receive the premium price for their cattle and to swallow the financial consequence if an animal is rejected or condemned. An alternative approach could be for the producers collectively to contract their own ways of transporting cattle to slaughter that don't involve the exchange of money or ownership. This could serve additional benefits of more closely integrating producers with the market fluctuations, enabling them to better take advantage of positive dynamics (Rich and Perry, 2011a). Furthermore, risk assessment of these systems has shown that any steps to reduce commingling with cattle from other herds that could be sources of possible exposure to infectious FMD can result in a substantially lower risk of acquiring infections before slaughter (Chapter Four). By handling transportation individually or in concert only with other participating herds, this approach could have risk reduction impacts beyond what was shown in the model. More generally, this voluntary program will select for the most commercially-oriented producers and partner them with an abattoir that is export-equipped and ambitious to expand their opportunities. By bringing together value chain actors who share a common goal and need each other to get there, this intervention could cultivate the local ownership needed for such a program to be successful beyond the initial pilot. Such collaboration is not simple in practice, and several mechanisms of the partnership would need to be clearly established before starting. These include the specific terms for how the producer would receive the premium so there is no risk of anyone feeling cheated or mistrustful, what would happen after the five year program has ended, and what would happen if the abattoir is being under- (or over-) supplied by cattle in the program relative to the throughput needed to be profitable.

One final benefit of the combination approach is the synergy of combining livestock identification and traceability with regular vaccination. First, having animals identified and in a database would allow registration of health events (such as vaccination) to enable tracking of the vaccination, immunity, and health or disease status of individuals. This could be used to monitor and improve the efficacy of the vaccination program and to guide vaccination strategies in other contexts, perhaps for targeting high risk populations or even to know if the vaccines being used for ring vaccination and outbreak response are protective against circulating strains. The routine vaccination and recording of this relatively small population of cattle could be used to refine the necessary aspects of effective vaccination including source, potency, quality assurance, and administration logistics. Having a better handle on these aspects of a vaccination program could improve general trust in the vaccine and its value for improved compliance and buy-in during future vaccination efforts. The identification and registration system could also be used for recording antibiotic and acaricide use as well as vaccination programs for other OIE notifiable diseases in the area, further improving animal health and efficiency.

Feedlots are rare but increasing in prevalence in Kenya as a way to concentrate cattle from many sources and finish / fatten them before slaughter (Agriterra, 2012; Gikonyo et al., 2018a). Focusing on feedlots as a source of cattle for export could be an interesting strategy, especially if those feedlots are supplied by cattle from private ranches and pastoralist herds and so would drive the supporting agricultural economy. However, it would be crucial to make sure there would be a market in which that meat would be competitive and profitable before making major investments, and especially to think about sources and prices for feed and forage given the expected trends and volatility of climate change over the next decade and beyond. The high cost of inputs can be a limiting factor to the profitability of feedlots in the region (Agriterra 2012, Kahi 2006, Rich et al. 2009). Even the low probability estimated by the model (one animal infected at slaughter out of 100) would not suffice to access a high-value (FMD-free) market, and substantial investment would need to be made for entry to any market with minimum FMD and sanitary requirements. Feedlots would need to strategize how they would manage FMD regarding a) incoming animals, b) surrounding livestock and wildlife in the region, c) what happens when there is an outbreak detected on a farm, and d) what happens when there is a positive individual or outbreak detected at the abattoir. They would need to secure adequate and timely support from a diagnostic lab, vaccine supplier, and Veterinary Services and of an abattoir committed to the necessary animal and carcass handling protocols, quality assurance procedures, and potential investment in additional traceability and transparency measures. They may consider additional investments in electronic identification systems for maintaining health and production records and a contract with Veterinary Services for developing and certifying a farm biosecurity plan. Careful planning of the resources required, capacity available, and beef price and demand expected should be carried out before assuming that a high input feedlot system would generate the required high return.

This study has a number of limitations, most notably a large number of assumptions about how intervention strategies would be structured and events would unfold. Any of these programs would require partnership and buy-in from diverse stakeholders to be effective, and the first step of any intervention would be to identify those key partners to hear out their own goals and motivations and their capacity to participate. It would also be important not to neglect or create a negative relationship with those who do not participate, and to place an emphasis on communicating positive impacts for both the participants and for the whole region.

More technically, there are three primary limitations in the modeling approach that could impact the outcome and interpretation of results. The first is that each infected animal at slaughter is treated as independent, without incorporating other cascading events that are in motion when an event occurs. In reality, an infection is presumably part of an outbreak-- correlated with other infection events rather than randomly distributed throughout the year-- and there is a response by actors in the system when an infection is found. Incorporating these dynamics would not be expected to change the general trends observed in the results, but these factors should be considered before leaning too hard on the absolute values of risk produced here. Second, the mechanism of impact of vaccination utilized is simplistic and does not incorporate population dynamics over time or information about the actual effectiveness of vaccines used in each region against strains circulating. A modeling exercise, possibly combined with a pilot study to collect the necessary data specific to the region, could be used to refine the estimates of impact. At minimum, tracking vaccine effectiveness and immunity in the population would be a crucial piece of monitoring and refining a vaccination strategy. Finally, an important factor in both the cost and impact estimates was the relative participation by each production system and the offtake rate of cattle for slaughter expected from each. These figures could be finely adjusted with better knowledge of who would be expected to enroll, herd offtake and growth trajectories, and if/how participation in this program would potentially influence those projections in order to have a more concrete sense of costs to expect.

The decision for Kenya or Uganda to move forward with any strategy here depends on evaluating the benefits expected as a result. These could be considered in the categories of market access and animal health / productivity. Improvements in market access depend on what level of risk would be acceptable in target markets (assuming that CBT was accepted as a viable approach to achieve and demonstrate acceptable risk). Most likely, markets are dichotomized into those that are vigilant against FMD and would require negligible risk of transmission associated with trade of beef, and those that do not care about FMD and would accept products from these regions even with no interventions. The risk reductions achieved here may land these supply chains in a no-man's land without immediate reward in terms of market access. If there are trade partners that occupy the middle ground regarding their demand for beef and acceptable level of FMD transmission risk, then these interventions could be advantageous for both the importing and exporting partners. More likely, it is prudent to expect market access gains from these investments to come over a longer time horizon after building on the foundational sanitary, traceability, and FMD control progress made here. Incrementally building on an established track record, infrastructure and institutional capacity, and FMD control would then facilitate further progress into more FMD-sensitive markets.

More immediate benefits would largely come in the form of reduced impact from FMD in participating herds. An assessment of benefits associated with decreased FMD incidence should consider costs saved (treatment and control costs, impact of movement restrictions, replacement of sick, dead, or aborted animals) and revenue gained (improved reproductive efficiency and resulting gains, increased weight at sale for healthy animals). Additional though less easily quantified benefits could also include increased revenue for producers by increasing their agency and access to market information in the value chain. The LITS system may facilitate more effective vaccination for other important diseases in the area, further improving animal health and efficiency. If found to be economically favorable, then this type of intervention could be coupled with efforts to promote and develop the beef economy, focused on markets where the product is competitive based on its price and quality without necessarily requiring an FMD-free status for entry, while laying the foundational bricks of systems for traceability and disease control.

In summary, this analysis and discussion provide content for productively managing expectations regarding the development of export markets from Kenya and Uganda. The voluntary, combined LITS and vaccination program could be a way to achieve value for producers right now (e.g., through improvements in animal health and productivity) while also being strategic about developing future value. Even without immediate increases in revenue associated with a higher market value, they can focus on increasing the demand for, quality, and efficiency of beef produced, implement disease control and traceability systems, and be ready for the next round of strategic analyses to make another step forward from there. This builds on the spirit of the FMD Progressive Control Pathway. Though focusing on the risk associated with trade of the final product rather than disease occurrence in the region, this framing utilizes the same progressive approach to FMD management in order to achieve incremental steps forward.

These results may help review the steps proposed in the PCP, to move from the geographically-based management of risk, currently proposed, to a strategy associated with the reduction of risk in the product, which may be best adapted to the African context while mitigating risk for importing markets.

Appendix

Table 5-A1: Inputs for estimating cost of LITS only scenario

	Estimate	
Inputs	**Uganda**	**Kenya**
Cattle population in region	641,000	1,190,000
% that will voluntarily enroll	0.215	0.12
# cattle enrolled, initial	137,815	142,800
% new each subsequent year (of total pop)	0.24	0.18
# cattle enrolled, each subsequent year	33,076	25,704
% slaughtered per year	0.24	0.18
# slaughtered per year	33,075.6	25,704
working days/yr	227	230
head/working day, avg	146	112
cost per tag	$ 1.00	$ 1.00
cost per applicator	$ 30.00	$ 30.00
cost per motorbike	$ 1,500.00	$ 1,500.00
cost of fuel + maintenance per motorbike per day	$ 15.00	$ 15.00
monthly cost: office security, cleaning, AC	$ 100.00	$ 100.00
monthly salary IT development + support position	$ 2,000.00	$ 2,000.00
monthly salary program coordinator: full time	$ 2,000.00	$ 2,000.00
monthly salary farm coordinator: full time	$ 800.00	$ 800.00
monthly salary abattoir inspector: full time	$ 800.00	$ 800.00
per diem for AHAs by sublocation: initial enrollment	$ 30.00	$ 30.00
premium paid by abattoir per kg	$ 0.27	$ 0.27
kg/carcass, average	140	140

Total, year 1	**$ 1,741,384.79**	**$ 1,472,000.96**
Total per year, years 2-5	**$ 1,381,500.68**	**$ 1,099,646.28**
Total for 5 year program	**$ 7,267,387.53**	**$ 5,870,586.08**
Year 1 -- start-up + first year costs	**$ 1,741,384.79**	**$ 1,472,000.96**
Materials	**$ 141,949.45**	**$ 147,084.00**
Tags	137,815	142,800
Applicators	138	143
Database + infrastructure	**$ 115,000.00**	**$ 115,000.00**
Hardware, software, server, developer + admin	$ 100,000.00	$ 100,000.00
Office space (cost/yr)	$ 9,000.00	$ 9,000.00
Additional hardware / IT / office costs	$ 6,000.00	$ 6,000.00
Human resources	**$ 229,200.00**	**$ 229,200.00**
IT development + support position (full time)	1	1
Program coordinator, veterinarian (full time)	1	1
Farm/data coordinator, AHA (full time)	1	1
Inspector/monitor at abattoir (full time)	1	1
Animal identifiers, 1 per sublocation x 30 days	180	180
Enrollment + implementation	**$ 23,500.00**	**$ 23,500.00**
motorbikes	1	1
motorbike fuel + maintenance (days)	200	200
Unexpected start-up costs	$ 3,000.00	$ 3,000.00
Stakeholder consultation + awareness	$ 15,000.00	$ 15,000.00
Development of program SOPs + guidelines for each stakeholder group	$ 1,000.00	$ 1,000.00
Training on program procedures	$ -	$ -
Subsidy to abattoir for piloting program + premium payments to producers	**$ 1,231,735.34**	**$ 957,216.96**
Years 2-5 -- annual needs	**$ 1,381,500.68**	**$ 1,099,646.28**
Materials	**$ 41,165.34**	**$ 33,829.32**
# tags	39,966.35	32,844

# applicators	39.96635	32.844
Database + infrastructure	**$ 34,000.00**	**$ 34,000.00**
database maintenance	$ 25,000.00	$ 25,000.00
office space	$ 9,000.00	$ 9,000.00
security, cleaning, AC	$ 1,200.00	$ 1,200.00
Human resources	**$ 67,200.00**	**$ 67,200.00**
IT development + support position (full time)	1	1
Program coordinator, veterinarian (full time)	1	1
Farm/data coordinator, AHA (full time)	1	1
Inspector/monitor at abattoir (full time)	1	1
Other ongoing	**$ 4,200.00**	**$ 4,200.00**
motorbike fuel + maintenance (days)	200	200
stakeholder meetings - 1 per year	$ 1,200.00	$ 1,200.00
Abattoir subsidy	**$ 1,231,735.34**	**$ 957,216.96**
Monitoring + evaluation / improvement	**$ 3,200.00**	**$ 3,200.00**

Table 5A-2 Inputs for estimating cost of vaccination only scenario

Inputs	Uganda	Kenya
Cattle population in region	641,000	1,190,000
% of population enrolled	100%	100%
doses / cow / year	2	2
doses/year	1,282,000	2,380,000
cost/dose	$ 1.40	$ 1.20
working days/year	227	230
offtake	*0.145*	*0.14*
# head cattle /day	*81.88986784*	*144.8695652*
pay/mo for vx team members	$ 700.00	$ 700.00
cost of fuel/d for vx	$ 10.00	$ 10.00
cost/syringe	$ 41.00	$ 41.00
cost/needle	$ 0.27	$ 0.27
# doses per syringe lifetime	10,000	10,000
# doses per needle	50	50
cost/coveralls	$ 22.00	$ 22.00
cost/boots	$ 8.00	$ 8.00
cost/ice pack	$ 9.00	$ 9.00
cost/cooler	$ 45.00	$ 45.00
doses/bottle of vx	100	100
fridge storage capacity (bottles)	320	320
cost per fridge	$ 555.00	$ 555.00
cost per sample (shipping + testing)	$ 15.00	$ 15.00
cost - back up generator	$ 1,500.00	$ 1,500.00
Cost distr + delivery per dose	$ 0.07	$ 0.08
Total start-up costs	**$ 27,617.34**	**$ 38,639.06**
Total costs per year	**$ 1,898,415.00**	**$ 3,048,762.00**
Total program cost	**$ 9,519,692.34**	**$ 15,282,449.06**
Start-up costs	**$ 27,617.34**	**$ 38,639.06**
Storage	**$ 12,617.34**	**$ 23,639.06**
Bottles of vaccine per 6 mo.	6,410	11,900
# refrigerators	20.03125	37.2
Back-up generator	1	2

Engagement	**$ 15,000.00**	**$ 15,000.00**
Stakeholder consultation + awareness	15,000	15,000
Yearly costs	**$ 1,898,415.00**	**$ 3,048,762.00**
Vaccine cost	**$ 1,794,800.00**	**$ 2,856,000.00**
Vaccine doses	1282000	2380000
Storage	**$ 2,000.00**	**$ 4,000.00**
Electricity / generator fuel	$ 2,000.00	$ 4,000.00
Delivery	**$ 82,410.00**	**$ 158,100.00**
# vx'd per team per day	1,883	1,725
# teams	3	6
# people per team	3	3
transportation/team/day	$ 30.00	$ 30.00
Supplies	**$ 13,205.00**	**$ 24,662.00**
syringes	128.2	238
needles	25,640	47,600
boots per person	2	2
coveralls per person	2	2
coolers per team	2	2
ice packs per team	8	8
Sero-monitoring	**$ 6,000.00**	**$ 6,000.00**
# animals sampled	400	400
# sampled per team per day	40	40
# sampling days required per team	3.3	1.7

Chapter 6: Conclusion

The objective of this project was to characterize the probability of FMD infection among cattle at slaughter in Kenya and Uganda and to evaluate the cost-effectiveness of interventions to reduce that risk. The purpose was to generate evidence and insight for plans about how (and if) to pursue entry to international beef markets which would require demonstrating a negligible risk of FMD transmission associated with exported goods. This approach provides a framework for other FMD-endemic, beef trade-aspiring countries to similarly gauge what actions and systems would be needed to reach an acceptable level of risk, and the cost and capacity required to support such investments.

The first step was to characterize the appropriate populations, structure, and variables to construct a model for risk assessment among cattle at slaughter in Kenya and Uganda. Chapter 3 describes how this was achieved by partnering with East African veterinarians enrolled in an extended training program to build capacity related to international trade. Because the objective was to enable creative thinking about risk in specific value chains, it was important to have granularity about how the risk level and processes vary between systems in order to later brainstorm and evaluate potential interventions. This approach addressed two major and related hurdles to traditional risk assessment: a) data scarcity, especially in places that tend to have diverse and informal value chains, and b) tapping into unwritten local knowledge / subject matter expertise in a way that generates credible information that can be used for quantitative analysis.

The results of this work revealed several insights relevant to mapping and analysis of livestock systems more generally. We found that risk processes differ between management systems, with an especially clear delineation in Kenya between agro-pastoral/pastoral and ranching/feedlot system groups-- highlighting the important interactions between management factors and health or risk dynamics. Second, the results highlighted that FMD infection and sale for slaughter are not always independent events for cattle in Kenya and Uganda. This finding reinforces the importance of learning about causal and correlational dependencies between variables in a specific setting being modeled. Specifically, for risk assessments examining the movement or sale of animals in endemic environments, we suggest it would be judicious to characterize the relationship between sale and disease of cattle in the population of study. Finally, the decision of an inspector to report an animal suspected of FMD infection (instead of ignoring or falsifying the result) was identified as an event on the risk pathway, separate from the sensitivity of an inspection to diagnose disease. This underscored how the motivations and actions of value chain actors influence the ultimate risk level in a product and should be acknowledged to improve the accuracy of model estimates and effectiveness of policy design.

The second step was to use the information from aim one to quantify the baseline risk -- the probability of infection at slaughter -- for animals originating from each production system. This step involved specifying input values and distributions for the variables identified in aim one and translating the conceptual relationships into a probabilistic mathematical model, as described in chapter 4. Given the endemicity and prevalence of FMD in cattle systems, and the extent of commingling that occurs by the time of slaughter, the probability of infection among cattle from all eight production systems evaluated was estimated to be not negligible, though the overall risk was substantially lower for cattle originating from Kenyan feedlots and ranches compared to the other six systems evaluated. In Uganda, semi-intensive and ranching systems showed the potential to reach similarly low risk levels if able to severely limit the exposure to new infections after leaving the herd. It is notable that these four systems are the most commercially oriented and the least prevalent in both countries. This indicates that interventions intended to lower infection risk among cattle at slaughter with an objective of improving market opportunities could be most successfully implemented if focused on regions and supply chains with a relatively high concentration of these systems.

The risk estimates and sensitivity analyses provided insight about influential factors that could be leveraged to lower the probability of FMD among beef cattle at slaughter from select populations. We found that animals infected en route were more important than those infected from the herd of origin for nearly all production systems (exceptions were ranches in Kenya and pastoralists in Uganda). For Kenyan ranches, the detection and removal of infected animals was identified as a potentially important point for intervention. Based on these findings, several candidate intervention strategies were identified. One approach was preventive vaccination to provide protective immunity for cattle in these systems: by reducing both the prevalence and transmission of disease, this approach could effectively lower the probability of infection through both risk pathways (infection at the herd of origin or en route to slaughter). Another option was to improve the quality and probability of FMD detection at the abattoir, something naturally coupled with a system for animal identification and traceability. An alternative approach was to focus on creating and improving value chains with animals exclusively sourced from feedlots and/or ranches in Kenya, given the distinctly lower risk associated with cattle from these systems.

One final observation was that the prevalence of disease in the herd of origin had relatively little influence in determining the probability of infection at slaughter for cattle who would potentially be commingled with infectious animals through the processes of transportation, sale, and holding before slaughter. Focusing scarce resources on limiting disease at the farm level without also reducing exposure opportunities between farm and slaughter would be relatively ineffective.

The third step was to evaluate the cost-effectiveness of interventions that could reduce risk in specific value chains. Scenarios were generated using the insights from step two and compared based on estimated costs and the level of risk expected to achieve. The scenarios evaluated were a livestock identification and traceability system (LITS), preventive vaccination campaign, and a combination of both LITS and vaccination, all assessed for Narok County, Kenya and the South Western region of Uganda. An additional scenario of herd-level biosecurity among feedlots in partnership with an export abattoir in Kenya was also evaluated. Preventive mass vaccination was the least cost-effective strategy, even for a relatively small region. It would require a relatively high investment for not the best return with many obstacles on the path, and may not be an advisable strategy especially for the purpose of targeting export opportunities. Strategies that involved voluntary rather than compulsory participation had more favorable cost-effectiveness ratios. The greatest reduction in risk at the lowest cost was obtained through a voluntary program that combined a LITS system with biannual preventive vaccination and a premium price at slaughter for participants. This strategy capitalized on synergy between two simultaneous types of intervention for both cost savings and compounding of benefits. More generally, this voluntary program would select for the most commercially-oriented producers and partner them with an abattoir that is export-equipped and ambitious to expand their opportunities. By bringing together value chain actors who share a common goal and need each other to get there, this intervention could cultivate the local ownership needed for such a program to be successful beyond the initial pilot.

Evaluation of the benefits expected from pursuing those strategies can guide if and how to move forward. Reduced impact of FMD will generate positive returns through improved health and efficiency and avoided costs of treatment and control. Immediate benefits from market access may be negligible if the risk level achieved is not acceptable to targeted trading partners. While a significant reduction from the baseline probabilities of 0.53 and 0.56, these results still do not translate into a negligible level of risk (considering 4,100 (Kenya) and 2,100 (Uganda) infected cattle slaughtered per year based on the assumptions about participation and offtake rates for this scenario). More likely, it is prudent to expect market gains from these investments to come over a longer time horizon as they become stepping stones to continuous improvement.

The novelty of this thesis work is associated with proposing the use of a risk analysis framework to create a pathway for the progressive control of FMD considering commodity base trade (rather than disease elimination) as the ultimate goal. An immediate impact of this framework is that the insights generated here can guide priorities for investment in beef supply chains, specifically regarding how and if to target international markets with FMD-related barriers to entry.

In order to use commodity-based trade as a pathway to overcome such barriers, a country would need to achieve and demonstrate a level of FMD-transmission risk associated with the product that is acceptable to target markets. To move beyond commodity-based trade *per se* towards competition in premium, FMD-free markets, this risk would further need to be equivalent to that presented by the export of beef from zones or compartments recognized as free from FMD. The OIE Terrestrial Animal Health Code (TAHC) recommends procedures for the export of beef from countries or regions where disease remains endemic, including the following: cattle have been for three months in a zone where vaccination occurs regularly and an official control program exists, have been vaccinated at least twice with appropriate timing relative to slaughter, were held for 30 days in a quarantine or establishment with no FMD occurrence within 10 kilometers, have been transported directly to slaughter with no contact with other animals, have been slaughtered in an officially designated abattoir, subjected to ante- and post-mortem inspections within 24 hours each side of slaughter, and carcasses deboned with lymph nodes removed and appropriate maturation procedures including pH testing (TAHC Article 8.8.22). The risk assessment and scenarios evaluated here were created to assess the current and potential risk associated with beef produced from Kenya and Uganda with reasonable interventions made in the existing systems and processes, rather than assuming a prescribed set of procedures. They demonstrate that under baseline conditions, the probability of an infected animal at slaughter from any production system is greater than the risk that would be associated with animals originating from the steps outlined above. Under the intervention scenarios evaluated, the lowest possible risk achieved would be through working exclusively with highly-organized, vertically integrated systems (such as feedlots) that could implement and document their own biosecurity and animal health protocols. This approach would exclude the overwhelming majority of the cattle value chain. The other scenarios evaluated, to include a larger region or pool of producers, indicate that there is no silver bullet that can be purchased or funded to transform existing systems and supply chains into beef exporters with an equivalently low FMD transmission risk.

As an alternative to premium, FMD-free markets, the countries could negotiate bilateral agreements with regions that have more lenient FMD requirements—willing to tolerate a risk higher than that specified by OIE standards but that place some value on FMD management and documentation. This approach would require identification of those specific markets and their requirements, and consideration of competing beef suppliers who would also be eligible to sell to those markets if a CBT-based approach was adopted. Specific partners should be identified and the expected beef price and demand in that market evaluated before moving forward with investments expectant of revenue generated from trade with this type of region.

A remaining option is to shift away from targeting FMD-sensitive markets altogether and to develop exports to beef deficit countries that do not require a particular FMD risk associated with the product. In this case, investments could focus on making beef production more efficient, competitive, and profitable. Efforts to control and reduce the impact of FMD would be in hand with other disease control and animal health measures along with steps taken to improve management, nutrition, and marketing, but would not require the depth in animal health investments as noted above.

Given those options and the insights and results of this work, the recommendation regarding development of the beef sector in these two countries is to focus on improving the efficiency and quality of beef produced and the supporting institutions and infrastructure; not to expect or depend on premium market access, though keeping requirements related to SPS and FMD on the radar for the longer time horizon. Feedlots and other value chains featuring vertical integration could initially focus on improving the efficiency of production, then target a decreased risk associated with the product and improved SPS capacity (through steps such as those described in this work), possibly with the eventual goal of becoming a disease-free compartment (requirements as defined by TAHC Article 8.8.4 include the presence of an official control program and absence of vaccination). If achieved, a disease-free compartment could then target premium markets with a beef product that they have already developed and demonstrated to be competitive in regional markets. In regions with a concentration of commercially-oriented producers and abattoirs, investments should focus on cultivating, improving, and incentivizing the production of efficient, high quality beef products. They should establish institutions and infrastructure that can support a healthy and thriving livestock population now and could implement an official disease control program (for FMD and other important livestock diseases) and potentially other SPS requirements in the future. The analytical framework used here could help identify investments that would support these goals of incremental improvement, as outlined below.

This body of work generated two innovative contributions to the practice and application of risk analysis for animal health and trade. The first is an approach to evaluating interventions to manage FMD that builds on the spirit of the Progressive Control Pathway, focused on the risk associated with trade of the final product rather than disease occurrence in the region. The second is a participatory method of building, parameterizing, and applying analyses during such evaluations to improve the quality of results as well as the impact of the process.

The approach utilized here demonstrates a framework for evaluating investments related to control of endemic transboundary disease control and market access that integrates the complex context of animal health, production, and trade. This risk for transmission of the transboundary disease (here, FMD) can be lowered to a level acceptable to trade partners by either eliminating disease in the source population and region, or by taking measures to reduce the risk in the final product (commodity-based trade). The Progressive Control Pathway has established the importance of incremental achievement toward disease management for eventual elimination or control of disease in the region. A similar progressive approach could target stepwise improvement of the risk in the commodity, working toward market access through CBT. That approach, demonstrated here, requires (first) understanding and estimating the baseline risk associated with beef produced by specific supply chains and (second) the expected impact of interventions that could modify that risk. This estimation provides a way to benchmark and demonstrate improvements in the risk of the product associated with possible mitigation measures, allowing (third) comparison of interventions based on cost-effectiveness and expected benefits and tradeoffs. Such benefits may not immediately include market entry: incrementally improving the transmission risk associated with the product creates a gradation of risk in the supply but does not guarantee that the same gradation exists in the demand. It should not be automatically assumed that any progress made by the would-be exporter will result in a corresponding level of increase in new market access. Even so, risk metrics can (fourth) guide incremental improvements in order to gain ground toward a level of risk acceptable to FMD-sensitive markets while also considering more immediate domestic priorities for livestock health and production. These metrics can be used to support, rationalize, and compare projects that move a country or value chain toward market access in contrast to ambitious but ungrounded claims that may be unrealistic, unsuccessful, and an ultimately unrewarding use of resources.

It is worth noting that such interventions are often framed as a pathway out of poverty through development of international export markets for beef. It is important to remember that successful international trade depends on both market access and the ability to sell a profitable product once in that market. When interventions are proposed for the purpose of achieving market access, it is necessary to eventually circle back and interrogate the expected reality if that particular bottleneck of market entry is removed.

The participatory and systems approach to risk analysis presented here has particular value for contributing to the analysis and decision framework described. The partnership with local professionals in a hybrid between participatory and expert elicitation techniques was novel in an animal health setting and beneficial in how it gathered information to be able to characterize and quantify risk in data-scarce settings, and in the quality of information collected-- giving insight into causal relationships to help inform an appropriate model structure and risk management strategies. The real opportunity would be to continue that type of partnership into the intervention evaluation stage. Firsthand knowledge of how the systems work could improve both the design and representation (model) of candidate interventions that are appropriate for the reality of the local setting. Costs, inputs, and other quantitative parameters could be derived while incorporating qualitative and quantitative insights about human actions and incentives as well as important dependencies and dynamics that could substantively impact modeled results. Group model building of system dynamics models (Lie et al., 2017; Vennix, 1996) could be a template for planning and facilitating this type of approach that harnesses the rich, qualitative knowledge of participatory activities while also collecting quantitative insights to inform model structure and parameters.

The other benefit of our participatory approach was its placement within a capacity-building course for veterinary professionals. This ensured that participants had been trained in the concepts and basic methods of risk assessment applied to animal health and so were equipped to contribute as subject matter experts with an understanding of the techniques and rationale being used. It also provided the environment, platform, and relationships to facilitate the iterative process and questions with discussion that provided the quality of information for a useful analysis. Perhaps more importantly, there was the expectation that this activity would be something that enhanced their own capacity-- to use the technique being demonstrated, and to improve and refine their perspective of the system they work in and its interacting components. As professionals who are invested in improving animal health and livestock systems, their planning and decisions impact the outcome being discussed. It is reasonable to expect that the participatory exercise of mapping and interrogating the system, risk factors, and relationships from many professional viewpoints contributed to an updated understanding of their own role related to FMD and trade. The intention was also to demonstrate the value of systematically evaluating options in the context of where and how they will be applied, modeling the framework described above in action. From here, it would be beneficial to utilize monitoring tools such as pre- and post-evaluations of participant knowledge to verify, compare, and improve the combined training and elicitation activities in achieving such outcomes. The continued development and practice of similar participatory approaches-- that facilitate robust, data-driven evaluation and planning in partnership with the decision-makers of the local system-- will generate positive impact regardless of the model output or resulting decisions made.

In summary, the output and process of this work provide useful contributions to improve decision-making regarding investments for animal health and trade in regions with endemic trade-sensitive diseases. In Kenya, a feedlot-focused, abattoir-partnered approach may reach the lowest, most cost-effective, achievable risk. Specific opportunities need to be evaluated in terms of the capacity, cost of SPS investments, costs of production, and competitiveness of the resulting product. In both Kenya and Uganda, regionally-focused investments in LITS and vaccination among willing producers and an ambitious export abattoir could be an avenue to make gains in FMD and animal health while reducing risk in the product produced and taking steps toward foundational traceability and disease control capacity. The framework of incremental progress with a focus on commodity risk complements the FMD-PCP, providing a way to benchmark slow and steady forward motion, and should be used to evaluate disease control and SPS interventions that intend to achieve market access. Participatory approaches that embed data collection for decision analysis into training opportunities for local professionals are a rich way to improve the quality of data and analysis while also building capacity of participants to appreciate the complexity of systems in which they work and the value of analytical approaches to decision-making.

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