A framework for ecologically and socially informed risk reduction before and after outbreaks of wildlife-borne zoonoses

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Lancet Planet Health 2025; 9: e41–52

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Despite increasing emphasis being placed on the inclusion of upstream ecological and social perspectives for zoonotic disease control, few guidelines exist for practitioners and decision makers to work with communities in identifying suitable, locally relevant interventions and integrating these into public health action plans. With an interdisciplinary group of Kenyan stakeholders, we designed and tested a comprehensive framework for the co-design, evaluation, and prioritisation of beneficiary-oriented, ecologically and socially informed interventions for preventing and controlling outbreaks of wildlife-borne zoonoses. Our approach used four globally important wildlife-borne pathogens—Rift Valley fever virus, Congo–Crimean haemorrhagic fever virus, and the causative agents of anthrax and rabies—enabling stakeholders to develop a shared understanding of complex transmission pathways, identify a broad array of measures targeting ecological, biological, and social processes governing outbreaks of these pathogens, and explore trade-offs for specific interventions. The framework can be applied early in the decision-making process to encourage broader, cross-sectoral co-production of knowledge, ideas, and consensus on the control of complex zoonotic diseases.

Introduction

Zoonotic diseases, which sit at the juncture between ecosystems and human and animal health, pose one of this century's greatest threats to human wellbeing. Although wildlife is often associated with newly emerging or re-emerging human pathogens (of which approximately 70% detected between 1940 and 2006 originated in wildlife), they also contribute to the epidemiology of many endemic zoonoses, such as rabies, brucellosis, and leptospirosis.[1–4] Zoonoses for which wildlife populations are likely (but not necessarily obligate) reservoirs and have an important role in their epidemiology, therefore, represent a considerable risk to people.[5] Henceforth, we refer to these as wildlife-borne zoonoses. Other important examples include diseases caused by rodent-borne viruses (such as Lassa virus), anthrax (caused by *Bacillus anthracis*), and diseases caused by some enteric bacteria.[6–8] The impacts of many of these diseases are highest in tropical countries, where human populations, who often also keep livestock, have close interactions with wildlife and the urban, forest, or rangeland environments in which they live.[9] In these settings, transmission between animals (both domestic and wild) and humans occurs against a backdrop of dynamic and often challenging environmental and social conditions (such as climate change, habitat fragmentation, and inadequate access to health care) that can amplify disease risk and determine the degree to which wildlife-borne disease hazards are realised.[10]

The complexity of linked social and ecological (henceforth socioecological) systems poses challenges and opportunities for the control of wildlife-borne zoonoses. The socioecological context potentially renders conventional medical and veterinary interventions less effective for controlling pathogens with complex transmission pathways. For example, the sensitivity of vectors such as mosquitos to changing climatic conditions can complicate efforts to target vaccination of livestock against Rift Valley fever virus.[11,12] However, if each epidemiological step in these transmission pathways is viewed as a leverage point at which key ecological or social processes can be disrupted, a wider array of possible interventions can be unlocked.[13] Because many of these leverage points sit upstream of human or livestock infection (eg, agricultural and conservation land-use policies that have the potential to mitigate disease risk, manipulation of infection dynamics in wildlife reservoirs and vectors, and moderation of contact with people and their livestock), addressing them requires consideration of ecology and sociology in addition to use of conventional epidemiological approaches.[14] Integrating socioecological interventions and conventional approaches allows for an effective and sustainable approach to risk management[13] but also has broad societal impacts on ecosystem integrity, agricultural development, and poverty alleviation that extend far beyond the disease in question.[15]

Despite scientific consensus on the value of applying systems thinking to disease control, the real-world impact of this approach on those who remain at highest risk of wildlife-borne zoonoses in tropical countries has yet to be realised. Broadening public health action plans to include the design and successful implementation of socioecological interventions, together with implementation of policy that is supportive of these actions, is not without its challenges. Due to the difficulty of conducting experimental studies that involve manipulation of natural systems and human behaviour

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and a paucity of investment in research and development, the epidemiological outcomes of many promising ecological interventions remain unmeasured. For example, a recent review of control measures that have both ecological or conservation and public health outcomes found that 70% of proposed interventions had little or no existing evidence.[16] Even when evidence is available, context-specific and pathogen-specific variation in transmission pathways can make it difficult for practitioners—particularly in low-resource settings—to establish the effectiveness of an intervention that might have been successfully implemented elsewhere. Interventions that are sufficiently well understood must be further evaluated to identify whether implementation is feasible, whether they could cause ecological or social harm (eg, negatively affecting biodiversity or ecosystem services or disenfranchising particular members of society), whether they are socially acceptable, and whether goals that might vary between stakeholders (eg, biodiversity conservation *vs* human health) can be met.[16] The process of evaluating and prioritising interventions to achieve locally relevant risk reduction, therefore, requires engagement and approval from a broad range of stakeholders, from communities whose lives are directly affected to scientists and national policy makers working in public health and natural resource management.

An important first step towards mainstreaming the inclusion of upstream socioecological control measures into local and national public health planning is to encourage multisectoral stakeholders—including community members—to develop a shared understanding of complex transmission pathways and the dynamic landscapes in which they operate; subsequently, stakeholders can work together to identify suitable interventions along these pathways. After finding little published guidance for how this goal can be achieved, we have developed a pipeline for the co-design, evaluation, and prioritisation of beneficiary-oriented, ecologically and socially informed interventions for preventing and controlling outbreaks of wildlife-borne zoonoses.

A pipeline for the co-design, evaluation, and prioritisation of prevention and control measures for wildlife-borne zoonoses

We began by designing a conceptual framework to represent the different epidemiological stages at which interventions could be targeted before and after outbreaks of wildlife-borne zoonotic disease occurring in humans or their animals (figure 1). We designed this framework to be easily applicable by different stakeholders according to their objectives and the point at which they sit along transmission pathways. Stakeholders include ecologists, epidemiologists, and communities looking to block transmission from wildlife or livestock (or both) to humans and thereby reduce the likelihood of emergence events, as well as public health officials designing measures to reduce onward transmission to people once an outbreak has occurred. Existing frameworks that describe the ecological and social pathways linking wildlife-borne zoonoses to humans and their animals and the opportunities for targeting interventions along these pathways were used as a guide.[13,17,18]

To test this framework and develop a pipeline to use it to prioritise interventions for wildlife-borne zoonotic diseases, we assembled a group of 24 experts and stakeholders with diverse expertise in zoonotic disease management in Kenya. African rangelands were chosen as a model system because they constitute roughly 43% of the continent's land area and are home to between 50 and 200 million nomadic pastoralists and their livestock, who interact with wildlife through shared resources in landscapes that are known to harbour emerging pathogens.[19,20] Four exemplar wildlife-borne zoonotic pathogens that circulate within these contexts were selected on the basis of their impact on human and veterinary public health in Kenya, global epidemic potential, and differing modes of transmission. Rift Valley fever virus and Congo–Crimean haemorrhagic fever virus are priority WHO emergency pathogens transmitted by mosquito and tick vectors, respectively, whereas anthrax relies on environmental transmission, and rabies is directly transmitted through animal bites.[21] Rift Valley fever, anthrax, and rabies have been prioritised among the five most important zoonoses in Kenya.[22] We purposely selected four pathogens with differing modes of transmission to introduce as much epidemiological variability as possible when testing the framework.

The group met over 2 days in Nairobi to develop the pipeline. We drew inspiration from the co-production process outlined by Asaaga and colleagues.[23] For the duration of the workshop, participants were split into two subgroups, ensuring equal representation of different stakeholders. Facilitators helped steer each subgroup through three participatory exercises, with the intention of circumventing typical power dynamics and encouraging equitable contributions from different stakeholders. Each subgroup was assigned two of the four pathogens (Rift Valley fever virus and *B anthracis* or Congo–Crimean haemorrhagic fever virus and rabies virus) and began by reviewing the epidemiology of each pathogen and how that related to our conceptual framework. Once the groups had developed a shared understanding of the pathogen's transmission pathway, nominal group technique (a participatory consensus-building technique)[24] was used in conjunction with Saaty's Analytic Hierarchical Process (AHP)[25] to collectively identify and prioritise pathogen-specific interventions within the context of our framework and produce a generalisable set of criteria for evaluating these interventions. Evidence-based interventions identified through a scoping review conducted before the

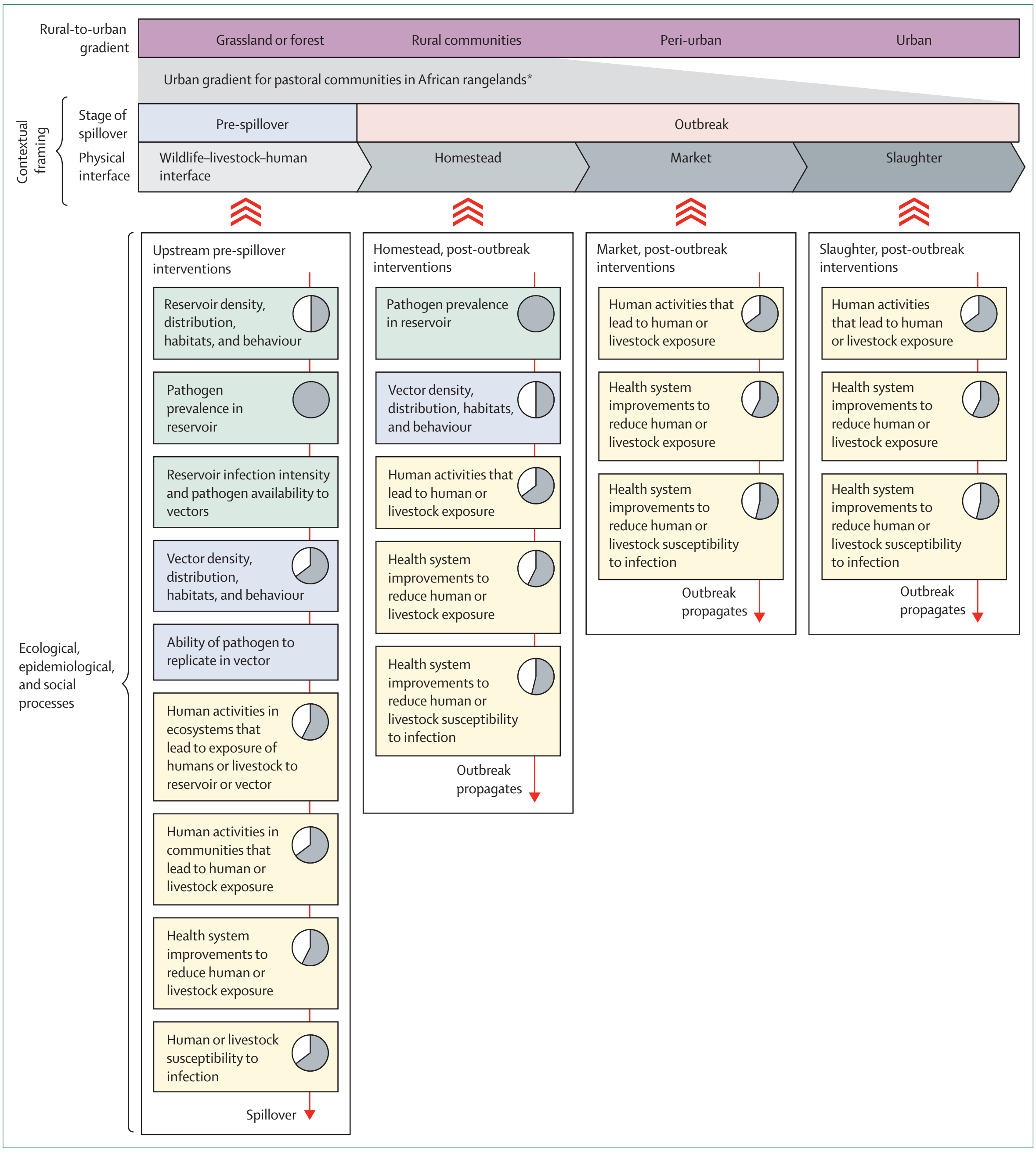

***Figure 1:* Conceptual framework to represent the epidemiological stages at which interventions could be targeted before and after outbreaks of wildlife-borne zoonoses**

The framework consists of three nested hierarchical levels: stage of spillover, physical interfaces (modelled on an African pastoral landscape), and the ecological, epidemiological, and sociological processes taking place within these interfaces. Grey segments within pie charts represent the proportion of evidence-based interventions obtained through our literature review that were also identified by participants during the 2-day workshop to identify and prioritise interventions for four exemplar pathogens. The absence of a pie chart indicates that no interventions were identified through the literature review or during the workshop. Box colours signify whether the intervention describes an ecological (green), epidemiological (blue), or social (yellow) process.*Examples of how the framework could be adapted for other sociogeographical contexts are in the appendix (p 9).

See Online for appendix

workshop were carried forward and considered alongside participants' suggestions.

In this Personal View, we show, step by step, how decision makers and planners operating at the interface of public health and natural resource management could use this pipeline for various purposes. These purposes include developing a shared understanding of target pathogen systems that considers ecology, livelihoods, beliefs, culture, and gender to ensure a locally relevant understanding of risk; identifying

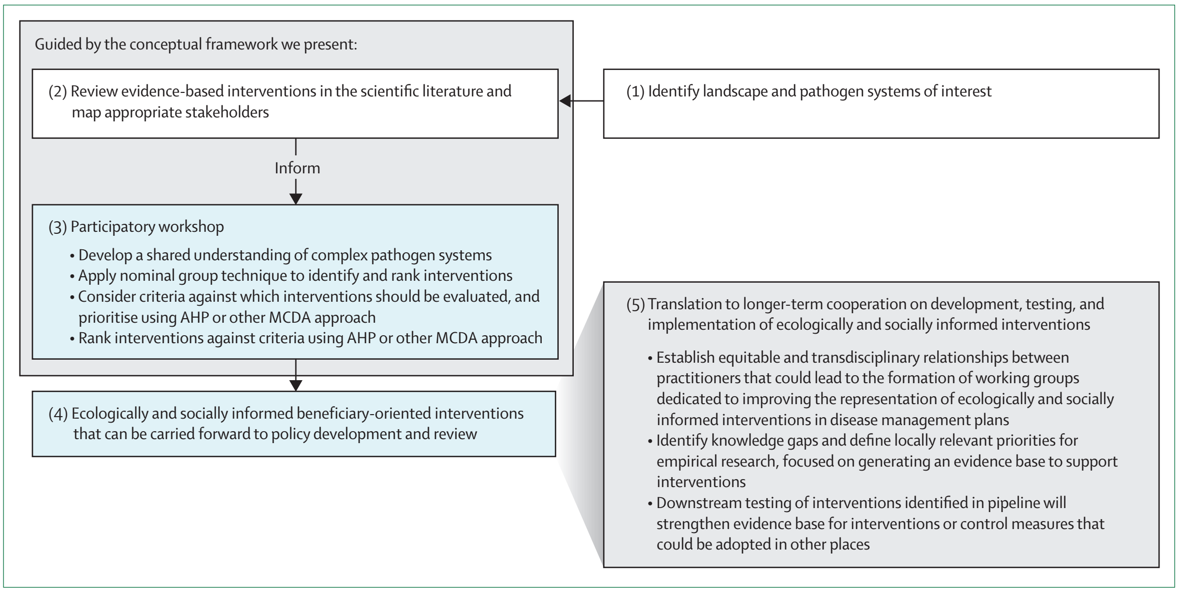

Figure 2: **Overview of our pipeline for the co-design, evaluation, and prioritisation of beneficiary-oriented, ecologically and socially informed interventions for preventing and controlling outbreaks of wildlife-borne zoonoses**
AHP=Analytic Hierarchical Process. MCDA=multicriteria decision analysis.

suitable, pathogen-specific entry points for interventions (preventive or reactive) that are ecologically, socially, or medically informed; and evaluating and prioritising new, locally relevant knowledge to be incorporated into decision making as it becomes available (figure 2). Used in this way, the framework could help decision makers navigate logistical barriers to achieving co-production of interventions.

Step one: identify and engage the right stakeholders

To assemble our working group, we used a stakeholder mapping exercise to identify a balanced group of cross-sectoral actors involved in management of wildlife-borne zoonoses at local and national scales. These stakeholders included Kenyan Government representatives (with expertise in natural resource management, wildlife health, human and animal epidemiology, public health policy, and microbiology), members of pastoralist communities, and research scientists (ie, experts in ecology, disease ecology, and epidemiology). Community representatives were selected to represent the views of pastoralists residing in northern and southern Kenya, who maintain an interface with wildlife, livestock, and disease vectors in community-managed rangelands. Representation from different stakeholder groups was as follows: seven research scientists, three representatives from local government, sixteen representatives from national government, one politician (from northern Kenya), and two community members (appendix p 6). Two other community representatives were invited but did not attend.

Ensuring equal representation and gender balance across stakeholders and subject matter experts is crucial to avoid biases in the decision-making process, as gender roles and professional perspectives can influence perceptions of disease risks, prioritisation of interventions, and weighting of criteria.[26,27] Although our group contained a diverse range of expertise, the low proportion of women (six [25%] of 24 participants) is likely to have introduced biases into the decision-making process. Language barriers are also an important consideration for ensuring that all members of a group can converse freely. Our workshop was conducted in English, but most stakeholders also spoke Swahili as their primary language. As such, non-specialist participants were able to confer with other members of the group when seeking clarification about how to express Swahili terms for which there was no direct translation into English and receive support with understanding English definitions and terminologies.

Step two: develop a shared understanding of complex transmission pathways

When faced with complex challenges, stakeholders require a baseline level of common knowledge to effectively work together in identifying solutions. The complex landscape of ecological, social, and biological processes that govern disease emergence is well established in the scientific literature. However, there are few published examples of stakeholders being engaged in this more complete socioecological approach so that it can be used to inform real-world disease management planning.

Our conceptual framework groups interventions at three hierarchical levels along a hypothetical gradient

	Ranking (pre-sensitivity analysis)	Adjusted ranking (post-sensitivity analysis)	% change in outcome (negative)	% change in outcome (positive)
Rift Valley fever virus				
Targeted vaccination of livestock between epidemics	1	1	1·1%	1·1%
Passive surveillance of livestock abortions	2	2	1·0%	1·0%
Early warning based on risk models to guide surveillance (and extend to future climate scenarios)	3	2	1·1%	1·1%
Entomological surveillance targeted at natural biotypes during high-intensity rains and during increases in animal trade, including insecticide resistance	4	3	0·8%	0·8%
Ensure availability of diagnostic tests	5	3 and 4	0·9%	0·9%
Training on biosecurity and biosafety for front-line workers in animal and human health in communities	6	4 and 5	0·7%	0·8%
Sensitise community to how their behaviour can put community members at risk, including challenging predisposing practices and beliefs	7	5	0·6%	0·7%
Infection prevention control for community members at high risk	8	5 and 6	0·6%	0·7%
Establish sentinel herds in high-risk areas	9	5 and 6	0·6%	079%
Community-driven reporting of entomological, climatic, and vegetation changes associated with outbreaks	10	7	0·5%	0·6%
Congo–Crimean haemorrhagic fever virus				
Entomological surveillance targeted at natural biotypes during high-intensity rains and during increases in animal trade, including insecticide resistance	1	1	1·2%	1·1%
Sensitise community to how their behaviour can put community members at risk, including challenging predisposing practices and beliefs	2	1	1·0%	0·9%
Infection prevention control for community members at high risk	3	1 and 2	1·0%	1·1%
Integrated vector control: chemical vector control (eg, rotational use of acaricides on livestock and in livestock shelters and chemical barriers for humans)	4	2 and 3	0·8%	0·9%
Enhance lab capacity (ie, personnel and testing)	5	3	0·9%	0·9%
Modify habitat to interrupt vector life cycle (eg, clearance of low vegetation and prescribed burning)	6	3	0·9%	0·9%
Limit livestock movement from *Hyalomma* spp-infested areas to non-*Hyalomma* spp endemic areas	7	4	0·7%	0·8%
Prioritise and lobby for matching funds to support research on ecological drivers of Congo–Crimean haemorrhagic fever virus	8	4	0·6%	0·7%
Spatial separation of livestock from homesteads and wildlife	9	5	0·5%	0·5%
Vaccination of livestock against ticks (experimental)	10	5	0·4%	0·4%
Bacillus anthracis				
Community-based reporting of suspicious sick and dead livestock	1	1	1·1%	1·1%
Targeted vaccination of animals in high-risk areas (wildlife and livestock)	2	1 and 2	1·0%	1·0%
Build capacity for rapid response within human and animal health practitioners	3	2 and 3	1·1%	1·0%
Early warning based on risk models to guide surveillance (and extend to future climate scenarios)	4	2 and 3	1·0%	1·1%
Community-driven syndromic surveillance of wildlife deaths	5	3 and 4	0·9%	1·0%
Target surveillance in areas deemed to be at high risk	6	3 and 4	0·9%	1·0%
Sensitise community to how their behaviour can put community members at risk, including challenging predisposing practices and beliefs	7	4	0·8%	0·9%
Enhance lab capacity (ie, personnel and testing)	8	4	0·8%	0·8%
Infection prevention control for members of communities at high risk	9	5	0·6%	1·6%
Network modelling of animal movement and trade to identify where downstream control measures should be targeted	10	5	0·5%	0·6%
Rabies virus				
Vaccinate 70% of domestic dogs in a population	1	1	1·3%	1·1%
Community awareness and sensitisation around recognition and avoidance of rabies in domestic animals and wildlife (including dog ownership)	2	1 and 2	1·2%	1·2%
Education campaign in schools to target children (a population at high risk)	3	2	1·2%	1·1%

(Table 1 continues on next page)

	Ranking (pre-sensitivity analysis)	Adjusted ranking (post-sensitivity analysis)	% change in outcome (negative)	% change in outcome (positive)
(Continued from previous page)				
Enforce Rabies Act of 1965 and follow WHO's strategy to eliminate dog-mediated human rabies deaths by 2030	4	2	1·2%	1·1%
Community-driven syndromic surveillance of wildlife and domestic animals, including reporting of dog bites	5	2 and 3	1·1%	1·2%
Proper waste management to reduce resources for dogs	6	3 and 4	0·9%	0·9%
Euthanise animals suspected of rabies	7	4 and 5	0·8%	0·8%
Increase availability of quick turnaround tests for labs and field	8	5	0·7%	0·8%
Spay and neuter domestic dogs	9	6	0·5%	0·6%
Nationwide community-led dog census	10	6	0·5%	0·5%

The last two columns indicate % variation of judgements (weighted uncertainty) for each intervention.

Table 1: **Rankings for each of the ten most important pre-spillover interventions for each of our exemplar pathogens, considering their relative importance when evaluated against nine criteria**

from rural to peri-urban to urban. The first level is stage of spillover (pre-spillover interventions being those that aim to prevent pathogen release from a wildlife reservoir into humans and their livestock, and outbreak interventions being those that aim to control pathogens once they have spilled over and are propagating among humans or their livestock); the second is interface (ie, the physical interface, from a sociocultural perspective, at which interventions are targeted for each stage of spillover); and the third level is the category of intervention within each interface, according to the biological and sociological processes that are being targeted (figure 1).

By embedding the complex biological and sociological barriers that wildlife-borne zoonoses must overcome to infect and subsequently transmit in human and livestock populations within locally relevant physical interfaces, this framework helps contextualise complex transmission pathways for multisectoral stakeholders who might not have formal training in ecology or epidemiology. We found that open group discussion of our four exemplar pathogens within the context of this framework enabled stakeholders to develop a more complete and locally relevant understanding of pre-spillover and post-spillover risk. Having a visual reference for the interface also allowed participants to relate to the part of the spillover process to which their work or livelihood directly related. Visualising the spillover process was considered an important step towards identifying suitable entry points for interventions along each pathogen's complex transmission pathways.

Although not discussed in our workshop, this framework could also be used to consider pre-existing policies and actors that affect or are affected by the disease system. These could include national policies for the control of specific pathogens. Discussing pre-existing policies before progressing to step three of the pipeline would reduce redundancy in the process of identifying interventions and could uncover opportunities for these policies to be strengthened or implemented. For instance, several interventions that targeted entry points for post-outbreak control of Rift Valley fever virus, Congo–Crimean haemorrhagic fever virus, and *B anthracis* at market and slaughter, identified during the workshop, could be grouped under an umbrella measure of enforcing Kenya's Meat Control Act 356,[28] Food, Drugs and Chemical Substances Act 254,[29] and Public Health Act 242.[30] More broadly, this type of exercise could have an important role in facilitating the sharing of information about the current regulatory or policy landscape with respect to the diseases being discussed and enabling policy makers to learn from community members where there might be gaps in feasibility or implementation.

Step three: identify illustrative interventions for how wildlife-borne zoonoses can be controlled before and after outbreaks

Before the 2-day workshop, for each of the four exemplar wildlife-borne zoonotic pathogens, we did a scoping review of peer-reviewed publications, following the PRISMA extension for scoping reviews to identify interventions that had either been implemented or proposed on the basis of empirical evidence. Evidence-based interventions were assigned to epidemiologically meaningful groups within our framework (figure 1). In cases where the authors felt that an intervention that was in the literature for one pathogen could be applied for the control of another, the intervention was listed under both pathogens (eg, vector avoidance methods applied to control Rift Valley fever virus that could also be applicable to Congo–Crimean haemorrhagic fever virus).

The review was conducted in two stages; a rapid review was conducted in September, 2023, to identify evidence-based interventions to carry forward into the workshop, and a more detailed post-workshop review was conducted in November, 2024, for the purposes of this Personal View. The rapid review identified a total of 140 full-review sources for Rift Valley fever virus, 71 for Congo–Crimean haemorrhagic fever virus, 74 for *B anthracis*, and 329 for rabies virus. Management practices extracted from these sources were grouped by categories of ecological, epidemiological, and social processes within our framework (figure 1). 130 interventions were carried forward to the workshop: 37 for Rift Valley fever virus (21 pre-spillover and 16 post-outbreak interventions), 34 for Congo–Crimean haemorrhagic fever virus (21 pre-spillover and 13 post-outbreak interventions), 27 for *B anthracis* (12 pre-spillover and 15 post-outbreak interventions), and 32 for rabies virus (21 pre-spillover and 11 post-outbreak interventions). The post-workshop review identified an additional 14 interventions (three for Rift Valley fever virus, two for Congo–Crimean haemorrhagic fever virus, seven for *B anthracis*, and two for rabies virus).

After completing a detailed review of each pathogen's ecology and epidemiology with respect to our conceptual framework (step two), workshop participants were encouraged to identify suitable interventions along each transmission pathway (table 1). Across all pathogens, participants proposed 95 (66%) of 144 interventions identified through our review and contributed an additional 34 potential control measures (appendix pp 1–5). A percentage breakdown of interventions from peer-reviewed literature identified by workshop participants at each eco-epidemiological stage within our framework is in figure 1. Altogether, 164 ecologically, socially, and medically informed interventions spanning the breadth of our framework were identified by workshop participants. The ten most important pre-spillover interventions for each pathogen—as ascertained by simple rank ordering—are in table 1. These results, together with feedback from workshop participants, indicate that stakeholders were able to develop a common understanding of entry points for interventions along each pathogen's transmission pathway and apply this understanding to discuss and propose diverse interventions.

The comprehensive list of interventions co-developed during the workshop, a substantial proportion of which mirrored evidence-based interventions published in peer-reviewed literature, suggested that this framework is effective in allowing stakeholders to identify a broad array of measures that target ecological, biological, and social processes to prevent spillover from disease reservoirs (domestic or wild) and control outbreaks in humans and animals once they occur. The framework can also be applied to wildlife-borne zoonoses with differing modes of transmission, as shown by the wide array of interventions that was identified for all four exemplar pathogens. As other studies have found, applying nominal group technique with diverse stakeholders proved efficient in identifying many interventions across complex transmission pathways within a short time.[23,31]

Step four: define and select criteria

Appropriate criteria are essential to evaluate whether interventions meet stakeholder goals and subsequently prioritise control measures, given resource constraints. All participants were involved in selection of criteria for evaluating the viability of interventions for wildlife-borne zoonoses. 11 general criteria (harmless, contained, consistent, feasible, acceptable, impactful, effective, affordable, scalable, sustainable, and cost-effective) proposed by Hopkins and colleagues[16] as being indicative of viable solutions that reduce human infectious disease burdens and advance conservation goals were presented to participants during the workshop. Through group discussions, nine criteria specific to evaluating interventions within the context of our framework were identified. Following the approach of Hopkins and colleagues,[16] criteria were assigned to one of three groups (table 2).

Three criteria for assessing the ecological and social harm that could be caused by an intervention and whether the intervention performs consistently as expected were grouped under negative impacts that interventions could have on humans and the environment. Two criteria, feasibility and acceptability, related to the achievability of interventions, with feasibility further subdivided into accessibility, legality (specific to Kenya), and affordability. Although these subcriteria were not treated as standalone measures, the group acknowledged their importance and potential relevance for others adopting the framework. Four additional criteria—cost-effectiveness, inclusivity, effectiveness, and sustainability—were grouped as assessing whether interventions meet stakeholder objectives. Effectiveness was divided into eight subcriteria: adaptability, breadth, evidence, impact, innovation, measurability, timeliness, and scalability. These criteria align broadly with those proposed by Hopkins and colleagues[16] for evaluating health and conservation interventions, albeit with key differences, such as nesting of affordability under feasibility and scalability under effectiveness. The addition of subcriteria such as accessibility, legality, and adaptability reflects practical considerations for implementation and achievement of desired outcomes. However, the complexity of nesting many subcriteria under a single criterion (eg, effectiveness) could challenge objective comparisons. Groups using this framework are encouraged to discuss intervention performance in relation to both criteria and subcriteria, critically assess their applicability to the disease system in question, and consider elevating select subcriteria to full criteria

	Description	AHP weighting
Will the intervention have positive outcomes for humans and ecosystems?		
Ecologically harmless	Does the intervention have a detrimental impact on ecosystems (including animals and humans)?	12·9%
Socially harmless	Does the intervention disenfranchise or have other social impacts on humans?	15·3%
Consistency	Does the intervention perform reliably as expected?	1·5%
Can the intervention be done?		
Feasibility*	Can the intervention be practically implemented in the current setting?	19·8%
Accessibility	Are the tools required to implement the intervention accessible?	··
Illegality	Is it illegal to conduct the intervention?	··
Affordability	Is the intervention affordable for livestock owners to implement?	··
Acceptability	Is the intervention socially and ethically acceptable to all parties?	6·6%
Does the intervention meet stakeholder goals?		
Cost-effectiveness	Does the intervention provide value for money or sufficient return on investment?	4·2%
Inclusivity	Does the intervention draw on local knowledge, and does it promote a multisector approach?	3·4%
Effectiveness*	To what extent is the intervention effective, according to the subcriteria?	23·1%
Adaptability	Can the intervention be adapted to changing conditions or priorities?	··
Breadth	Does the intervention have any impact beyond the target pathogen?	··
Evidence-based	Does the intervention have a scientific evidence base to draw from?	··
Impact	Does the intervention have sufficient impact on ecosystem and human and animal health?	··
Innovative	Does the intervention advance the state of its science?	··
Measurability*	Are the impacts of the intervention measurable?	··
Timeliness	Does the intervention operate at a timescale relevant to the problem?	··
Scalability	Can the intervention be scaled to address the geographical extent of the problem?	··
Sustainability	Can the intervention be sustained for the timescale required to address the problem?	13·2%

Criteria were grouped into three categories, per the approach of Hopkins and colleagues.[32] AHP=Analytic Hierarchical Process. *Criteria are divided into subcriteria.

Table 2: **Criteria and subcriteria for assessing the viability of interventions for wildlife-borne zoonoses, identified through participatory discussions with stakeholders**

where appropriate. Detailed descriptions of all criteria and subcriteria are in table 2.

The importance of each criterion was weighted using the AHP online tool on the Business Performance Management Singapore (BPMSG) platform), whereby the group compared the importance of each criterion against all other criteria using a nine-point scale (table 2).[33] Saaty's 1–9 scale[25] is commonly used in AHP and requires participants to make pairwise comparisons indicating the relative importance of criteria. Thus, here, when comparing criteria, each participant was asked whether they considered criterion X to be more important than criterion Y, and if so, by how much. A score of 1 designated equal importance and 2–9 indicated increasing relative importance. The consistency of the group's pairwise judgements in comparison with random judgements was evaluated with the consistency ratio. A consistency ratio of less than 0·1 is generally deemed acceptable for AHP, but values of up to 0·2 are deemed acceptable for larger numbers of pairwise comparisons being conducted by non-expert respondents.[34] By allowing complex, multicriteria comparisons to be simplified, this process enabled our cross-sectoral group to reach a consensus on how interventions should be evaluated. Effectiveness was weighted highest (23·1%), followed by feasibility (19·8%), socially harmless (15·3%), sustainability (13·2%), and ecologically harmless (12·9%; table 2). The consistency ratio for pairwise comparisons was 0·21.

For the **BPMSG platform** see https://bpmsg.com/

Although weighting criteria by importance through AHP was considered a useful way to obtain consensus among diverse stakeholders, the process could be subject to biases originating through gender balance and representation of subject matter expertise among workshop participants. Therefore, we recommend that groups using this framework in future dedicate time after prioritisation to understand the order in which criteria are ranked.

Step five: explore trade-offs for specific interventions in more depth

Ideally, each intervention should be discussed in sufficient detail for all stakeholders present to be familiar with its objectives and able to assess (on the basis of their own values) whether it is worth investing in. To this effect, we recommend that the criteria described in step four (and outlined in table 2) be used to guide in-depth discussions of each intervention so that individual stakeholders are prepared to evaluate the intervention's viability as part of the prioritisation process, with clarity on its role. As far as possible, this process should be augmented with scientific evidence showing the intervention's effect (eg, epidemiological data). These in-depth discussions are particularly important when implementation of data-limited interventions is being considered, for which extra steps (eg, further data collection through research or adaptive implementation) might be required to address uncertainty in the intervention's outcomes.

For interventions that are poorly understood or could have complex effects across multiple sectors such as ecosystem, livestock and human health, and livelihoods, stakeholders might need to conduct a more focused assessment that considers specific activities, their short-term outputs, and longer-term desirable or undesirable outcomes. This assessment can be achieved using a theory-of-change approach, as outlined by Hopkins and colleagues.[32] Starting from baseline conditions, specific interventions can be followed to their multisector endpoints. Interventions that emerged from our workshop, such as destruction of mosquito breeding habitat and control of invasive plant species for Rift Valley fever virus, which might have complementary or conflicting effects on biodiversity conservation and human or animal health, resulting in win–win or win–lose scenarios, would be ideal candidates for this approach. More in-depth analysis of the trade-offs for specific interventions could be expanded to compare variants of the proposed interventions on the basis of qualitative outcomes relating to ecosystems, livestock and human health, effect sizes, and cost-effectiveness. This approach could also be an effective way to refine and adapt interventions over time, through repeat engagement with stakeholders.

Due to time constraints and the effort required to identify interventions for four pathogens, we were not able to conduct a detailed assessment of each intervention during the 2-day workshop. Therefore, we suggest that groups using this framework to prioritise interventions narrow their focus to a single pathogen and dedicate more time to this activity. As part of the co-development process, this narrowing down could be achieved by holding an initial framing workshop that explicitly focuses on developing a shared understanding of the pathogen's transmission system and completing a comprehensive review of interventions that could be applied (ie, steps two, three, and four of this pipeline).[23]

Step six: prioritise interventions

As a final step in our pipeline, interventions were prioritised on the basis of how they scored when evaluated against criteria identified during the workshop. Working with pathogens assigned to each subgroup, individual participants used AHP to conduct pairwise comparisons between all interventions for a given pathogen with respect to each evaluation criterion, using the same nine-point scale. Due to time constraints, participants completed this exercise using the BPMSG web interface after the workshop. The final prioritisation of pathogen-specific interventions was calculated using the weighted product model from the additive aggregation of each participant's judgements and criteria weights.[33,35] Sensitivity analysis was run for each pathogen to assess the stability of intervention rankings under changes in parameters by identifying the criterion and intervention most likely to cause a change in intervention rankings.[36] Weighted uncertainty was also examined by randomising through Monte Carlo simulation the value of all judgements by plus or minus 0·5 on the nine-point scale.[33] In the interests of time, this exercise was only conducted for the top ten upstream interventions identified during the workshop for each pathogen (table 1).

The most highly ranked interventions targeting pre-spillover processes for each exemplar pathogen (evaluated against our nine criteria with AHP) are in the appendix (pp 1–5; table 1). Sensitivity analysis showed that judgements for each intervention across participants were stable; after random simulation of all judgement inputs, the outcome consistently changed by less than 1·2% (denoted as weighted uncertainty) on either side. However, applying these levels of uncertainty to the order in which interventions were ranked introduced considerable overlap between rankings. Intervention rankings were also robust to simulated changes in criterion weights—changes in weighting for the Absolute-Any critical criterion (the criterion most likely to cause a change in interventions rankings for each pathogen) of 3%, 4·1%, 3·3%, and 4·4% would be required to reorder the rankings of interventions for rabies, anthrax, Rift Valley fever, and Congo–Crimean haemorrhagic fever, respectively. Because these values are higher than the maximum weight uncertainty (1·2%), our prioritisation of interventions can be considered stable to changes in the weighting of criteria.

AHP proved to be an efficient way to create a prioritised list of interventions on the basis of stakeholder comparisons of interventions against different criteria. Participants with divergent levels of professional experience found the pairwise comparison approach intuitive, and the sensitivity analysis showed that participants' judgements were fairly stable. However, there were limitations—probably due to low participation in online pairwise comparisons after the workshop—that made it difficult to assess the robustness of the AHP approach. For example, uncertainty introduced by the sensitivity analysis meant that some interventions' rankings could not be differentiated and had to be grouped (table 1). Because of the small number of participants, we were also unable to measure consensus between group members' judgements, another possible indicator of the suitability of this approach.

AHP is just one of several multicriteria decision analysis (MCDA) approaches. This approach was chosen because of the ease with which different and conflicting views of stakeholders can be incorporated into group decision making.[37,38] As with all MCDA approaches, limitations—particularly the subjectivity of the process—need to be considered when interpreting weighted and prioritised criteria and interventions. Although group discussions were aimed at achieving a baseline level of understanding and, therefore, overcoming knowledge bias between individuals, personal experiences and differing levels of expertise probably introduced uncertainty into the outputs. Ensuring equal representation of stakeholder groups through stakeholder mapping is, therefore, crucial for obtaining a balanced representation of different stakeholders' priorities and perspectives throughout the processes. Methods such as group fuzzy AHP, which uses fuzzy logic to reduce uncertainty in how stakeholders make judgements, can also help account for stakeholders' uncertain decisions when conducting pairwise comparisons.[39]

Although MCDA-based prioritisation is a useful way to differentiate interventions that are ineffectual from those most likely to achieve stakeholder goals, this process should represent the first step in a longer-term, stakeholder-led effort to refine and operationalise promising interventions for a target disease system.

Tried-and-tested measures (eg, medical interventions such as vaccination of livestock and infection prevention control for individuals at high risk of infection) can be implemented easily, whereas those that are less well understood might require further co-development, testing, and comparison, which could be done in silico. For instance, scenario models targeted at specific interfaces within our framework (eg, vector population dynamics in pastoral landscapes or the passage of livestock between household, market, and slaughter interfaces) could be used to compare the effect of different control measures on exposure or infection within a statistical or mathematical model and, therefore, on an outbreak's simulated trajectory.[40,41] Integrating relevant data (such as local environmental factors governing vector distribution or information regarding structures of livestock value chains) into these models could improve their accuracy in a local context. In circumstances whereby scenario models are unfeasible or immediate action is required, adaptive implementation can be used to compare how well different variants of an intervention perform against one another in practice.[16,42]

Search strategy and selection criteria

We did a scoping review of peer-reviewed publications to identify evidence-based interventions for each pathogen, following PRISMA-SCR guidelines. The following syntax (without date restrictions) were used to conduct a targeted, pre-workshop search on Sept 4, 2023, in PubMed: "rift valley fever" AND (livestock OR wildlife OR mosquito) AND intervention AND control; ("Crimean-Congo hemorrhagic fever" OR CCHF OR CCHFV) AND (livestock OR wildlife OR ticks) AND intervention AND control; anthrax AND (livestock OR wildlife) AND intervention AND control; rabies AND (domestic OR wildlife) AND intervention AND control. For the purposes of presenting a more rigorous scoping review for publication, the review was updated in Nov 14, 2024, to include PubMed, Web of Science, and Embase.

For both stages of review, JMH, KELW-T, MCV, NB, SA, and SC systematically reviewed publications (n=1143) according to inclusion criteria aimed at filtering duplicates and irrelevant articles before conducting an in-depth review of retained articles (appendix p 8). Once duplicates were removed for each of the four pathogens (n=182), only review articles, research studies, and case studies were taken forward, and articles were removed if deemed very unlikely to contain information relevant to interventions for wildlife-borne zoonoses (n=238) or if not written in English (n=1). One-sentence descriptions of interventions for each pathogen that had been either implemented or proposed based on empirical evidence were extracted from the remaining articles (n=722) and assigned to epidemiologically meaningful groups within our framework (figure 1). To be carried forward, interventions had to meet the following criteria: they were self-identified as interventions that had been implemented or proposed to address one or more of the four target pathogens (through prevention, mitigation, or response); if implemented, there was appropriately evaluated evidence to suggest that the intervention had achieved the desired outcome; and, if proposed, statistical analysis had shown that the intervention could be effective or the reviewer felt that there was a sound scientific basis for assuming that the proposed intervention could be effective. Geographical constraints for each intervention were not set—instead, we relied on expert review to determine whether interventions were of relevance to our chosen system. In cases where the authors felt that an intervention in the literature for one pathogen could be applied for control of another, the intervention was listed under both pathogens (eg, vector avoidance methods applied to Rift Valley fever virus control could also be applicable for Crimean–Congo haemorrhagic fever).

Conclusions

An increasing body of literature calls for the inclusion of ecological and social perspectives to evaluate zoonotic disease risk and inform interventions, but few guidelines exist for integration of such interventions into public health action plans.[18,43] At the same time, engaging beneficiaries in the design and implementation of disease surveillance and control efforts can diversify management options and lead to more socially and politically acceptable solutions.[44] By combining these objectives, we present an adaptable framework that aims to promote more effective and sustainable approaches to control of wildlife-borne zoonosis. Potential uses for this framework include identifying and prioritising knowledge gaps within complex disease systems to direct research efforts and developing local, national, or regional action plans for disease prevention and control.

By encouraging meaningful engagement between local and national authorities tasked with synthesising risk reduction measures, subject matter experts (ie, scientists), and communities, our approach promotes core tenets of co-production: early engagement of stakeholders who are not traditionally included in disease control planning (including beneficiaries whose cooperation is required to implement interventions); addressing of power dynamics to facilitate integration of knowledge and skills from across sectors and develop an appreciation of the diverse interests and values that different stakeholders possess; and incentivisation of sustained stakeholder interest, required for longer-term development, testing, and refinement of interventions.[45,46]

Because this framework is most effective for encouraging broad, cross-sectoral co-production of knowledge, ideas, and consensus on complex disease systems, it should be applied early in the decision-making process to initiate sustained interest and engagement between stakeholders on the pathogen system in question. Although we developed and tested the framework in the context of an African rangeland system, it could be adopted for use in other important wildlife-borne zoonosis systems (appendix p 8). As well as being used to consider disease control measures from a systems-wide perspective, with small modifications, the framework could be used to recognise knowledge gaps and set research priorities, map policy and governance landscapes for complex disease systems, and identify systemic One Health challenges. We found it to be an affordable and time-efficient process—the workshop cost only US$2000, and a small group of four scientists and veterinarians without previous expertise in workshop facilitation were able to prepare and coordinate proceedings. There are several outstanding questions and opportunities for further development—eg, whether the framework can be embedded effectively within public health systems to remove barriers to achieving desired health outcomes for humans, animals, and ecosystems. Other questions include whether the ranking and prioritisation process is robust enough to deal with complex environmental and social trade-offs (a feature of many wildlife-borne zoonoses) and whether the steps outlined in this framework translate to longer-term cooperation in terms of developing, testing, and implementing ecologically and socially informed interventions. Finally, it should be considered how the framework could be extended to facilitate this process at timescales relevant to changing environmental and socioeconomic conditions.

Contributors

JMH, KELW-T, and SM conceived the study. JMH, KELW-T, MCV, NB, SA, and SC designed the conceptual framework, conducted the scoping literature review, and designed the workshop process. JMH, SA, MCV, and SC facilitated the workshop. All authors participated in the workshop, thereby contributing intellectually to the conceptual framework and to selection and prioritisation of criteria and interventions. All authors provided comments on the manuscript and gave final approval to submit for publication.

Declaration of interests

JMH, MM, and EMF were supported by the US Department of Defense's Defense Threat Reduction Agency (grant HDTRA12210018). The content of the information does not necessarily reflect the position or the policy of the federal government, and no official endorsement should be inferred. All other authors declare no competing interests.

Acknowledgments

Ending Pandemics, a project of TIDES Center, a not-for-profit organisation (501c3) in the USA, funded this work (grant 505341). The views and opinions expressed in this Personal View are those of the authors and do not necessarily reflect the official policy or position of any agency. The collection of data adhered to the legal requirements of the Smithsonian Institution and country in which the research was conducted. The study was reviewed by the Smithsonian's Institutional Ethics Review Board and considered exempt. The project was granted a NACOSTI research permit under which the research was permitted to be conducted in Kenya. Consent for participation was obtained through email or verbal communication before the workshop and was also assumed on the basis of in-person participation. At the beginning of the workshop, all participants were made aware that their responses during the workshop would be documented, analysed and included in this publication. We would like to thank the Department of Veterinary Services within the Kenya Ministry of Livestock Development, the Kenya Wildlife Service, and Wildlife Research and Training Institute for their help and support.

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