A One Health Ecosystem Approach for Understanding and Mitigating Spill-Over of Tick-Borne Diseases in India's Degraded Forests

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Interdisciplinary ecosystem approaches, that jointly study ecological and social processes underpinning zoonotic disease risk across degraded ecosystems, informed mitigation of Kyasanur Forest Disease in south India by identifying which communities are most at risk and why. Co-production resulted in risk information and tools tailored to local communities, health workers and disease managers.

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Abstract

Exposure to zoonotic diseases can trade-off against livelihood-critical activities, particularly for tropical forest-dependent communities. Inter-disciplinary ecosystem approaches are critical to understanding this zoonotic spillover since the ecological and socio-political processes that make people vulnerable are jointly

studied across degraded ecosystems. Moreover, One Health co-production of research and tools with cross-sectoral stakeholders can bridge gaps in knowledge and disease management between sectors. The MonkeyFeverRisk project applied these approaches to a case study of human viral tick-borne disease, Kyasanur Forest Disease (KFD), affecting forest-dependent communities in the Western Ghats, south India, to inform management. Multiple tick species and vertebrate hosts are involved in Kyasanur Forest Disease Virus transmission, including wild rodents and shrews, monkeys and birds, while humans are "dead-end" hosts contracting the disease when bitten by infected ticks. By sampling across habitats within fragmented forests, we found that the risk of human exposure to infected ticks extends outside forests to forest edges, plantations, houses and gardens. The highest risk of human spillover was found in diverse agro-forestry landscapes, created when the moist evergreen forest is replaced with plantations and rice cultivation. Risks and impacts of KFD were highest for socially vulnerable, marginalised groups (e.g. lower caste, landless, elderly-headed households), exposed to ticks through occupations in forests, plantations and cropland. Aside from mortality, disease impacts include long-term, debilitating health issues, loss of income and reduced forest access. Key barriers to effective KFD prevention within these communities included limited information about KFD and its transmission, low efficacy of and mistrust in currently available vaccines and tick repellents, and livelihood concerns. Co-production delivered web-based tools to guide management, identifying high-risk areas, and education materials for local communities, health workers and managers detailing risks from ticks and tick-bite prevention measures.

What is the Incremental Value that makes this a One Health Case?

This case illustrates how interdisciplinary ecosystem approaches, that jointly study ecological and social processes underpinning zoonotic disease risk across degraded ecosystems, can provide evidence identifying which individuals and communities of people are vulnerable, and when, where and why they are at risk. Co-production of knowledge with cross-sectoral stakeholders resulted in contextualised risk maps, decision support tools and risk guidance tailored for local forest-dependent communities, health workers and disease managers

Learning Outcomes

1. Recognise the value of ecosystem approaches for understanding and mitigating zoonotic spillover, where the ecological and socio-political processes that make individuals and communities vulnerable are jointly studied at the human-animal-environment interface across degraded landscapes.
2. Understand how tools and risk guidance can be tailored to local needs and contexts through the co-production of research and models with disease and land managers, experts and communities across sectors.
3. Describe the types of adaptive actions that communities may take to reduce disease risk and impacts and how these actions are linked to livelihoods and disease information.

Background and Context

Globally, a key cost of altering forest structure and accessing forest goods and services is the increased exposure of humans and livestock to multi-host, zoonotic pathogens (Millenium Ecosystems Assessment, 2005). Zoonotic pathogens are those that are transmitted naturally between animals and humans. Forest habitats are a significant source of emerging infections of people and livestock because they support complex ecological communities, including a high diversity of wildlife hosts and arthropod vectors (Kar *et al*., 2014). Upsurges in the incidence of multiple high-burden zoonotic diseases have been linked to deforestation or re-afforestation in Lower Middle Income Countries and to forest usage (Morand and Lajaunie, 2021). Forest communities are rendered even more vulnerable by their remoteness from healthcare infrastructure and socio-economic marginalisation. Understanding the historical, socio-political, ecological and environmental processes that make forest-dependent communities vulnerable to zoonotic pathogens as the environment changes is critical to the design of effective, locally relevant interventions and require interdisciplinary approaches (Dzingirai *et al*., 2017).

One Health approaches are particularly critical for India where around 200 million people live next to forest ecosystems, which are often badly degraded, and depend on forests for food, fuel, livestock fodder and other non-timber forest products. India is highly ranked worldwide in burden and risk of further emergence of zoonotic diseases from wildlife and domestic animals (Grace *et al*., 2012). MonkeyFeverRisk was an Indo-UK project involving the UK Centre for Ecology and Hydrology (UKCEH), the Ashoka Trust for Research in Ecology and Environment (ATREE), the Indian Council for Medical Research's National Institute for Epidemiology (ICMR-NIE) and the National Institute for Traditional Medicine (ICMR-NITM), the Indian Council for Agricultural Research's National Institute of Veterinary Epidemiology and Disease Informatics (ICAR-NIVEDI), and the Department of Health and Family Welfare Services (DHFWS), Karnataka State Government and was funded by the UK Research Councils under the Global Challenges Research Fund. Implemented between 2017 and 2020, MonkeyFeverRisk aimed to develop an interdisciplinary framework to help communities minimise exposure to zoonotic diseases whilst maximising the livelihood benefits derived from tropical forests and to produce evidence-based risk guidance and a web-based decision support tool to guide interventions. The project focused on the tick-borne infection, Kyasanur Forest Disease (KFD), that affects rural communities in and around the forests of the Western Ghats mountain range in southern India (Box 1).

The MonkeyFeverRisk project took a One Health ecosystem approach in that we linked expertise and knowledge across disciplines and sectors to understand how interacting hazard, exposure, vulnerability and adaptive capacity for KFD were all influenced by landscape change and the policy context (Figure 1). Within our conceptual ecosystem framework, the ecological hazard from zoonotic pathogens at risky interfaces between human habitation, agriculture and forest are assumed to be determined by geographical and seasonally varying interactions between wildlife, livestock and vectors that are sensitive to land use change. Whether this hazard results in disease spillover and impacts, depends on human behaviour and priorities and diverse cross-sectoral policies that drive exposure (forest and resource use, land use and agricultural policy), vulnerability to infection and uptake of adaptive measures (risk perceptions, knowledge networks, access to health care, health policy). Within our ecosystem approach, these intersecting processes underpinning hazard, exposure and vulnerability to KFD were jointly studied in the same set of communities and villages across degraded forest gradients as well as at a broader scale, through epidemiological modelling of outbreak patterns, integrating human, animal and environmental data and factors. Importantly, to bridge known disconnects between zoonotic disease research and policy (Leach and Scoones, 2013)

Box 1. The complex Kyasanur forest disease system and its impacts.

Kyasanur Forest Disease (KFD) is caused by Kyasanur Forest Disease Virus (KFDV; genus Flavivirus). For humans, KFD is a debilitating and potentially fatal haemorrhagic disease, with 400–500 reported cases a year and a mortality rate of up to 10% in unvaccinated people. Key affected communities include smallholder farmers engaged in cultivation and grazing of cattle in and around forests, day labourers in plantations and tribal groups who gather non-timber forest products (Kasabi *et al*., 2013). Around 69% of smallholder farmers and tribal groups surveyed in the region reported being concerned by the impact KFD has had on their livelihoods (Asaaga *et al*., 2021a). As well as affecting diverse social groups, the transmission cycle of KFDV is complex involving different life stages of hard tick species from several genera (principally *Haemaphysalis*) and vertebrate hosts, including wild rodents and shrews, monkeys and birds (Work *et al*., 1959; Pattnaik, 2006). Humans contract KFDV when bitten by an infected tick but are incidental or "dead-end" hosts for the disease. Monkeys, principally the black-footed grey langur (*Semnopithecus hypoleucos*) and the bonnet macaque (*Macaca radiata*) are highly susceptible to KFD and can serve as sentinels. They are hypothesised to act as amplifying hosts by feeding larvae but concrete evidence is lacking (Burthe *et al*., 2021). Cattle are not direct hosts for KFD since they do not develop viraemia of long duration, but may increase and move tick populations through their importance as a blood meal host. The initial emergence of KFD in the 1950s was linked to deforestation for human settlements and roads (Work *et al*., 1959) but human outbreaks remained restricted to focal areas of Karnataka State last century. Since 2014, however, human cases have been detected in four neighbouring states (Tamil Nadu, Kerala, Goa and Maharashtra). Despite this spread to new areas, and extensive subsequent landscape changes, evidence on ecological hazard and exposure have not been collected since the 1970s. It is critical to rapidly understand the landscape and ecosystem conditions favouring KFDV transmission in the degraded, fragmented landscapes of southern India and the subset of these conditions that lead to human disease and societal impacts, to inform interventions (Purse *et al*., 2020). KFD impacts are managed currently through vaccination, awareness campaigns and promotion of tick protection measures in and around recently affected areas. However, constraints on availability and efficacy of the vaccine, and poor uptake of vaccination and personal protection measures can exacerbate epidemics (Kiran *et al*., 2015). Thus, targeting of tailored interventions towards the most vulnerable communities is critical.

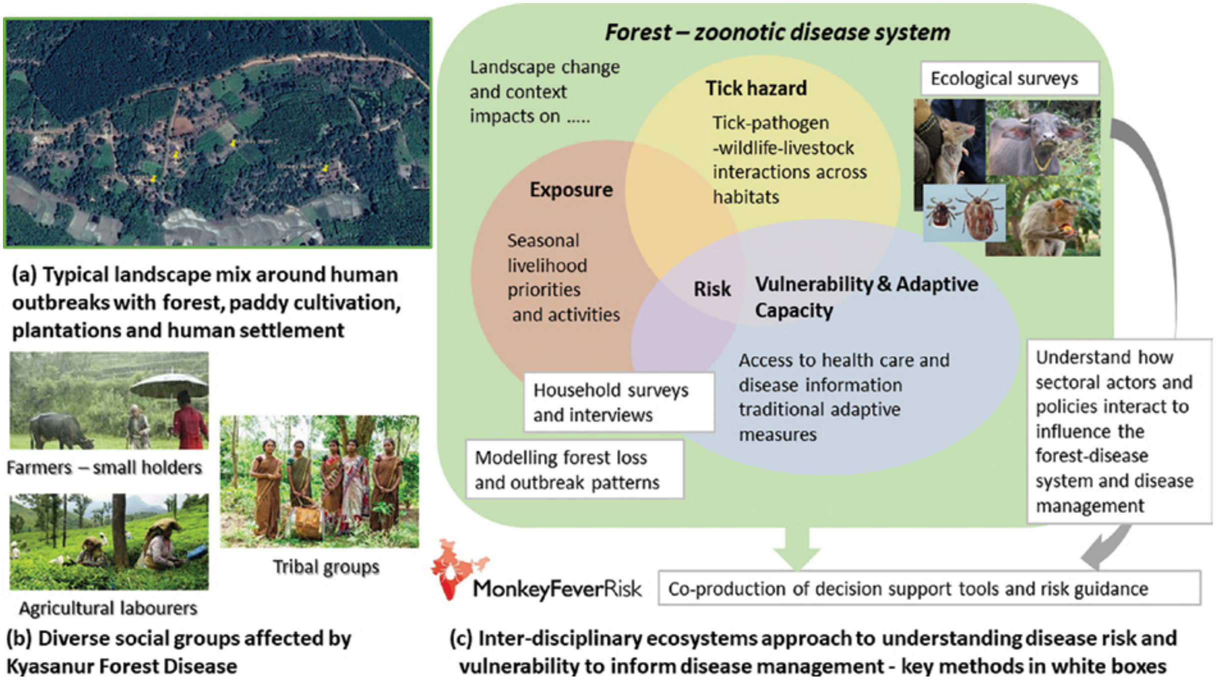

Figure 1. Key components of the MonkeyFeverRisk ecosystem approach to understanding and mitigating Kyasanur Forest Disease in degraded forests in south India.

and between sectors (Asaaga *et al*., 2021b), we used a participatory co-production process to engage key, diverse stakeholders across sectors (including Public Health, Animal Health, Agriculture, Forestry) and scales (community-level up to districts, states and national level), as both knowledge holders and decision-makers, to ensure the research and decision support tools were tailored to local needs and policy contexts.

Transdisciplinary Process

We engaged stakeholders in an iterative and collaborative participatory co-production process (Asaaga *et al*., 2022), in which we decided on the knowledge gaps and research objectives together (framing), integrated their existing knowledge into our research and resulting tools (knowledge integration) and validated the impact of the tools and guidance on zoonotic disease management (experimentation). During the framing stage, across the project team, we mapped the diverse actors and institutions across sectors and scales that hold knowledge about or influence zoonotic disease systems or management. Representative actors (from Public Health, Animal Health, Forestry, Agriculture and Social Welfare) were brought together within a participatory framing workshop at which they were asked using open questions to identify and rank key risk factors for KFD and to identify the evidence needed and requirement for tools to help to inform management decisions (Tables 1 and 2, respectively).

Among the highly ranked landscape-level risk factors identified were forest loss and degradation, human use of forests including settlement, encroachment and grazing as well as lack of knowledge of alternative hosts and tick species involved in KFDV transmission. This consolidated the project focus on understanding (i) how the hosts and vectors involved in transmission were linked to forest loss and to habitats at the interface between human habitation, agriculture and forests (hazard); and (ii) how the risk of human exposure to KFDV is linked to different seasonal livelihood activities in these interface habitats and to deforestation and adaptive measures (exposure and vulnerability). Joint ecological and social surveys and interviews were conducted in 30 villages with high (>4), medium (1–2) and low human cases (0) of KFD (from 2016 to 2018) and varying proximity to forests across two Districts. One District had been affected by KFD since the 1950s (Shivamogga District in Karnataka, 18 villages) and one affected more recently, since 2014 (Wayanad District, Kerala, 12 villages) (Asaaga *et al*., 2021a).

To understand which habitats pose the highest risk of exposure to KFD-infected ticks within the interface between villages, plantations, paddy fields and forests, ticks and small mammals (as potential reservoirs of KFDV infection) were sampled in each habitat type in each village. Tick burdens and infection rates were also measured on the small mammals and cattle with the latter related to cattle movements through the

Table 1. Risk factors identified and ranked by participants of the framing workshop, and how these were integrated in the MonkeyFeverRisk project.

Ranking	Risk factors	Number of votes	How risks were addressed in project
1	Lack of education/ awareness	10	Tick information cards were produced to inform local communities about risks from ticks and tick protection measures. Development of an educational video in progress.
2	Under- or late reporting of monkey deaths	9	Accounted for in data interpretation in risk modelling.
2	Deforestation and/or forest degradation	9	Integrated as a risk factor in models.
2	Lack of awareness of preventative measures (tick repellents, vaccination)	9	Measured in cross-sectional household surveys. Tick information cards produced (see above).
3	Lack of awareness or understanding of alternative hosts	8	Addressed in household and ecological surveys.
4	Human use of forests	7	Addressed in household surveys and in spatial risk modelling.
4	Low vaccination coverage	7	Addressed in household surveys and in spatial risk modelling.
4	Poor diagnostics and surveillance	7	Improving surveillance and diagnostics is not a direct project aim but could result from a strengthened One Health network. Ecological analysis of vectors and alternate hosts will inform surveillance strategies.
4	Lack of One Health policy	7	Project established a One Health WhatsApp network on KFD, project members attended National and State level technical committees on KFD and discussed the One Health approach.
5	Poor data management	6	The project provided a blueprint for future data management on KFD, for example ensuring that cases were georeferenced at a household level to capture landscape conditions favouring spillover.
5	Poor understanding of tick ecology	6	Addressed in ecological surveys.
6	Side effects and concerns about vaccines	5	Measured as part of the household surveys but not a direct research project aim.
7	Living in or around forests	4	Addressed in risk modelling, household surveys and ecological surveys (stratified by forest proximity).
7	Favourable environment for ticks	4	Addressed in ecological surveys (habitat associations were measured).
7	Poor tick identification	4	Addressed in ecological research and capacity building (see Table 2).

landscape. At broader scales across affected Districts and states, historical patterns of human outbreaks were compiled and analysed within computer models in relation to the different landscape, climate, host and social risk factors. These models allowed us to understand key determinants and locations for spillover and produce risk maps to guide surveillance and mitigation measures (Purse *et al*., 2020). Classification of high-resolution multi-temporal remote sensing images (Landsat TM) was used to map patterns in cover and loss of forest types across affected Districts while government census data were used to integrate cattle densities and densities of marginal workers linked to occupations in forests and proximity to Public Health Centres (Purse *et al*., 2020).

Other Public Health or social risk factors identified by stakeholders related to vulnerability and adaptive capacity, including lack of awareness of KFD and preventative measures, low acceptance and coverage of vaccination, poor diagnostics and surveillance. These were addressed in the design of our household surveys with communities and in key-informant interviews with disease managers and community health officers. In order to integrate our knowledge of ecological hazards obtained from the habitat-specific tick and host surveys with data on human social behaviour, we also recorded rates at which humans picked up ticks during their day-to-day activities in the landscape (walk-through surveys).

After the initial joint framing of the research, we conducted a further stakeholder workshop, where we presented some preliminary research findings and a prototype of the decision support tool (DST) to cross-sectoral stakeholders, who shared insights and feedback based on their own experiences and expectations. In addition to the stakeholder workshop, 11 targeted key-informant interviews with District

Table 2. Key needs identified by participants of the framing workshop – and how these needs were addressed in the project.

Key needs identified by workshop participants	How needs were addressed in project
Human resources: need for better trained manpower; more equipment; tick experts and taxonomists	Institutional capacity for morphological and molecular tick identification was built in partner institutes and within the health system (training of District entomologists). Tick taxonomy resources were developed that will be made publicly available.
Improved surveillance: need for active surveillance; surveillance for disease, vectors and hosts	Outbreak analysis provided risk maps and models that were integrated into a desk-based App "KFDExplorer" to improve targeting of surveillance. Ecological Surveys advanced understanding of the ecological communities most strongly linked to KFD and developed protocols for tick and small mammal surveillance.
Better diagnostic facilities	Not a direct research project aim but the One Health network can advise on location/type of facilities.
Better communication: real-time reporting; social media use	Part of the experimentation phase.
Funding for research and action	Not a direct research project aim but opportunities were communicated through the One Health network.
Better understanding of disease ecology: alternative hosts and vectors; seasonality; tick movement; tick distribution; tick ID and taxonomy	Ecological surveys and research advanced this understanding and produced Tick Information cards (see above). Published review of the ecological evidence base for current KFD management for disease managers (see Burthe *et al*., 2021).
Vaccines and vaccination innovations: better quality/efficacy/single dose; availability; shelf life	Not a direct research project aim.
Multi-sectoral coordination: better communication and coordination	Stakeholder workshops; WhatsApp groups, establishing a One Health network.
Raise profile of KFD and hence generate political will for KFD control and management	Project members engaged with a wide range of media outlets to raise awareness of KFD and attended National and State level government technical committees on KFD to provide advice and describe the One Health approach.
Improved knowledge, awareness and better practices for KFD management	Tick information cards produced and video in progress – see above). Published review of the ecological evidence base for current KFD management (Burthe *et al*., 2021).
Improve detection of at-risk human populations early	Ecological surveys and spatial risk models improve understanding of the landscape conditions favouring spillover, whilst the household survey indicated livelihood risk factors and activities for KFD.
Restrict human-forest interface wherever feasible	Covered in household surveys as part of raising awareness. Analysis of ecological data to identify important non-forest interfaces (other than forest) affecting human spillover dynamics.
Remove invasive species	Ecological surveys measured links between invasive plants, tick abundance and KFD.

and state-level disease managers involved in KFD management were conducted to afford them the opportunity to experiment with the DST and give feedback on potential ways they would use the tool and avenues for improvement. This participant-driven engagement process allowed stakeholders to reflect on the usefulness of the tool, and other potential beneficiaries as well as the tailoring of specific functionalities to better accommodate stakeholder preferences.

Project Impact

Improved Understanding of Who is at Risk of KFDV Exposure and KFD Impacts

> *"When we talk about KFD, as it is new disease to us, it brought the uncertainty, about our hamlet, activities, our medicinal practice, our health system, so that made us feel bad always. It [KFD] is not manageable by us. (Leader of a tribal village, Wayanad)."*

The MonkeyFeverRisk project advanced understanding of which groups in society are most vulnerable to KFD, their perceptions and adaptive measures. According to household surveys and key-informant interviews, small-holders from households that were low caste, land-poor, Below Poverty Line (BPL), headed by an elderly person, and information-poor perceived themselves as most vulnerable to KFD-related impacts. These groups are at a significantly higher risk of exposure to ticks and contracting KFD due to their occupations in forests, plantations, and crop fields along the forest fringe (see Figure 2). In communities affected since 2018, in Sagara Taluk, Shivamogga District, for example, plantation workers (Arecanut) (46%), housewives (18%) and farmers (15%) constituted the majority of cases (n=39) and 65% of respondents had visited forests or plantations within 10 days prior to diagnosis (n=23). There was generally limited awareness of KFD in the surveyed communities (even in those with recent cases), with about two-third of survey respondents not employing any strategies to prevent tick bites. Households with better access to information were more likely to take adaptive actions, which included vaccination, avoiding visits to forests, wearing protective clothing and footwear, applying tick repellent and attempting to diversify their income away from forest-related sources (Asaaga *et al*., 2021a). Barriers to taking these actions, aside from lack of information, included low efficacy of the current vaccine and tick repellents (DMP oil), mistrust, religious or cultural or livelihood concerns. Communities were also using traditional, 'home-made' repellents (e.g. neem oil, fenugreek extract, paraffin oil) as a means to protect themselves and their animals against ticks. Empirical experiments are needed to determine how effective these traditional repellents are in protecting people against ticks (Burthe *et al*., 2021).

Figure 2. Key activities that pose a high risk of coming into contact with high numbers of ticks and Kyasanur Forest Disease Virus. (a) collecting firewood and (b) leaves from forest where ticks at high density; (c) storage of leaves that may harbour ticks for fertiliser or animal bedding; (d) movement through forests for grazing or collection of Non-timber Forest Products; and (e) resting on forest floor.

The differences in patterns of KFD vulnerability highlight the need for context-specific prioritisation and targeting of interventions. Homogenous labelling of smallholders as 'vulnerable' could compromise or operate to favour certain intervention pathways, which might threaten or worsen the already precarious livelihoods of certain social groups (e.g. tribal forest-dependent households) with weaker bargaining power or influence (Asaaga *et al*., 2023). Thus, existing policies banning people from entering forests in response to KFD outbreaks are likely to have very adverse effects on their livelihoods and wellbeing. Any proposed intervention (e.g. forest bans, diversification of livelihood activities) should be relevant to local livelihood contexts and evaluated against potential negative consequences. Policies addressing forest use should also be mindful of the historical conflicts surrounding conservation and forest protection in these regions.

Improved Understanding of Where the Risk of Spillover is Highest and Why

Much of the current and previous management recommendations for preventing human cases of KFD have assumed that the risk of human exposure to infected ticks is largely restricted to forest habitats. However, preliminary evidence from MonkeyFeverRisk on the numbers of ticks and infected ticks in different habitat types has shown that this risk also extends to forest edges, plantations and even around houses and gardens. Although forests have higher tick abundance than cropland or other village spaces, abundances are still high in these non-forest habitats. KFD-infected individuals of the suspected main tick vector, *Haemophysalis spinigera*, were found across habitats including around houses and gardens. Moreover, it was found that dry leaves (i.e. leaf litter that is collected from forests for various household purposes), can support high numbers of nymphal and larval ticks. Therefore, whilst forest habitats support high numbers of ticks, other habitats, including around homes, pose a significant risk to humans from tick bites. Tick burdens on people moving through the forest during livelihood activities can be very high, reaching up to 30 ticks/150m in some sites, highlighting the critical need for effective tick-protection measures, such as protective clothing and repellents.

Our surveys found substantial numbers of infected individuals of other tick species than *Haemophysalis spinigera*, the species historically implicated in KFD transmission, including *H. bispinosa* and *Ixodes spp*, which are often associated with cattle. These species may have different habitat preferences and seasonality to *H. spinigera*, and so may extend the habitats and seasons in which KFD can persist and spillover, beyond those favoured by *H. spinigera*. There is also some evidence from a laboratory study that KFD may be transmitted in Ixodes from adult female ticks to their eggs, so-called transovarial transmission (Singh *et al*., 1968).

Alongside Public Health and Animal Health practitioners, we undertook a systematic review of the empirical ecological evidence base for disease management (Burthe *et al*., 2021). By using new frameworks that identify the hierarchical series of barriers that a pathogen needs to overcome before spillover to humans occurs (Sokolow *et al*., 2019), we identified which barriers were targeted by current management, evaluated the existing evidence for KFD disease mitigation measures and gave recommendations for their improvement, and identified knowledge gaps and research priorities (Table 3). In particular, our review highlighted that the role of cattle and primates in KFD dynamics is not well understood or underpinned

Table 3. Key research priorities that would improve management strategies for preventing KFD spillover. Each priority is linked to one of the hierarchical barriers that a tick-borne pathogen needs to overcome before human spillover can occur, indicating whether each would (a) refine current management and surveillance in the short term and/or (b) facilitate the development and future implementation of integrated, ecological interventions in the long-term. A full list of research priorities and hierarchical barriers is detailed in Burthe *et al*. (2021).

Research priority	a. refines current management or surveillance (short-term)	b. facilitates future ecological interventions (long-term)
Barrier: Vector density, distribution, habitats and behaviour		
1. Quantify abundance and infection rates of tick vector species across different habitats within the agro-forest mosaic (integrate into stratified tick surveillance)	X	X
2. Determine whether cattle are amplifying and spreading tick species or acting to dilute infection by comparing tick burdens and KFDV-infection rates on cattle, wildlife hosts and people, in settings varying in host densities	X	X
3. Quantify abundance and infection rates of ticks found in different types of dry leaf litter, used for animal fodder and bedding, under different treatments in villages	X	X
Barrier: Vector host associations: contact rates with people		
4. Quantify effectiveness of different acaricide formulations, doses and frequencies of application in reducing tick burdens on cattle, for those species involved in KFDV transmission and for natural as well as chemical repellents	X	

Continued

Table 3. Continued

Research priority	a. refines current management or surveillance (short-term)	b. facilitates future ecological interventions (long-term)
5. Determine whether acaricide resistance is widespread in tick populations in India, in tick species involved in KFDV transmission, for acaricides applied both to animals and to the habitat.		X
Barrier: Human activities in ecosystems 6. Quantify rate of contact between people and ticks during different activities in and around the forest	X	X
Barrier: Pathogen prevalence, infection intensity in reservoirs and pathogen availability to vectors 7. Determine role of dead and dying monkeys in generating hotspots of transmission: quantify burdens, age structure, feeding history, and infection rates of ticks found on dead and dying monkeys, small mammals and in nearby habitats and people at the same time as measuring host infection levels	X	X
8. Determine role of live monkeys in transmission through infection of larvae via systemic circulation and/or supporting co-feeding between nymphs and larvae: quantify burdens, age structure, feeding history (via blood meal analysis), and infection rates of ticks found on live monkeys, small mammals, and nearby habitats and people at the same time as measuring host infection levels		X
9. Determine role of small mammals in transmission through infection of larvae via systemic circulation and/or supporting co-feeding between nymphs and larvae: quantify burdens, age structure, feeding history, and infection rates of ticks found on live monkeys, small mammals, and nearby habitats and people		X
10. Determine whether sequence data can be used to elucidate spatial and temporal diversity in KFD, whether such diversity is linked to vectors or hosts, and to infer spatial movement of KFD in order to better understand transmission and spatial scale of risk.		X
Barrier: reservoir density, distribution, habitats and behaviour 11. If monkeys are confirmed as important amplifying hosts for KFDV and contributing to transmission risk via infected ticks to humans, quantify their habitat associations, movement rates and interactions with people across agro-forest landscapes	X	X
12. If small mammals are confirmed as important reservoirs for KFDV and contribute to transmission to humans, quantify their habitat associations, movement rates and interactions with people across agro-forest landscapes	X	X

by evidence. Thus, management practices such as burning monkey carcasses, insecticide spraying and controlled burning of vegetation around the sites of monkey deaths are particularly unfounded. It is thought that monkey deaths reflect localised hotspots of transmission, but our review highlights a lack of evidence for this hypothesis and suggests instead that monkeys may rather be sentinels of KFDV infection within an area. A better ecological understanding of the role of small mammals, ground-nesting birds, monkeys and cattle in transmission as well as the socio-political and environmental factors affecting human exposure, would enable a wider range of management solutions to prevent KFD spillover, beyond those targeted at humans.

Modelling of historical disease patterns (2014–2018) in relation to key environmental and social risk factors indicated that human spillover of KFD is most likely in diverse forest-agricultural mosaics, of the kind that is created when a forest is removed for plantations and paddy cultivation (Purse *et al*., 2020). High-risk areas in Shivamogga District, which has a history of human KFD cases dating back to the 1950s, contained a high cover of moist evergreen forest and plantation and low cover of dry deciduous forest and high densities of indigenous cattle. These findings and the observation that large outbreaks in the 1970s and 1980s were precipitated by the replacement of evergreen forests with cashew nut plantations under international development projects (Nichter, 1987), align with the idea that KFD is an 'ecotonal disease' (occurring particularly at transition zones between vegetation types) (Pattnaik, 2006). Other studies have indicated that migrant agricultural labourers in plantations have been widely affected in recent outbreaks in Maharashtra and Goa (Patil *et al*., 2017).

Provision of Tailored, Evidence-Based Decision Support Tools and Risk Guidance

Risk maps, produced from these models, at District and State levels (Figure 3), predicted new hotspots of outbreaks in future years (2019, 2020) with high accuracy, increasing confidence in their value for spatial targeting of interventions. During workshops, stakeholders reported that risk maps could be used before the KFD season (from taluk to state levels) to identify high-risk areas, especially those outside prior known outbreak sites, where tick surveillance and awareness-raising activities could be initiated. These risk maps have since been integrated into a web-based geographical decision support tool. This tool was co-produced with and tailored to the needs of cross-sectoral decision-makers and is in use by the Virus Diagnostic Lab, Shivamogga,

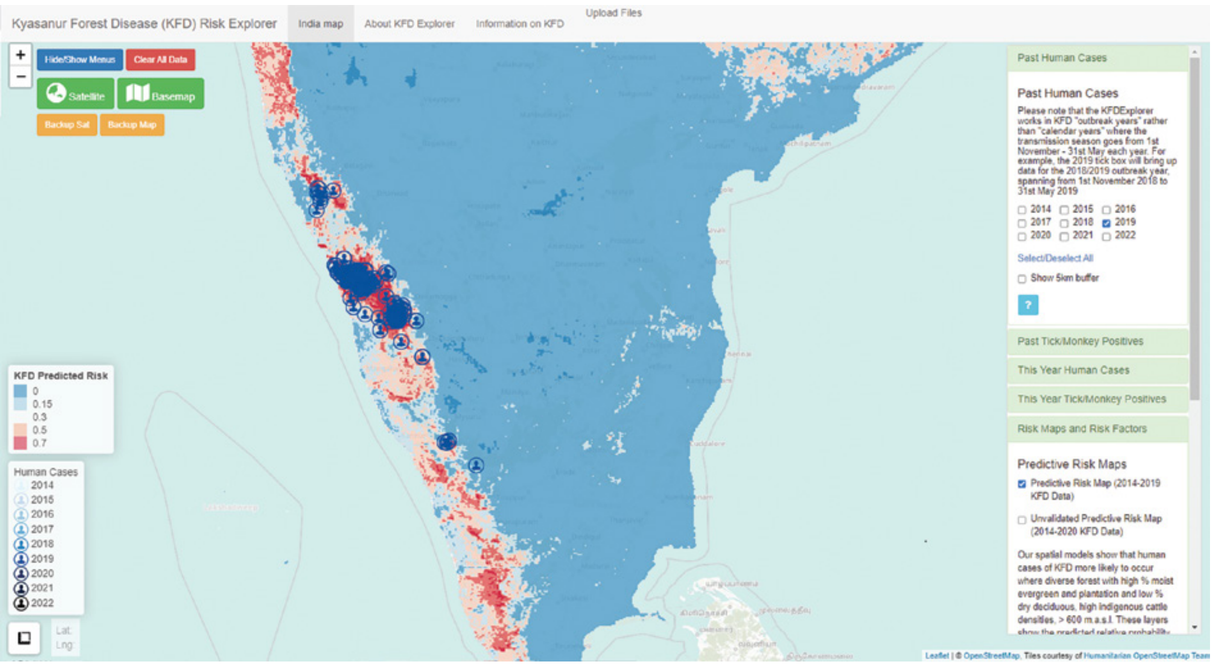

Figure 3. Snapshot of the KFDExplorer Tool showing south India overlaid with the human cases reported in 2019 to the Department of Health and Family Welfare Services (Karnataka) and the areas predicted to be highly suitable for spillover of KFD to humans in red versus areas predicted to be unsuitable for spillover in blue. As indicated by the right-hand menu options, users of the tool can also view environmental risk factors, surveillance data for monkeys and ticks and people, and a detailed base map of landscape contextual features that guide management such as villages and roads.

which plays a central role in KFD management in the region (as part of DHFWS). The tool allows users to view surveillance and outbreak data in real-time, alongside information on risk factors, 'at-risk' populations, landscape features and health system resources of relevance to management (Purse *et al*., 2020).

Our participatory research identified limited access to relevant disease information (including recommended personal protective measures) as a key risk factor for KFD and highlighted that disease information should be carefully contextualised for affected communities, particularly for the often 'at-risk' marginalised land-dependent groups. Co-designed health interventions that are sensitive to socio-economic and cultural contexts could avoid mistrust and livelihood uncertainties and thereby maximise potential uptake and effectiveness. In this sense, the MonkeyFeverRisk team co-produced tick information cards in local languages and a video to help educate and inform affected communities about the risks from ticks and tick protection measures (see https://www.monkeyfeverrisk.ceh.ac.uk/kfd).

Systems Level Outcomes and Challenges of Co-Production

The co-production process also resulted in broader outcomes at a systems level including improved policy visibility of KFD and a broader culture of inter-sectionality between cross-sectoral stakeholders fostered through the workshops and a dedicated WhatsApp network for sharing information relevant to KFD (Asaaga *et al*., 2022). We learned that co-production processes are resource intensive and have to be continually adapted to external events that alter the changing availability and priorities of stakeholders and policy makers, such as the COVID-19 pandemic and the 2018 floods in south India.

Project Outlook

Though the decision support tools were transferred to the local health department in 2020, we are exploring mechanisms for updating the risk maps annually and integrating the tools into existing health information systems to foster wide and easy access across sectors. It will be critical to address whether these co-produced tools enhance longer-term disease preparedness in terms of human cases avoided due to improved targeting of interventions and whether the cross-sectoral engagement and ownership of the tool will be sustained (Asaaga *et al*., 2022). As part of the subsequent IndiaZooRisk project partnership (also funded by UK Research and Innovation's Global Challenge Research Fund), we are applying ecosystem approaches to advance understanding and mitigation of other neglected, ecologically complex zoonotic diseases that affect forest-dependent communities in the Western Ghats, including Scrub Typhus and Leptospirosis. This will include capturing how seasonal tick and reservoir host ecology interact with current human uses of forest to underpin exposure and exploring the role of knowledge networks, income diversification and human mobility as mechanisms for adapting to the impacts of these often underdiagnosed febrile illnesses. Through continued co-production, risk guidance, risk maps and decision support tools will be adapted for these additional pathogens but also for other key affected communities, including pastoralists that graze their animals in the Western Ghats for part of the year.

Conclusions

For Kyasanur Forest Disease affecting forest-dependent communities in south India, a joint investigation of the socio-ecological processes underpinning disease risk advanced understanding of the breadth of tick species and reservoir hosts involved in transmission and habitats in which exposure can occur and the role of forest change in spillover. It also enhanced our understanding of the diverse social groups affected and their barriers and opportunities for adaptation to the disease. Through the co-production process, stakeholders shaped the development of decision support tools and risk guidance (e.g. multi-lingual tick information cards for affected communities) in a manner that met their needs and priorities concerning KFD management – tailoring which is difficult to achieve through a conventional researcher-driven approach. Our interdisciplinary approach, engaging with project partners and post-doctoral scientists embedded in the local Health Department, was critical for tailoring vector-borne disease surveillance, risk models and information to the scale of and priorities for forest use, to Public Health interventions and information systems and for understanding how ownership of tools can be transferred and sustained into the future. Key priority knowledge gaps were identified including understanding the relative importance of small mammals, cattle and monkeys in transmission and exposure of diverse forest users to KFD, both seasonally and across habitats, and exploring the role of knowledge networks, income diversification and human mobility as mechanisms by which communities adapt to impacts of zoonotic febrile illnesses

Group Discussion Questions

1. What were some of the key elements of the MonkeyFeverRisk ecosystem approach to understanding tick-borne zoonotic disease from multi-purpose agro-forest landscapes? Can you think of other zoonotic disease systems to which an ecosystem approach could be applied and why?
2. What do you understand by co-production? What do you think might be the main challenges in implementing these approaches?
3. Which were some of the key actors and beneficiaries involved in the co-production of the research and tools and what roles did they play?
4. What were the important stages of the co-production process and what were the benefits of tailoring the research to the needs of end users?
5. MonkeyFeverRisk highlighted some key gaps in our knowledge that are hampering tick-borne disease interventions. Which gaps would be most important to address first and which scientific methods could you use?

Further Reading

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Further information about the MonkeyFeverRisk and IndiaZooRisk projects including funding information can be found at the following links: https://monkeyfeverrisk.ceh.ac.uk/; and https://gtr.ukri.org/projects?ref=MR%2FT029846%2F1.

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