Prevention and response to rabies incursions in Low-and-Middle-Income Countries (LMICs)

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BA, DVM, MSc

Submitted in fulfilment of the requirements for the degree of
Doctor of Philosophy (PhD) in Infectious Disease

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SEPTEMBER 2025

To Kat and Mike

Abstract

Rabies is a viral, zoonotic disease that kills 59,000 people annually, mainly in low-and-middle-income countries (LMICs) in Africa and Asia, through dog-to-human transmission. To eliminate dog-mediated human rabies deaths, the 'Zero by 30' global strategy developed by WHO and fellow international organisations recommend a sustained 70% vaccination coverage in dog populations. However, in rabies-endemic countries, rabies surveillance is severely limited due to lack of political will and insufficient resources for rabies detection, treatment and prevention. Rabies control measures including diagnostic tools, dog vaccines and post-exposure prophylaxis or PEP for humans, are undersupported in LMICs, therefore resulting in poor case detection and reporting, and high numbers of human deaths. Nevertheless, the path toward dog rabies elimination is straightforward, and has been achieved and sustained by many high-income countries (HICs), although incursions from LMICs are occasionally reported.

My objective was to explore different strategies aimed at controlling rabies incursions in LMICs. I used a transdisciplinary approach involving analysis of past incursions, real-time evaluation of an incursion as it unfolded into an outbreak, and assessment of a novel intervention that could potentially reduce rabies transmission. Beginning with an introductory chapter, this thesis focuses on what constitutes a rabies incursion and the current status of rabies surveillance and control measures worldwide. Next, in Chapter 2, I performed a systematic review of rabies incursions reported globally from 2001 to 2022 to highlight the catalytic role that incursions have played in global rabies (re-)emergence. My analysis identified incursions that resulted in outbreaks mainly in LMICs, and pinpointed

common factors that contributed to different outcomes, from those that were contained to those causing fatal outbreaks and establishing endemic circulation. My findings illustrated the importance of preparedness and response capacity to minimize resurgence in nearby rabies-free zones, which is typically lacking in LMICs.

For the third chapter, I investigated the detection and response to a dog-mediated incursion in the previously rabies-free island province of Romblon, Philippines. A positive canine rabies case was initially detected in late 2022, and led to the detection of more than 40 positive samples within a year, as well as two laboratory-confirmed human rabies deaths. Lack of surveillance and suspension of mass dog vaccination activities due to COVID-19 restrictions contributed to the introduction of rabies into Tablas Island, which was human-mediated via boat travel. Contact tracing and dog vaccination were initiated but reach was limited. Integrated bite case management (IBCM) was essential for detection of this outbreak, and phylogenetic analysis of outbreak samples revealed possible introductions from rabies-endemic provinces within the Philippines.

My fourth and fifth chapters describe the implementation of long-lasting collars during a mass dog vaccination event in Puerto Galera municipality, Philippines. In the fourth chapter, I evaluated the feasibility of incorporating collars into vaccination campaigns by interviewing practitioners about their experiences with using collars. I also administered questionnaires to community members to gauge their behavior changes toward collared dogs, and conducted transect surveys to assess collar durability. While practitioners experienced minimal difficulty with learning and applying collars, questionnaire answers exposed a lack of understanding of rabies transmission among the local community. Most believed that dogs are susceptible to rabies even when vaccinated, and reported displaying indiscriminate behavior toward collared and non-collared dogs. Understanding of rabies among residents must therefore be improved for collars to induce a change in human behavior toward collared dogs. Collars were found to be vulnerable in coastal conditions as most were lost within months, necessitating a different material for improvement of collar durability. In Chapter 5, I used mark-resight survey results to estimate the free-roaming dog population and vaccination coverage in Puerto Galera, capitalizing on the deployment of collars. I determined that overall vaccination coverage was low, especially among free-roaming dogs, and that the dog population in Puerto Galera is severely underestimated. Targeting vaccination toward free-roaming dogs caused significantly increased coverage in an area where vaccination of free-roaming dogs was prioritized.

Summarized in my final chapter are the main conclusions to be drawn from this thesis: incursions in rabies-free zones in LMICs are frequent, underscoring the importance of targeting and sustaining rabies vaccination in rabies-endemic areas. Delayed incursion detection results from gaps in rabies surveillance, which can be enhanced with tools like IBCM, while genomic sequencing can determine incursion sources. LMICs such as the Philippines face unique cultural challenges to rabies elimination: knowledge gaps on rabies and traditional practices that have normalized free-roaming dogs are some of which have prevented rabies control interventions like collars from being more effective. My work shows that key priorities for LMICs like the Philippines should be sustaining control strategies (particularly dog vaccination and rabies surveillance) and improving rabies education, to accelerate progress toward the ‘Zero by 30’ goal.

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Acknowledgements

The opportunity to pursue a PhD would not have been possible, first and foremost, without my supervisors Katie and Nai, who believed in me from Day One, and should take full blame for my thrilling foray into the field of rabies. My career in epidemiology started when I struck up conversation with Katie in a conference, and she graciously offered to share her contacts with me so that I could center my research project on rabies, which had been my plan (and main motivating factor) when starting my master's degree. Katie has never failed to go through every written and rewritten paragraph of mine, giving me feedback at a moment's notice. She has forever been empathic and understanding, making sure to remind me whenever I'm being too hard on myself.

Nai has been instrumental in cultivating my newfound passion for social sciences. He has always been attentive and helpful, pointing me toward various seminars and classes that have let me broaden my knowledge inside and outside the classroom. Through his recommendations, I've gotten to explore several amazing places in the UK and brush up on new and interesting social science concepts through seminars. He has been a constant calm, guiding force all throughout this whirlwind of a journey.

In the Philippines, my primary mentor has been Dr. Mary Elizabeth 'Betsy' Miranda, who also introduced me to the rest of my SPEEDIER/FETPAFI family: Eric, Brandy, Alan, Diane, Ateng, Duane, Sheryl and Gian. Dr. Betsy has been a never-ending treasure trove of knowledge and experience, and has served as an unlimited source for words of wisdom. She never stopped encouraging me to take greater leaps in my career, and has always had my best interests at heart. Courtesy of her bakeshop, I've had a constant supply of tasty pastries and snacks. Rabies research in the Philippines has taken many great strides thanks to her, and she has been an inspiring leader whose lifelong passion for public health infects those around her.

I am also eternally thankful to my real life family: my best friend and husband Jonathan, whose patience, support and encouragement was crucial to surviving this whole journey. He stood by me through degree after degree after degree, and never held it against me when I'd tell him: "This is the last one, I swear" (which always turned out to be a lie). He has sat through three of my graduations, no matter how long or arduous, and has built a life for us that I love, all while accompanying me on my adventures across several continents, and juggling these trips with his own demanding career. I'm equally thankful to our amazing pets Kitty, Syao, Jake and Taako (who have all crossed the rainbow bridge), as well as Bolin, who've always made me smile whether right next to me or through years of memories with them.

As for my family, my parents Bambi and Krip have always checked on me no matter where I am on this earth, and I've always had amazing lunches and dinners to come home to, shared with my brothers Alyo and Aric, and Maddie, Icee, Aria and Azazel. My other set of parents, Alen and Roly gave me a second (and third, and fourth…) home, as have JP, Trish, Aerin, Calliope, Raya, Arvin, Lilia, Jun-Jun, Analyn, Randy and Arlene.

My extended family has cheered me on every step of the way, consisting of Maris and Pocholo, Nina and Albert, Mel and Cathy, Twink and Paulo, Carrie and Rico, and Arnel. My cousins have kept me rightfully humble: Jodie, Kitkat, Mica, Jao, Jacpat, Jamie, Willis, Juancho and Theo, reminding me to live up to our creed, "Macaraig Clan 4 lyfe". I also am grateful to Edwin and Jeanine, Dindo and Filma, Girlie and Didit, Karen, and

Mick, who took care of me in the US. Meanwhile, Nennie and Mel are always there to support me whenever I'm in the UK. Similarly, to my Camden buddies, Liane, Luis, Luna and Luca, I'm glad British Council gave us the opportunity to meet. I am equally thankful to Liana, Aika and Presley, for making sure we had an amazing time in Germany.

I am grateful for Team Fire: Miya, Timmy, Nico, and Martin, whose own careers have motivated me to try harder and harder. I am also thankful to Team VAWN: Van, Nerico, AB, Winni, and Toto. I would have been helpless in Scotland without my University of Glasgow family: Essel, Anna, Antonella, Matilda, Catherine, Smitha, Ellie, Tasmin, Martha, Danni and Mafalda, whose brilliance and talent I've always tried to emulate. They have made Glasgow a warm and inviting place no matter how frigid the weather got.

I would also like to thank the following, for without them I would have not been able to finish my PhD: Dr. Daria, Dr. Apple, Marife, Aga, Heidee, Zyd and Amiel of the Municipal Agriculture Office, Dr. Josue, Dr. Shynie, Ma'am Mitch, Dr. Jobin, Dr. Pido, Dr. Bettina Quiambao, Dr. Ryan Wallace, Worldwide Veterinary Service (WVS), Boehringer-Ingelheim, as well as Dr. Daniel Streicker and Dr. Taya Ford for being wonderful assessors. The communities of Puerto Galera, Calapan and Tablas Island have graciously hosted me time and time again, and I owe a lot to the barangay health workers and tireless ABTC nurses who have always cooperated with us.

Lastly, none of this would be possible without University of Glasgow who provided me this opportunity, as well as The Wellcome Trust for funding my studies.

Declaration

I declare that all contents described and presented in this thesis resulted from original research that was carried out by myself, Mirava Yuson, the author, unless where otherwise cited or acknowledged. All collaborative and co-authored work is indicated in this declaration, with each contributor and their corresponding credits described in detail. All of this writing was completed under the close supervision of Professor Katie Hampson and Dr. Nai Rui Chng. This thesis has not been submitted for any other degree at the University of Glasgow or any other institution. It is solely my own work with contributions to my research chapters (2-5) as follows:

I designed and wrote the study for Chapter 2. Dr. Eleanor Rees was second reader of papers included in the review and provided advice on the study design and analysis. We co-reviewed all literature for our systematic review and tabulated all found incursions. I wrote the initial draft, and all co-authors contributed to reviewing the final draft. The chapter has been prepared as a manuscript for submission to Proceedings of the Royal Society B with the following co-authors: Eleanor Rees, Katie Hampson, Nai Rui Chng and Mary Elizabeth G. Miranda.

Chapter 3 was a joint first-authored publication between myself and Dr. Criselda "Essel" Bautista. I was responsible for the IBCM component while Essel was in charge of the genomics sections; thus, I wrote the first draft sans the genomics-related analyses and discussion. I collected epidemiological data as part of the SPEEDIER project, which was first implemented in 2019 and with which I was personally involved in training government partners in IBCM. I also conducted constant follow-ups to ensure that enhanced (IBCM) surveillance data was collected. With the help of co-authors, I analysed information regarding the Romblon outbreak and public health response.

For Chapters 4 and 5, I conceptualised the study design, performed data collection and analysis, and wrote up the findings. Gian Mangcucang, Sheryl Pablo, Dr. Van Denn Cruz, Dr. Nerico Gregorio and AB Lopez-Gregorio also assisted me with collecting data by conducting mark-resight surveys and distributing questionnaires, while Tasmin Alexander helped as second coder of interview transcripts. The fourth chapter has been prepared as a manuscript for submission to CABI One Health with the aforementioned co-authors and Daria Manalo, Mary Elizabeth G Miranda, Nai Rui Chng and Katie Hampson. Dr. Mafalda Viana assisted me in creating a Bayesian model for Chapter 5.

Mirava Yuson

Abbreviations

- ABTC - Animal Bite Treatment Center
- AHW - Animal Health Worker
- BHW - Barangay Health Worker
- BI - Boehringer Ingelheim
- DFAT - Direct Fluorescent Antibody Test
- DOH - Department of Health
- EID - Emerging Infectious Disease(s)
- FAO - Food and Agriculture Organization of the United Nations
- FETPAFI - Field Epidemiology Training Program Alumni Foundation, Inc
- GARC - Global Alliance for Rabies Control
- GIDA - Geographically Isolated and Disadvantaged Area(s)
- HDR - Human-dog ratio
- HIC - High-income country
- IBCM - Integrated Bite Case Management
- IEC - Information, Education and Communication
- IHR - International Health Regulations
- LGU - Local Government Unit
- LMIC - Low- and middle-income country
- MAO - Municipal Agriculture Office
- MHO - Municipal Health Office
- MDV - Mass dog vaccination

- MIMAROPA - Mindoro-Marinduque-Romblon-Palawan
- ORV - Oral rabies vaccination
- PCR - Polymerase Chain Reaction
- PEP - Post-exposure Prophylaxis
- PHO - Provincial Health Office
- PHW - Public Health Worker
- PVO - Provincial Veterinary Office
- RABV - Rabies virus
- RADDL - Regional Animal Disease Diagnostic Laboratory
- RDT - Rapid Diagnostic Test
- RHU - Rural Health Unit
- RITM - Research Institute for Tropical Medicine
- SPEEDIER - Surveillance integrating Phylogenetics and Epidemiology for Elimination of Disease: Evaluation of Rabies Control in the Philippines
- WOAH - World Organization for Animal Health (formerly OIE)
- WHO - World Health Organization
- WVS - World Veterinary Service

Chapter 1

Introduction

1.1 Background

Neglected tropical diseases (NTDs) are a series of diseases and conditions that were classified by the World Health Organization in the early 2000s due to their ubiquity in resource-challenged countries (Hotez et al., 2020). The current list includes 25 diseases, having been expanded to include rabies in 2013 (WHO, 2013). NTDs cause 200,000 deaths and considerable economic loss yearly (WHO, 2021), with nearly 30% of deaths caused by rabies alone, mainly in Asia and Africa (Hampson et al., 2015).

Rabies virus (often shortened to 'RABV') is a type of lyssavirus that is pathogenic among mammals, and can zoonotically be transmitted to humans through saliva, most often via biting by dogs (Hankins & Rosekrans, 2004). It is an ancient disease that has been described as early as 500 B.C.E. in ancient Greek literature (Blanton & Wallace, 2016). While its precise origins are unknown, evidence shows that its worldwide spread was a direct effect of European colonization (Baer, 2007). Among NTDs, rabies is an outlier in a myriad of ways: it is the only source of viral infection apart from dengue, its mortality is 100%, it is vaccine-preventable as long as vaccination is completed before signs manifest, and unlike other NTDs, vaccines for humans and dog vaccines are permitted globally. For humans, post-exposure prophylaxis (PEP) is a common treatment following biting incidents and similar exposures involving dogs or other mammals, whereas for dogs, mass dog vaccination (MDV) is one of the main approaches to controlling rabies in rabies-endemic countries. Thus, ensuring adequate supply and full access to human and dog vaccines, along with building public health response capacity and strengthening surveillance, are three strategies outlined in WHO's road map for rabies from 2021 to 2030 (WHO, 2021a). These recommendations were originally published in 2018, when WHO, GARC, WOAH (formerly OIE) and FAO developed 'Zero by 30', a global strategic plan to eliminate human-mediated rabies deaths by 2030 (WHO et al., 2018).

As reported in 'Zero by 30', empirical and statistical evidence shows that sustaining a vaccinated coverage of 70% among dogs would disrupt rabies transmission and eventually lead to elimination of dog-mediated human rabies deaths (Britton, 2020). Other recommended approaches outlined in “Zero by 30” strategies include raising awareness, administering PEP, and employing One Health approaches to enhance rabies surveillance. One Health, in reference to rabies, involves interdisciplinary collaboration between animal and human health sectors for disease response and prevention (Mackenzie & Jeggo, 2019). Integrated Bite Case Management (IBCM), a One Health approach highlighted in “Zero By Thirty”, relies primarily on human and animal health intersectoral coordination for case finding (Swedberg et al., 2022) (Fig. 1.1). Healthcare workers perform risk assessments on patients involved in bite incidents to determine whether the biting animal was a probable or confirmed rabies case based on its health status. A high-risk bite case involving an animal that is suspicious for rabies is reported to animal health workers for investigation and sample collection, while a low-risk or healthy animal indicates lesser need for PEP, which could then be allocated toward a patient involved in a high-risk bite case. Benefits of IBCM include improved case detection and reporting of human exposures, and preventing misuse or overuse of PEP in LMICs where resources, and therefore vaccine stocks, are often limited.

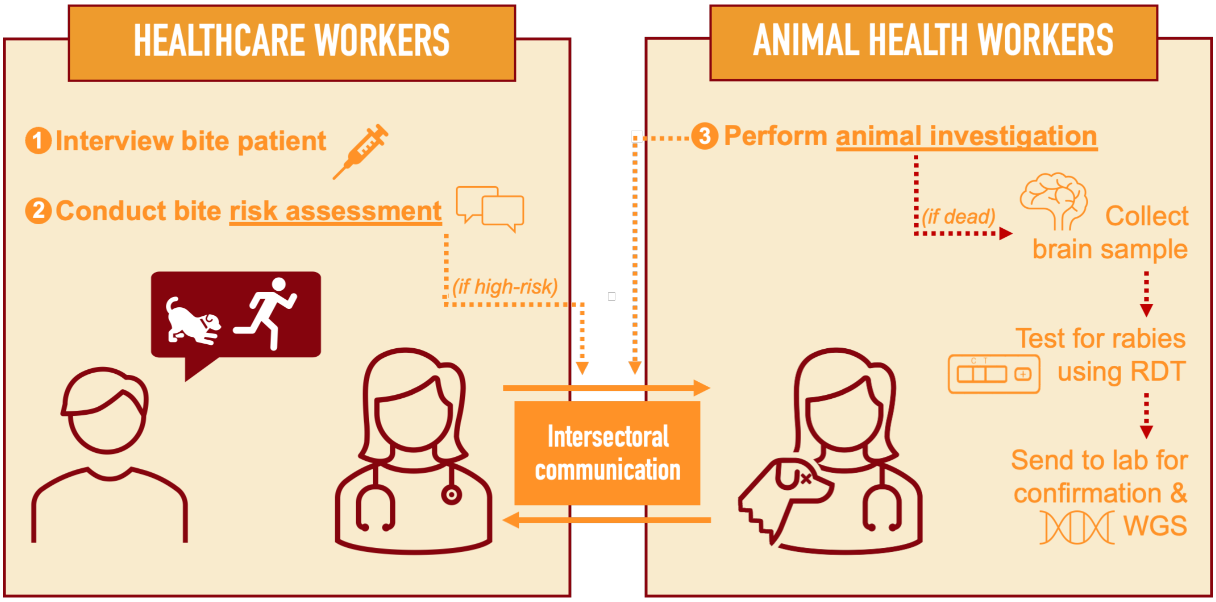

Figure 1.1: Integrated Bite Case Management (IBCM) step-by-step process. RDT = rapid diagnostic test; WGS = whole genome sequencing.

1.1.1 Defining incursions

Increasing case-finding in low-resourced areas, IBCM can be used to detect rabies incursions and support outbreak response (Lushasi et al., 2020; Yuson et al., 2024). While the term ‘disease incursion’ has no textbook definition, it is used interchangeably with ‘emergence’ or ‘introduction’ to denote the unprecedented appearance of disease. But there is one key difference: unlike ‘emergence’ and its emphasis on the disease’s discovery, or the novel detection of a new strain of infection, an ‘incursion’ emphasizes place over pathogen, highlighting a disease’s entry into a novel setting. A disease incursion occurs into a geographic area, and that area may encompass an entire country—for example, Australia being at risk of exotic disease incursions (Johnston & Scott, 1985)—or Oceania as a whole, wherein potential African swine fever incursions remain a critical issue (Kurian et al., 2021). Alternatively, an incursion may occur in a zone that is as constrained and specific as Australia’s Tennant Creek, where dengue-carrying mosquitoes threatened its dengue-free status in 2011 (Whelan et al., 2012).

Incursion detection is significant because it can signal an impending disease outbreak. Probability of disease outbreaks is heavily influenced by R_0 (the average number of cases infected by an individual in a susceptible population). Outbreaks are possible for diseases with low or high individual variation. However, for the same R_0, outbreaks would be less common for diseases with more individual variation based on the same number of introductions, and when they occur, they will be more explosive (Lloyd-Smith et al., 2005). In the context of incursions, that means more introductions are needed before an outbreak will occur with certainty (Hampson et al., 2009). Rapid response measures to incursions can reduce outbreak risk. Correspondingly, disease incursions will likely lead to secondary transmission and outbreaks if control measures–such as mass dog vaccination, to account for rapid turnover of domestic dogs–are not sustained where a disease was previously eliminated. Therefore, detection of incursions can unveil potential gaps in surveillance systems and show where disease control measures should be improved (Townsend et al., 2013).

Rabies incursions have steered the trajectory for control measures globally, especially with regards to biosecurity concerning animal trade and transport. Recognizing incursions in a timely manner enables quick public health response, allowing for measures to be implemented to prevent re-establishment (Banyard et al., 2010). Rabies elimination has been achieved in many countries through a combination of methods, with mass vaccination and stringent animal importation rules being among the most common for achieving and sustaining freedom from rabies. At present, with rabies still endemic in many countries, rabies-free countries are constantly under threat of incursions (also termed re-emergence, reintroduction), which are the result of a rabid animal making its way into a rabies-free zone from a rabies-endemic one (Yamada et al., 2019). In order to be classified as "rabies-free", a country must fulfil two requirements: first, no indigenous rabies case must have occurred there within two years, and secondly, rabies surveillance measures must be enacted consistently, including routine sample testing of potential animal hosts (World Organisation for Animal Health, 2011). Following incursions that led to secondary transmission, some rabies-free countries have lost rabies-free status temporarily, but regained it later. LMICs wherein the disease is endemic in domestic dog populations continue to work toward achieving rabies freedom, while sustaining efforts to maintain designated rabies-free zones. In the following section, I provide an overview of the historical basis of rabies circulation around the world, to provide the context for and progress towards achieving rabies freedom.

1.1.2 Rabies elimination progress across the world

Global rabies spread was made possible by human-mediated incursions, whereas natural movement of free-roaming dogs (and wildlife) facilitated local spread (Bourhy et al., 2008; Velasco-Villa et al., 2017). Emergence of rabies in wildlife was typically the result of spillovers into new hosts from dogs, and is a popular example of another type of incursion that occurs when rabies circulates sufficiently for a long time (Fisher et al., 2018). As of 2025, all High-Income Countries (HICs) have eliminated dog-mediated rabies, although wildlife rabies cases occasionally spread to domestic animals. Many Low-and-Middle-Income countries (LMICs), despite being rabies-endemic, contain local rabies-free areas but experience difficulties in sustaining or expanding these zones. Since the same kind of stochastic processes that result in incursions can lead to secondary transmission and eventually outbreaks and established endemicity, elimination programmes in LMICs aim to interrupt local transmission but then must also guard against incursions from endemic areas. Closer proximity to endemic areas increases the likelihood of receiving incursions, which is why maintaining freedom is harder in endemic settings, and is further hindered by poor surveillance and insufficient rabies control measures. But expansion of rabies-free areas is a self-reinforcing process, as by doing so, central areas where rabies has been eliminated will be less at risk. Despite economical barriers, LMICs have taken similar steps as HICs to control rabies.

1.1.2.1 Antarctica

There is no history of rabies in animals found in Antarctica as there are no terrestrial mammals (or bats) on the continent. Hence, no attempts have been made to conduct regular laboratory-based surveillance for lyssaviruses, greatly decreasing the likelihood for incursions to be detected (Rupprecht et al., 2018).

1.1.2.2 Oceania

The earliest, and one of the only historical accounts of rabies incursions in Australia took place in 1867 in Tasmania, where a child was bitten by a dog (Sparkes et al., 2015). But from the year 2000 onwards, no rabies cases were detected in all countries, islands and territories encompassed by Oceania, with the entire continent considered rabies-free (Bannazadeh Baghi et al., 2018). Although Australia and New Zealand have verified rabies freedom, rabies data is unavailable for other island countries, with surveillance neglected in countries with stray dog populations, such as American Samoa and Papua New Guinea (Vargo et al., 2012). The United States territory Guam, currently rabies-free, suffered a rabies outbreak in 1967, caused by dogs brought by military personnel that infected local stray dogs. It was resolved through mass culling and recurrent mass vaccination (Glosser & Yarnell, 1970).

1.1.2.3 Europe

The United Kingdom managed to achieve dog rabies elimination pre-vaccines in the late 1800s through mandatory leashing and muzzling, although the dog population was notably smaller during that time period (Muir & Roome, 2005). Countries like Hungary and Bulgaria became dog rabies-free in 1930 and 1954 after eliminating the disease in rural areas through strict pet ownership policies and mandatory vaccination, respectively. The development of the rabies vaccine in 1885 by Pasteur and its widespread distribution in the 1920s greatly reduced dog rabies prevalence and led to elimination in most European countries during the 20th century (Vega et al., 2021). Since then, France (Peigue-Lafeuille et al., 2004), Netherlands, Switzerland (Zanoni & Breitenmoser, 2003), Germany (Müller et al., 2012), Italy (Mulatti et al., 2013) and Spain (Pérez de Diego et al., 2015) have been dog rabies-free, but have suffered occasional incursions due to human-mediated dog importations from rabies-endemic countries, from where travelers adopted pets and brought them back to Europe (Johnson et al., 2011). Spanish cities Melilla and Ceuta, which share borders with Morocco, experience annual dog rabies cases (Hodgson, 2022). While stray dogs can be found in countries like Romania (Najar & Streinu-Cercel, 2012) and Greece (Giannakopoulos et al., 2016), both are described as dog rabies-free.

Rabies in wildlife, particularly foxes, was first reported during World War II and eventually spread across Europe through natural movement (Lojkić et al., 2021). Oral rabies vaccination (ORV), which involves laying vaccine-dosed bait for wild carnivores to consume, was initially developed as a rabies control measure against foxes, and is now widely used in many European countries, along with surveillance consisting of routine fox sampling (Henning et al., 2017). ORV is intensified or expanded along borders with rabies-endemic countries whenever incursions are detected (Robardet et al., 2014). Despite these efforts, some European countries sharing land borders have been unable to eliminate wildlife rabies, including Bulgaria (Robardet et al., 2014), Hungary (Smreczak et al., 2022), Austria (Vogl, 2002), Slovakia (Ondrejková et al., 2020), Serbia (Stankov et al., 2021) and Greece (Lojkić et al., 2021), due to lapses in ORV leading to occasional cases detected along border regions. In Greenland, rabies is endemic among Arctic foxes and has caused outbreaks in sled dogs (Mansfield et al., 2006).

Ukraine (Makovska et al., 2021), Moldova, Belarus and Russia (Picard-Meyer et al., 2012) are endemic for dog and wildlife rabies, due to lack of sustained rabies control efforts and proliferation of stray dogs. Belarus in particular, following the Chernobyl accident, had an explosion of abandoned-turned-stray animals (Mishaeva et al., 2007). Lack of surveillance data in countries such as Bosnia and Herzegovina make it difficult to discern rabies prevalence in dogs and wildlife.

1.1.2.4 North and South America

The United States of America eliminated dog rabies from the 1940s to the 1970s, but over several decades, continued to suffer from incursions from Mexico (Blanton et al., 2008). When Mexico became dog rabies-free in 2006 (Franco-Molina et al., 2021), it became easier for the USA to maintain freedom, although occasional international adoption of rabid dogs occurred yearly until stricter pet importation rules were enforced in 2021 (CDC, 2022). As of 2025, dog rabies is nearly gone from the hemisphere, having been eliminated through MDV (Velasco-Villa et al., 2017) in Uruguay, Paraguay, Chile (Vigilato et al., 2013), Colombia and Ecuador (Ortiz-Prado et al., 2016).

However, dog rabies remains endemic in Nicaragua (Rupprecht et al., 2022) and Honduras (Arias-Orozco et al., 2018), as well as Haiti, where political turmoil and natural disasters led to neglect of control measures (Seetahal et al., 2018). Bolivia is also a common source of rabies incursions into Brazil, where cases have been reported in dogs along the Brazil-Bolivia border region (Galhardo et al., 2019). Incursions from Bolivia have led to an outbreak in Brazil that was rapidly controlled with MDV (Rysava et al., 2020), and a separate outbreak in Peru (Jeon et al., 2019). In El Salvador and Venezuela, surveillance measures and MDVs are often resource-limited, and thus, dog rabies is occasionally reported (Sarrameda & Recuenco, 2024; Chavarría et al., 2022). Surveillance is similarly neglected in historically dog rabies-endemic countries including Suriname (Seetahal et al., 2018) and Guyana (Milstein et al., 2022). Despite being described as dog rabies-free, recent surveillance in Panama has been insufficient to confirm its freedom status (Vigilato et al., 2013).

In the absence of dog-mediated rabies, rabies remains a public health threat in Mexico, the Caribbean and other Central and South American countries due to vampire bats, as spillover to livestock frequently occurs (Franco-Molina et al., 2021). Vampire bat-transmitted rabies in cattle has been reported in Costa Rica (León et al., 2021), Belize (Becker et al., 2021), Cuba, Grenada (Seetahal et al., 2019), Trinidad and Tobago (Everard & Everard, 1992), Uruguay, Paraguay, Colombia (Bonilla-Aldana et al., 2022), Argentina (Margineda et al., 2021), Brazil and Peru (Benavides et al., 2016), with cases are expected to rise as environmental changes decrease forest coverage (Botto et al., 2019). Whereas in Canada, foxes are main wildlife reservoirs for rabies, and higher numbers of rabies cases tend to occur post-breeding season in spring, from occasional attacks on cats and dogs in urban areas (Simon et al., 2021). Mongoose rabies, a by-product of colonization, is endemic in the Caribbean islands of Puerto Rico (Ma et al., 2018), Cuba, Dominican Republic and Grenada (Morgan et al., 2020).

1.1.2.5 Africa

Rabies in dogs in Africa were reported as early as 1896, as an unintended outcome of colonialism (Andriamandimby et al., 2013). Outbreaks in Zambia in 1901 led to mass culling of dogs and stricter dog ownership laws (Munang'andu et al., 2011), while in 1904, rabies spread across the continent from Ethiopia to Zimbabwe until it was eliminated through similar practices (Johnson et al., 2004). Eventually, rabies was reintroduced to Zimbabwe in the 1950s (Pfukenyi et al., 2007). Shared borders enabled international spread from Angola to Namibia and Botswana in the 1940s (Sabeta et al., 2003), before finally reaching South Africa (Sabeta et al., 2003).

Most of Africa is currently rabies-endemic, and free-roaming dogs are common (Ali Osman et al., 2024; Faye et al., 2022; Lechenne et al., 2017; Rupprecht et al., 2022). Control strategies including MDV are negligible in Sub-Saharan African countries except South Africa (Haselbeck et al., 2021). In North Africa, MDV and culling are conducted with more efficiency, but cases are continuously underreported due to neglect of surveillance measures (Gautret et al., 2011; Marston et al., 2009). Unlike landlocked countries, the island territories are reportedly rabies-free, and being isolated, rarely get incursions as the absence of shared borders with other nations prevents natural movement of dogs (Mbilo et al., 2021). Such differences further highlight the challenges in rabies control currently affecting most of Africa: incursions and outbreaks are caused by a combination of local free-roaming dog movement and rarer long-distance (human-mediated) movement (Omodo et al., 2020; Townsend et al., 2013). As evidenced by genomic surveillance, rabies circulates endemically in local dogs at low prevalence (Mancy et al., 2022), while frequent introductions of new lineages from neighbouring rabies-endemic areas are a perpetual source of incursions (Bourhy et al., 2016). This is why control measures, especially MDV, need to be targeted toward rabies-endemic areas and maintained at high levels without interruption, which is a challenge in itself for low-resourced countries. To eliminate dog rabies in Africa, cross-country collaboration between nations–similar to the shared efforts previously seen in Europe and Latin America–would permit large-scale and continuous implementation of control strategies (e.g. MDV, PEP) leading to collectively high vaccination coverage and expansion of rabies-free zones (Bucher et al., 2023).

1.1.2.6 Asia

The majority of human rabies deaths occur in Asia, particularly in India, where rabies is speculated to have originated (Léchenne et al., 2019). Similar to Africa, high prevalence of dog rabies in Asian LMICs is often attributed to free-roaming dog populations and poorly sustained control measures (Kabzhanova et al., 2023). However, countries such as Japan, Hong Kong, Singapore, Brunei Darussalam, Taiwan and South Korea have maintained rabies freedom due to mass dog vaccination and stray dog population control. Strict border control measures were also enacted to reduce the risk of incursions from neighbouring countries such as China, which is geographically isolated from Taiwan and Hong Kong, and North Korea, whose political isolation benefits South Korea (Tenzin & Ward, 2012).

In Southeast Asia, human rabies deaths have been greatly reduced through PEP (Tenzin & Ward, 2012), although surveillance is limited and MDV is inconsistent, especially in rural areas (Léchenne et al., 2019). Human-mediated dog rabies introductions into Flores, Bali and Nias islands in Indonesia, and Sarawak in Malaysia, led to re-establishment of rabies after culling and dog vaccination attempts failed to resolve the outbreaks (Jatikusumah et al., 2021; Ward & Brookes, 2021). Timor-Leste was rabies-free until the reporting of a human case in 2024 (Amaral Mali et al., 2024).

For countries in Central Asia and the Middle East, surveillance data is limited (Counotte et al., 2016), with occasional cases reported in dogs (Sultanov et al., 2016; Kuzmin et al., 2004). Almost all of South Asia, with the exception of the isolated island archipelago of the Maldives, is rabies-endemic, with India alone accounting for 29% of global rabies deaths as no national rabies control program exists and rabies is present in dogs, livestock and wildlife (Tenzin & Ward, 2012). Sharing borders with Nepal and Bhutan, India is a constant source of incursions from which at least two outbreaks in Bhutan have originated. Meanwhile, Bahrain, Cyprus, Qatar, and United Arab Emirates are considered rabies-free and low-risk for incursions as they share only one land border with another country (Bannazadeh Baghi & Rupprecht, 2021). In places like Turkey and Iran, dogs are tied outside the house and kept as guards of livestock, which raises the risk of rabies transmission (Bannazadeh Baghi & Rupprecht, 2021). Due to the lack of reporting in rural areas where the disease is said to be predominant, the true burden of rabies remains underestimated (Léchenne et al., 2019).

1.1.3 Estimating local dog populations

Achieving and sustaining high vaccination coverage is the key to eliminating rabies, but to plan a vaccination campaign, and measure coverage and therefore progress, we need to know the dog population size–something often missing. Reaching the "Zero By Thirty" goal is especially challenging in LMICs, where vaccination coverage is difficult to calculate due to inaccurate or outdated dog population estimations. While indoor-kept owned dogs are counted through household surveys, the true number of owned and unowned free-roaming dogs in many LMICs is largely unknown. Often conflated for one another, an owned free-roaming dog has a designated owner who feeds, names and/or shelters the dog, but does not restrain it, giving it free range of public property. Conversely, unowned free-roaming dogs, which are equivalent to stray or feral dogs, have no single or true owner, but may willingly interact with the community. The line between owned and unowned free-roaming dogs is often blurred, as unowned free-roaming dogs are fed by the community (or subsist off community leftovers and waste) but are not claimed by any particular person, while owned free-roaming dogs receive care from a specific owner and may even have access to their home, but generally go wherever they like. On average, free-roaming dogs travel up to one kilometer away from home (Pérez et al., 2018). This evidence underlines some of the issues that come with estimating local dog populations using household surveys or transect surveys.

Household surveys are contingent upon asking community members how many dogs they personally own, and despite feeding dogs regularly or occasionally providing shelter, a person may not acknowledge ownership. In India, it is normal practice for Hindus to feed community dogs regularly as this is believed to increase their karma, but dogs are considered unowned (Corfmat et al., 2023). For transect surveys, which rely on counting dogs on sight, owned dogs kept indoors during the survey can go underreported as they are not observable, while dogs can be accidentally recounted due to their large home range (Sambo et al., 2018). Feral dogs, whose activity patterns tend to be nocturnal when living in cities, are also easily bypassed by transect and household surveys (Coronel-Arellano et al., 2021). Seasonal patterns also affect dog population estimations, as infectious diseases with high mortality (such as Distemper Virus) are more common in certain seasons and will reduce the dog population (Uddin et al., 2021), while seasonal breeding result in higher numbers of dogs in certain times of the year because of the proliferation of newly-born puppies (Brill et al., 2022).

Human-to-dog ratio (HDR) is used to provide dog population estimates that can range from 2:1 to more than 10:1 based on population density, type of survey conducted and other variables (Moran et al., 2022). Despite wide variation in HDRs observed across communities, they are often used in dog vaccination to estimate desired coverage. Varying cultural practices toward dogs may result in drastically different population estimates depending on the setting, and heterogeneity across local areas has also been observed. For example, according to dog population surveys in Chile, dog density was as low as one dog per km^2 in rural areas, but could reach as high as 1,500 dogs per km^2 in a city within the same region (Acosta-Jamett et al., 2010).

1.1.4 Dog vaccine marking strategies

Post-vaccination markers have been incorporated in dog vaccination in LMICs to display the dog's rabies vaccination status, generally to inform community members which dogs are "safe". Marking dogs, when coupled with transect surveys, has also been useful in data collection for estimating dog population and vaccination coverage (Childs et al., 1998). In one recent study, collars were used to examine community perception of dogs (Omar et al., 2023).

Dye (through the use of paint, spray, wax or crayon), ear tags, microchips, vaccination cards, and plastic collars have all historically been used in post-vaccination marking (Czupryna et al., 2023). While dye is quick, easy to apply and non-toxic with minimal risk of causing harm to dogs, it is temporary and is expected to fade within 5-7 days; therefore, surveys must be performed shortly after the mass vaccination (Conan et al., 2015). Colourings also tend to be less visible on dogs with dark fur, and are susceptible to erasure upon contact with water. Ear tags are an effective long-term marking method, but require sedation during application. Microchipping and vaccination cards are not visibly seen on dogs, as microchips are only detectable through an electronic reader, and vaccination cards are kept in possession of the owner. Collars, made of plastic (Fig. 1.2), paper (Adrien et al., 2019), or cotton-mesh (Cleaton et al., 2018), are a visible, low-cost, less invasive means of marking dogs. Similar to regular dog collars, plastic collars fitting too tightly (due to incorrect application) can cause choking, and accidental strangulation is possible if loose collars-turned-ligatures snag on objects (McEwen, 2016). Collars made of paper or cotton-mesh avert this risk, but are less permanent marking methods because they are easily removed. Overall, collar use in vaccination campaigns has not been fully explored in relation to its impacts on dogs and the local community and effectiveness for population estimation.

1.1.5 Rabies in the Philippines

The Philippines is an archipelago in Southeast Asia consisting of more than 7,000 islands. Rabies was introduced from China sometime in the 20th century spreading island-to-island (Tohma et al., 2014) and has since then remained endemic. Improved access to PEP decreased human rabies deaths considerably, and as of 2023, over 300 human deaths are reported annually. Similar to other LMICs in Asia and Africa, approximately 40% of deaths consist of children aged 15 years old and below (Soentjens et al., 2021). Although a number of local municipalities and provinces have been declared as rabies-free zones by the

Figure 1.2: A collared, free-roaming dog post-MDV in the Philippines.

Department of Health (Medina et al., 2016), rabies surveillance in some areas is neglected due to a lack of laboratory facilities or trained personnel. Therefore, it is suggested that the true number of rabies cases in humans and animals is considerably higher than the reported figures.

Rabies in the Philippines, like in many LMICs, is mainly transmitted through dog bites. Free-roaming dogs are common, and are often mistaken as strays despite having owners, making it difficult to estimate the local dog population based on household surveys (Atuman et al., 2014). Philippine rabies control programs focus primarily on MDV and PEP, in accordance with Republic Act 9482 (Anti-Rabies Act of 2007) (Espanola, 2015). PEP is given to bite victims through animal bite treatment centers (ABTCs) found nationwide (Swedberg et al., 2023). Rabies vaccination coverages vary between regions, ranging from 43-70% based on government reports (Department of Health, Philippines, 2019) and are often based on an estimated human-dog ratio (HDR) of 10:1, despite studies proving that the true HDR may be closer to 3.7:1 (Dizon et al., 2022).

1.1.6 Feasibility studies for complex interventions

In healthcare, an implementation is the integration of an evidence-based practice (or set of practices) into public health settings. Implementations with several components are termed as 'complex interventions' due to the number of factors, processes and people or groups involved in ensuring the intervention's success. The UK Medical Research Council developed guidance for complex interventions, which includes a framework to help examine other aspects of the intervention apart from just effectiveness, namely how the intervention's different parts interact, its direct and indirect impacts, and its adaptability in real-world settings (Skivington et al., 2021). Process evaluation is useful for working out whether the intervention itself isn't feasible because the mechanisms assumed to underpin its actions/effects are actually incorrect, or if the intervention works but is just not implemented as intended (Moore et al., 2015). These findings can therefore provide answers for what changes are needed for better optimization.

Process evaluation for complex interventions can include a variety of methods, such as semi-structured interviews, focus group discussions, questionnaires and field notes or observations. Qualitative data, when analysed, can pinpoint key mechanisms for successful implementation. An example of a theoretical framework for assessing feasibility is Normalization Process Theory (NPT), which often involves employing mixed quantitative and qualitative methods to identify the factors needed to successfully integrate an intervention into routine practice (Holtrop et al., 2016). To create an NPT construct framework, data (for example, responses in interviews) are categorized into four core constructs: (a) coherence, indicating the level of understanding among implementers, (b) cognitive participation, meaning openness to engagement with implementation, (c) collective action, to indicate the implementers' ability to deliver the implementation effectively, and (d) reflexive monitoring, which describes the capacity for modifying the intervention during the implementation to increase its effectiveness. Vaccination programs are an example of an intervention wherein evidence-based practice has led to improvement in human and animal health and welfare (Reyneke et al., 2023), and NPT, in particular, has been used in rabies-targeted mass vaccination strategies (Duamor et al., 2023).

1.2 Thesis preamble

For this thesis, I wanted to know why incursions in LMICs happen and what factors lead to their occurrence. I was interested in the differences between implementation of control measures, particularly why and how certain LMICs successfully prevented incursions from becoming outbreaks or resolved outbreaks, while outbreaks in other places resulted in re-established endemicity.

Chapter 2 consists of a systematic literature review, wherein I compiled a list of animal rabies incursions worldwide from 2001 to 2022. My objective was to assess how rabies incursions occur, and to evaluate the control measures taken by countries in preventing and managing recurrence, local transmission or outbreaks. For Chapter 3, my colleagues and I supported the collection and analysis of enhanced surveillance data from a recent rabies outbreak in Romblon, Philippines and used the results to investigate an outbreak. The findings of this investigation are reported in the chapter. I chose another research site in the Philippines for Chapters 4 and 5: Puerto Galera in rabies-endemic Oriental Mindoro province, for conducting a pilot study on the use of long-lasting collars in canine mass vaccination as signifiers of rabies vaccination status. Collars were originally implemented for community members to be able to distinguish vaccinated from non-vaccinated dogs, to reduce biting incidents involving dogs susceptible to rabies, in turn preventing dog-to-human transmission. Through a mixed methods research design, I collated quantitative and qualitative data on dog population, vaccination coverage, human behavior toward dogs, normalization of collar application, and collar durability.

In the final chapter (Chapter 6), I conclude my thesis by discussing the various data-driven approaches for controlling rabies that were highlighted in previous chapters. The final chapter summarizes the overarching lessons for rabies control programs in LMICs that can be drawn from my research and may serve as priority research questions for future studies.

Chapter 2

Emerging infectious disease or neglected endemic zoonosis? A systematic review of rabies incursions and outbreak spread

2.1 Author contributions

For this chapter, I designed the study, completed and submitted the PRISMA checklist, wrote the manuscript, developed the code and figures, and ran the random-effects model. Screening and identification of studies were done together with co-author Eleanor M. Rees.

2.2 Abstract

Rabies is a viral zoonotic disease that causes thousands of human fatalities yearly, mainly in Africa and Asia. Rabies incursions occur worldwide and movement of infected animals from rabies-endemic areas can threaten rabies-free zones, but incursion frequency and resulting outbreak risks have not been investigated. We carried out a systematic review of publications from 2000-2022 following PRISMA guidelines to identify rabies incursions and factors affecting their outcomes. A total of 160 publications were found describing 117 incursions of terrestrial rabies, both wildlife and dog-mediated. Our analysis shows that incursion risk is higher in countries containing or sharing borders with rabies-endemic zones, but human-mediated transport also facilitates incursions over longer distances. 20% of incursions lead to outbreaks, with a significantly higher risk in low-income and often rabies-endemic countries, where poor surveillance results in delayed detection and response. In high-income rabies-free countries, border control measures are neglected and often bypassed, but early responses to incursions have prevented outbreaks. This first comprehensive global review of rabies incursions underscores the importance of controlling rabies at the source (rabies-endemic areas) while strengthening preparedness in neighbouring countries, especially as rabies continues to be overlooked despite (re-)emergence in many countries.

2.3 Introduction

In the 21st century, three infectious diseases—Swine Flu, MERS and COVID-19, all of which are zoonoses—have resulted in worldwide pandemics (Piret & Boivin, 2021). Furthermore, diseases such as Avian Influenza are undergoing resurgences in disease-free areas (De Araújo et al., 2024), with each instance of emergence or re-emergence referred to as an incursion. Incursions result from the translocation of an index case into an area typically free of that disease, either through natural movement or human-mediated transport (Yamada et al., 2019). Incursions are synonymous with introductions in historically disease-free settings or reintroductions to places where the disease was previously eliminated. If left uncontrolled, incursions may lead to secondary transmission and subsequent infection of local hosts, sometimes in new species (Mollentze et al., 2013; Jiang et al., 2008; Yamada et al., 2019). Zoonotic transmission may also result, causing human morbidity and mortality (Mahardika et al., 2014; Townsend, Lembo, et al., 2013). Escalation into outbreaks (Windiyaningsih et al., 2004; Stevenson et al., 2016) has historically led to the establishment of disease endemicity if control measures are insufficient (Suseno et al., 2019; Castillo-Neyra et al., 2019). This process of incursions leading to outbreak spread is of great concern for emerging infectious diseases, and is the focus of global health security (Wenham et al., 2019).

Rabies is a neglected zoonotic disease that kills thousands of people each year worldwide, with 96% of human deaths occurring in rabies-endemic countries in Asia and Africa (Hampson et al., 2015). The rabies virus (RABV) is commonly transmitted in the saliva of an infected animal, with transmission by biting other mammals, including humans. Although rabies is incurable and has a 100% fatality rate, infection and death can be prevented in bite patients through administration of post-exposure prophylaxis (PEP) immediately after exposure. Control strategies for rabies rely on a multidisciplinary One Health approach, focusing primarily on disease prevention and elimination from source populations (Fooks et al., 2014). Vaccination campaigns targeted toward domestic dogs through mass dog vaccination (MDV) (Cleaveland et al., 2006), or toward wildlife through oral rabies vaccination (ORV) (Wallace et al., 2020), have led to the elimination of rabies from many countries (Černe et al., 2021; Stahl et al., 2014; Aréchiga Ceballos et al., 2022; Velasco-Villa et al., 2017). However, incursions of rabies have occurred over centuries as part of a slow-burn pandemic that can be traced back to rabies' initial spread to the Americas, and to much of Africa and Asia via human-mediated transport of domestic dogs

(Childs et al., 2007). The incorporation of molecular tools—for sequencing and phylogenetic inference—into surveillance has enabled more accurate incursion identification, by determining responsible lineages that inform possible sources of introductions (Campbell et al., 2022).

At present, a country or zone is considered “rabies-free” if no indigenous rabies case has occurred within the last two years in areas wherein active rabies surveillance measures are consistently maintained (Matouch et al., 2007; World Organisation for Animal Health, 2011). Countries in the Americas and Europe, which have eliminated rabies in major reservoirs such as domestic dogs (Hutter et al., 2016), or have maintained low numbers of rabies cases annually (Kanda et al., 2022), are often described as “rabies-controlled” (Gibson et al., 2022). To prevent rabies re-emergence, general biosecurity measures in rabies-controlled countries aim to deter the importation of infected animals by requiring a certificate of good health, proof of rabies vaccination and/or a mandatory quarantine period following travel (Ogden, 2021).

Our objectives for this systematic review were to assess the origins of rabies incursions this century and the effectiveness of resulting responses for saving lives, preventing outbreaks and maintaining rabies freedom. WHO and partners’ ‘Zero By Thirty’ global strategic plan exemplifies the importance of capacity-building and effective governance to end human deaths from dog-mediated rabies worldwide by 2030 (WHO et al., 2018). Examining common causes of rabies incursions and successful responses should shed light on threats and reveal opportunities to achieve the ‘Zero by Thirty’ goal, not only by informing control of this neglected zoonosis, but by preventing its re-emergence.

2.4 Methods

2.4.1 Search strategy

We pre-registered our review protocol on PROSPERO (ID: CRD42024439539) and followed PRISMA guidelines for systematic review reporting (Page et al., 2021). We searched five electronic databases: Scopus, Web of Science (Medline, Zoological Record, CABI Collection, SciELO), SEARCH, Embase and Global Index Medicus for articles published between the years 2001 and 2022, with search results restricted to English-language literature. The keywords “rabies” or “RABV” were combined using boolean operator terms with one of the following: *incursion, *emergence, reintroduction, re-introduction, cross-border, spillover, outbreak, *occurrence, translocation, imported or importing, as common synonyms for incursion.

After removal of duplicates, a two-stage screening process was used for selecting studies for inclusion in the full review (Fig. 2.1). Preliminary screening of titles, abstracts and keywords was completed by one author (MY), so as to include only those related to rabies incursions. The next phase of screening required two authors (MY, ER) independently examining manuscripts’ full texts for eligibility, and selecting literature that fulfilled the criteria described below after resolving any disagreements through discussion.

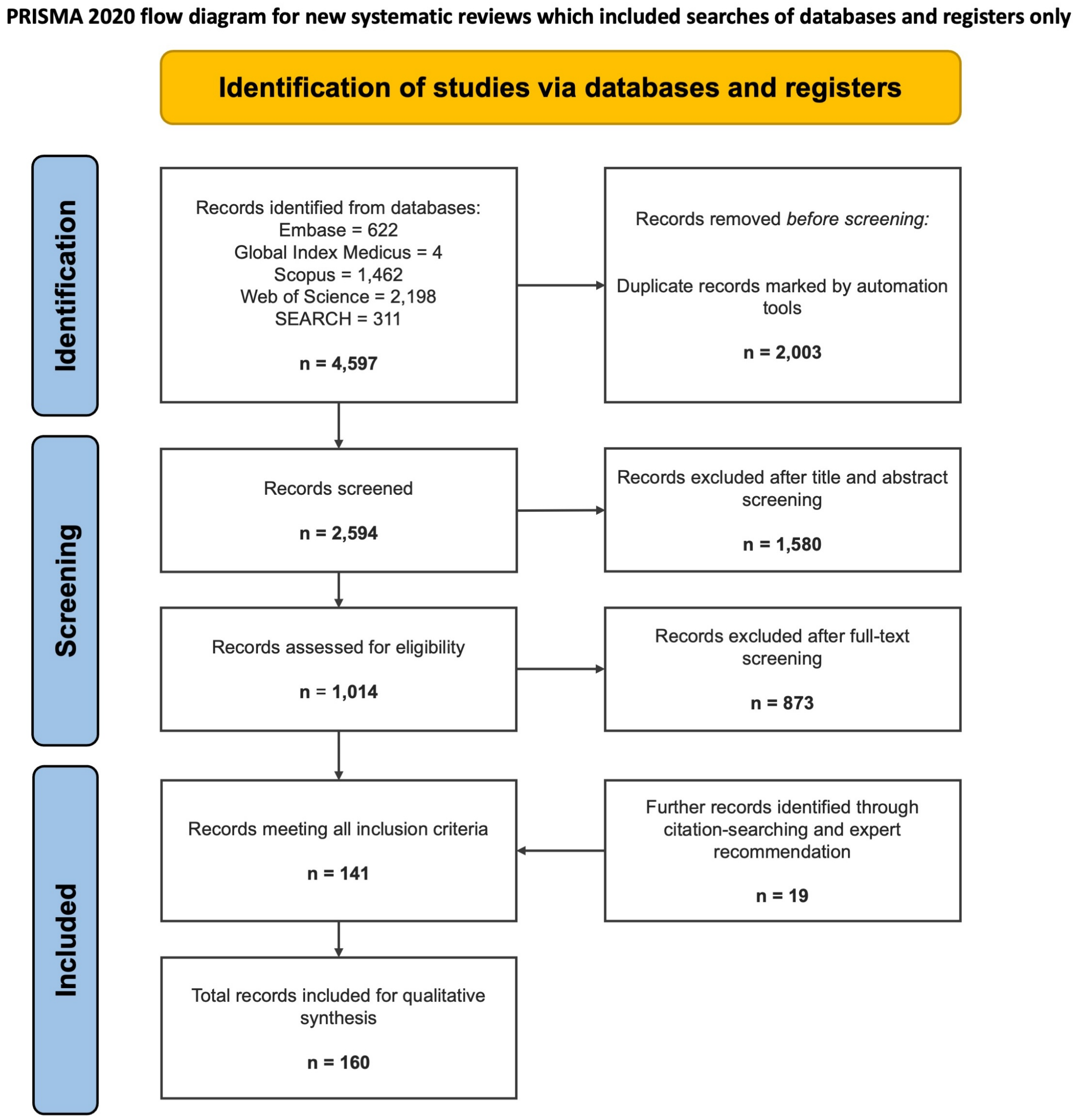

Figure 2.1: Flow diagram of publication selection following PRISMA guidelines. PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (Page et al., 2021).

2.4.2 Study selection

Rabies incursions are described as the "movement of the virus from an endemic border area into the free zone" (Jeon et al., 2019) that may or may not include importations or human-mediated transport of animals (Hudson et al., 2017; Dürr & Ward, 2015). Therefore, for the purposes of this review, incursions are defined as the movement of an infected animal from disease-endemic areas into disease-free or disease-controlled zones, in accordance with Yamada et al. (2019) and Jeon et al. (2019)'s aforementioned definitions. Criteria for inclusion were that:

1. The study must describe an incursion (rabid animal movement into a rabies-free or rabies-controlled zone);
2. The species of the animal involved in the incursion must be specified;
3. The year of incursion detection must be stated (through case confirmation or estimation); and
4. Both the incursion location and the origin location of the rabies virus must be mentioned.

The study was restricted to RABVs in terrestrial hosts Articles were excluded if they contained any of the following:

1. The species involved in the incursion is not stated.
2. The incursion involves a bat lyssavirus or other non-terrestrial hosts.
3. The year of the incursion is not stated.
4. The incursion location or the origin location is not defined.

2.4.3 Data extraction and analysis

From the selected publications, a final list of records was compiled, with data extracted by co-authors MY and ER on: (1) literature source, (2) the animal (species, age, vaccination status, ownership status), (3) the incursion event (date, origin location of infected animal, mode of travel, type of incursion, whether phylogenetic inference was undertaken), (4) place of incursion (relative distance from origin location in terms of borders crossed, country, enabling factors), (5) public health response, and (6) incursion outcomes (no local transmission, secondary transmission or outbreak). Based on details provided, incursions were classified as either natural or human-mediated incursions. Natural incursions were those that resulted from travel to a rabies-free zone without human involvement, whereas human-mediated incursions occurred when transport was facilitated by humans, usually by vehicle (cars, boats and planes).

For incursions involving one animal moving to several rabies-free or rabies-controlled zones in succession, we noted every location visited but classified them under the same incursion. For incursions that lacked supplementary details, we consulted reference lists for further information. Incursions that did not appear in the electronic search, but were known from personal communications were manually added to the final list.

We conducted this research as a qualitative review and did not assess publication bias. We synthesized our findings by calculating proportions with regards to data in specific categories (e.g. percentage of rabid animals whose translocation was human-mediated). To determine which factors were associated with incursions that led to outbreaks, we used a random-effects model, and pooled effect sizes.

Analyses were conducted using the R programming language version 4.2.2 (R Core Team, 2021). We used the gtsummary R package (Sjoberg et al., 2021) to generate tables summarizing characteristics of domestic animal and wildlife incursions, and the meta package (Balduzzi et al., 2019) to visualize outcome measures and incursion impacts on rabies status (no local transmission, secondary transmission or outbreak). Incursions without specified details were excluded from summary calculations.

Data and code are available from the Github repository:
https://github.com/miravayuson/Sysrev_incursions

2.5 Results

2.5.1 Overview of included studies

Our search yielded 2,568 records for screening following removal of duplicates (Figure 2.1) with 1,014 records retrieved after preliminary screening. Following full text reading, a total of 120 incursions were identified. These incursions were reported in 158 selected articles, of which 17 records consisted of gray literature that were cited in included articles, and were identified manually to provide additional details for specified incursions. These records were not identified in search databases as they were not peer-reviewed, scientific papers. Two additional incursions in two separate articles were identified through expert consultation, increasing the total number of identified incursions to 122 and the number of included records to 160 (Figure 2.1). A detailed list of all 122 incursions can be found in Supplementary Table S1.

2.5.2 Types, frequencies and geography of incursions

5/122 (0.04%) reported incursions occurred in livestock species (cows, horses). Since livestock are largely dead-end hosts for rabies, they are not generally considered a risk for further spread and were excluded from the following results. Characteristics of the other 117 incursions by domestic animals and wildlife (mostly carnivores) are described in Table 2.1.

Incursions were recorded across five continents and 35 countries (Figure 2.2), with most involving domestic dogs (66.7%). Remaining incursions were caused by arctic, red or unspecified foxes (17.9%), raccoons (7.7%), domestic cats (3.4%), jackals (1.7%), and in separate incidents, an anteater, an otter, a raccoon dog and a sable (0.9% each). One incursion involved both domestic animals (dog) and wildlife (fox, marten). 80/122 (65.6%) incursions occurred in rabies-free countries from rabies-endemic ones, while 42/122 (34.4%) incursions were detected in rabies-free zones within rabies-endemic countries, originating from a rabies-endemic zone or across international borders from a similarly rabies-endemic country. The US reported the most incursions of any country (17.1%), followed by France (14.5%), Germany and Canada (both 7.7%). All four countries are considered rabies-controlled, with cases in North America occurring mainly in wildlife, although cross-species transmission to domestic animals happens sporadically.

Incursions originated primarily from Asia (30.8%, 36/117), followed by Africa (27.4%, 32/117), Europe (22.2%, 26/117), North America (17.1%, 20/117) and South America (3/117, 2.6%), while none were recorded in or from Australia or Antarctica. Nearly half of incursions (45.3%) occurred internationally and frequently involved movement between countries sharing a land border (n = 42), while almost one third (29.9%) involved intercontinental travel, most commonly from Africa to Europe. Phylogenetic analysis was mainly used for characterising incursions that were in-country or between countries with shared borders, and inferred origins in 34/117 (29.1%) of incursions, including eight which had progressed to become outbreaks. The majority (8/10) of incursions in Africa were detected through phylogenetic analysis, compared to nearly half in Asia (12/25) and North America (14/29). Meanwhile, in Europe, phylogenetic analysis was only used for investigating one incursion, involving a puppy found on a highway in Spain and whose origins were ultimately traced to Morocco; case history and owner reporting were used instead for declaring incursions of domestic animals in Europe, and wild animals found near borders with rabies-endemic areas were presumed to come from across the border. Phylogenetic analysis was not used in South America, although has been used to investigate incursions in Peru since the publication search (Salazar et al., 2025).

14/117 (12.0%) incursions involved travel to multiple destinations, with at least 10 originating from Morocco, the most common country of origin for rabid animals. Human-mediated transport enabled dogs adopted from Morocco to pass through Spain (and on one occasion, Portugal) enroute to other European destinations, primarily France. Autonomous territories were sometimes part of an imported rabid animal's travel route, with four incursions involving dogs taken from Morocco to the Spanish cities of Ceuta or Melilla, which served as an entry point into Europe. Two incursions involved arctic foxes migrating from Russia to the Norwegian territory Svalbard.

Table 2.1: Characteristics of domestic animal and wildlife incursions. Incursions involving horses and cows (n = 5) have been excluded from the table as they are considered dead-end hosts. Unusual cross-species transmission events were reported as secondary spread to a different non-human species.

Characteristic	**Domestic** n = 82[1]		**Wildlife** n = 36[1]	
Incursion	Origin	Destination	Origin	Destination
Africa	31 (38%)	9 (11%)	1 (2.8%)	1 (2.8%)
Asia	31 (38%)	20 (24%)	5 (14%)	5 (14%)
Europe	10 (12%)	35 (43%)	17 (47%)	16 (44%)
North America	7 (8.5%)	15 (18%)	13 (36%)	14 (39%)
South America	3 (3.7%)	3 (3.7%)	0 (0%)	0 (0%)
Vaccination status				
Not specified	46 (56%)		NA	
Recently vaccinated	5 (6.1%)		NA	
Unvaccinated	25 (30%)		NA	
Vaccinated	6 (7.3%)		NA	
Age class				
3 months and below	20 (24%)		NA	
Adult	9 (11%)		NA	
Juvenile	11 (13%)		NA	
Not specified	42 (51%)		NA	
Incursion type				
Human-mediated	57 (70%)		4 (18%)	
Natural	16 (20%)		18 (82%)	
Not specified	9 (11%)		0 (0%)	
Phylogenetic analysis	21 (26%)		12 (55%)	
Secondary spread				
None	63 (77%)		23 (64%)	
Outbreak	16 (20%)		9 (25%)	
Limited	3 (3.7%)		4 (11%)	
Unusual cross-species transmission	6 (7.3%)		6 (17%)	
Borders crossed				
Within country	28 (34%)		14 (39%)	
Intercontinental	33 (40%)		1 (2.8%)	
Transboundary (international)	21 (26%)		21 (58%)	
Form of movement				
By air	38 (46%)		2 (5.5%)	
By land	37 (45%)		15 (42%)	
By water	2 (2.4%)		3 (8.3%)	
Unknown	5 (6.1%)		2 (5.6%)	

[1] n (%)

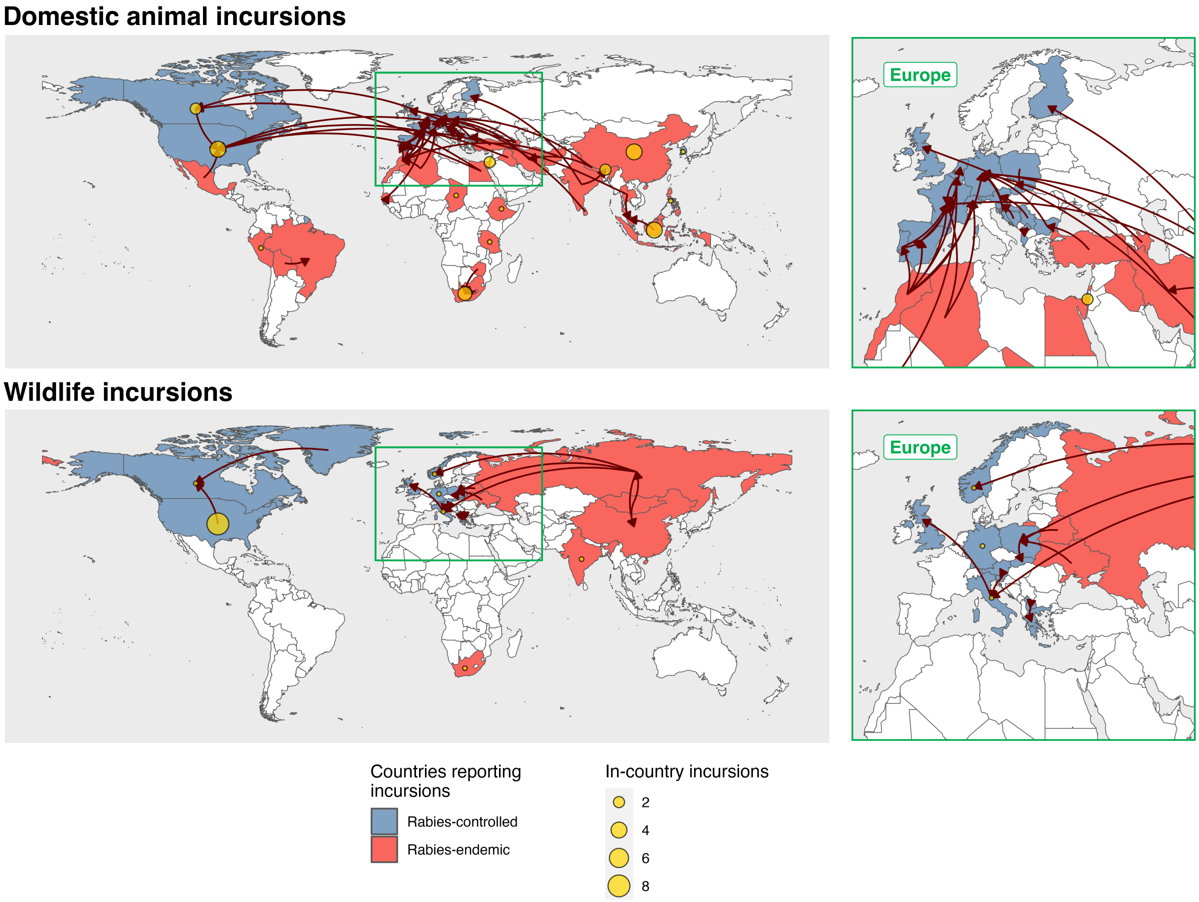

Figure 2.2: Human-mediated and natural rabies incursions reported across the world from 2001-2022. Countries that reported incursions were classified as "rabies-controlled" wherein dog rabies has been, or is close to elimination, with few recorded cases per year, or "rabies-endemic" if dog rabies cases are regularly reported or are presumed to occur regularly despite limited or no surveillance.

At least one incursion was recorded every year except in 2018, with a mean of 5.6 (95% Confidence Interval (CI): 4.4 – 6.9) incursions occurring annually and a maximum of 11 in 2008. An average of 2.3 (95% CI: 1.9 – 2.8) wildlife incursions were reported annually, (Figure 2.3), whereas 3.9 (95% CI: 2.9 – 4.9) domestic animal incursions (primarily dogs) were reported annually. An average of 1.5 incursions per year were investigated through phylogenetic analysis, peaking at five in 2016.

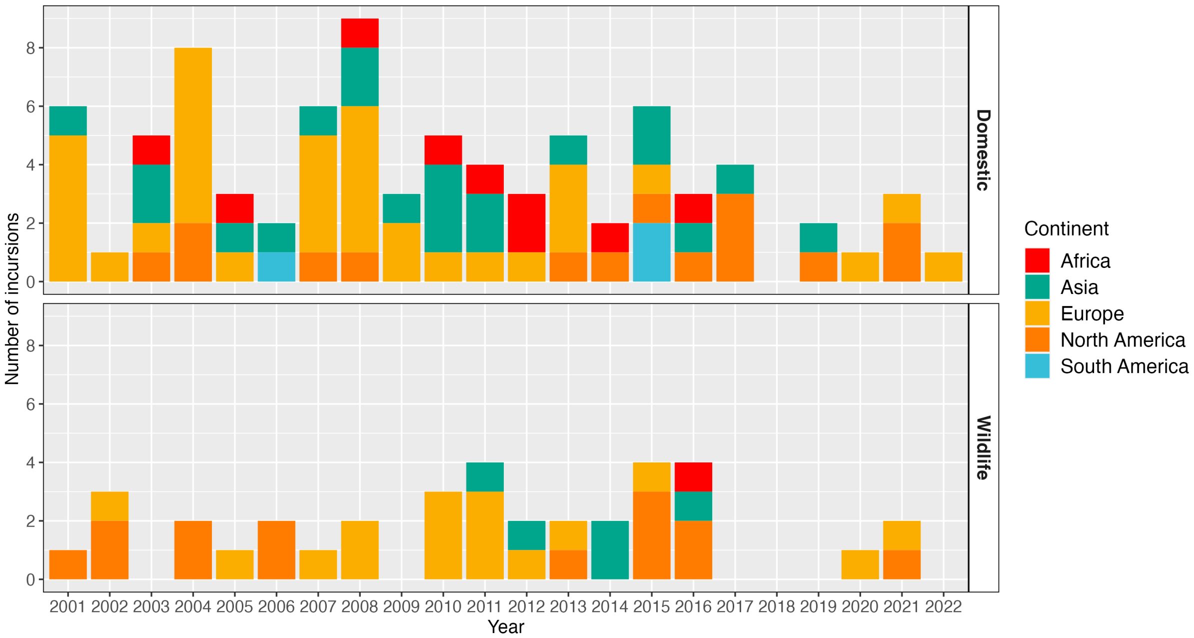

Figure 2.3: Time series of global terrestrial rabies incursions from 2001 until 2022. Incursion events are coloured by the continent where they were reported to have occurred.

Of the domestic animal incursions, 54 specified ownership status, with 49 from owned dogs, one from an unowned dog, and four from owned cats. 11 index dogs were considered vaccinated (certified or from owner recall), five of them having been so recently, and 21 were reportedly unvaccinated, including 12 puppies aged three months or below. In at least 17 incursions, dogs had been recently adopted, rescued or bought shortly before importation, with eight of these reportedly imported by animal rescue organisations or adoption shelters (Table 2.2). Most were imported as puppies.

The shortest interval between transportation and disease onset in the index case was 0 days, when rabies signs began during travel, while the longest interval was five months. Of the 40 domestic animal incursions with a recorded time frame between travel and disease onset, almost half (n = 17) showed signs within 14 days, a further 10 showed signs within one month, and for seven cases, rabies took more than one month for signs to manifest.

Table 2.2: Illegal importations of dogs leading to rabies incursions from 2001 to 2022.

Date	**Travel route**	**Age**	**Time between incursion and symptoms**	**Importation details**	**Sources**
Mar 2001	Morocco to France (via Spain)	3 months	7 weeks	Adopted during camping trip and imported by car through Spain; no border controls observed for rabies; delayed reporting of contact with another dog by owners, resulting in fine for withholding information	(Alvarez et al., 2022; Bruyere-Masson et al., 2001; Ribadeau-Dumas et al., 2016)
Oct 2001	Serbia to Austria	2 months		Illegally imported then sold to new owners	(Office International des Epizooties, France, 2001)
2002	Morocco to France (via Spain)	3 months	7 weeks	No vaccination certificate	(Mailles et al., 2011; Johnson et al., 2011)
2003	Algeria/ Morocco to Switzerland	<1 month		Suspected illegal importation from North Africa, dog found abandoned and was brought to animal shelter, later adopted	(Zanoni & Breitenmoser 2003; Johnson et al., 2011)
May 2004	Morocco to France (via Spain)	6 months		No vaccination certificate	(Ribadeau-Dumas et al., 2016; Servas et al., 2005)
Jul 2004	Morocco to France (via Spain)	4 months	1 month	Illegally imported through Ceuta by car; roamed unleashed at 3 summer music festivals, exposing >150 people	(Servas et al., 2005; Ribadeau-Dumas et al., 2016)
2004	Morocco to France (via Spain)	4 years		Illegally imported through Melilla	(Ribadeau-Dumas et al., 2016; Servas et al., 2005)
2004	Morocco to France (via Spain)	NA		Illegally imported	(Johnson et al., 2011)
2004	Morocco to France (via Spain)	4 years		No pet passport	(Johnson et al., 2011; Mailles et al., 2011)
2004	Morocco to Germany	8 months	27 days	No vaccination certificate, pet passport or health certificate but import permission granted under condition of vaccination and quarantine at owner's house in Germany; symptoms manifested while quarantined	(Johnson et al., 2011; Ribadeau-Dumas et al., 2016)

Continued on the next page

Oct 2007	Morocco to France (via Portugal & Spain)	>6 months	15 days	Cleared for importation despite visible injuries and short duration between vaccination and travel; secondary transmission to 1 dog; resulted in France losing rabies-free status for 2 years	(Johnson et al., 2011; Ribadeau-Dumas et al., 2016; Yamada et al., 2019)
Oct 2007	Morocco to Belgium	1 month	1 month	Cleared for importation despite no rabies vaccination or serology performed; no pet passport resulting in smuggling of dog on plane in handbag; resulted in Belgium losing rabies-free status for 6 months	(Van Gucht & Le Roux, 2008; Ehnert & Galland, 2009)
2007	Morocco to Germany	NA		Illegally imported	(Ehnert & Galland, 2009)
Apr 2008	Gambia to France (via Senegal & Belgium)	6 months	2 weeks	No serology; wounded but given health certificate; brought into passenger cabin of plane then journeyed by car	(Mailles et al., 2011)
Apr 2008	Sri Lanka to UK	10 weeks	6 days	Did not meet minimum age requirement; imported by rescue group along with >10 animals; symptoms manifested while quarantined	(Catchpole et al., 2008; Fooks & Johnson, 2015)
Jun 2008	Croatia to Germany	6 weeks	6 months	No vaccination certificate; imported to animal shelter; no control measures observed at EU border	(Johnson et al., 2011; Weiss et al., 2009; Ribadeau-Dumas et al., 2016)
2008	Morocco to France (via Spain)	3 months	18 days	Found on highway in Spain	(Johnson et al., 2011)
2008	Iraq to USA	11 months	3 days	Adopted by soldier and kept on military base before importation; transported with >20 dogs with no vaccination certificates; symptoms manifested while quarantined	(Hercules et al., 2018; Mangieri et al., 2008)
Feb 2010	Bosnia and Herzegovina to Germany	2 months	22 days	No vaccination certificate	(Eismann et al., 2010; Johnson et al., 2011; Ribadeau-Dumas et al., 2016)
Jul 2011	Morocco to France (via Spain)	3 months	4 days	No vaccination certificate, did not meet minimum age requirement, no travel certificate, not microchipped	(Mailles et al., 2011)
Feb 2012	Morocco to Netherlands (via Spain)	2 months	1 day	Purchased in parking lot; no border control measures observed at airport; stayed in passenger cabin of plane	(Ribadeau-Dumas et al., 2016)

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Jun 2013	Morocco to Spain	4 years	2 months	Previous importation attempt denied due to lack of serology; imported through Ceuta; escaped and attacked 5 people, resulting in loss of rabies-free status in Spain for 6 months; owners fined for not disclosing all information	(Suarez-Rodriguez et al., 2013; Pérez de Diego et al., 2015; Ribadeau-Dumas et al., 2016
May 2015	Algeria to France	7 months	9 days	No vaccination certificate, did not meet minimum age requirement, no identification documents	(Veterinary Record, 2015)
May 2015	Egypt to USA	>6 months	4 days	Imported by animal rescue organization along with >30 pets (dogs, cats) with falsified vaccination certificate; transported with fracture injury in same crate with own puppy	(Latzer et al., 2022; Sinclair et al., 2015)
Dec 2017	Egypt to USA	6 months	1 day	Imported with 3 other dogs by animal rescue organization with suspected falsified rabies vaccination document; bit 1 person before boarding plane	(Latzer et al., 2022; Hercules et al., 2018)
Jan 2019	Egypt to USA (via Canada)	2 years	1 month	Imported with >20 other dogs with suspected falsified vaccination certificate; bit 1 person during examination	((Raybern et al., 2020; Latzer et al., 2022)
Feb 2020	Morocco to France	3 months		No vaccination certificate	(Bacigalupo et al., 2022)
Jul 2021	Republic of Türkiye to Germany (via Bulgaria)	2 months	11 days	No vaccination certificate	(EFSA & ECDC, 2022)
Jul 2021	Iran to Canada (via Germany)	3 months	11 days	Imported by animal rescue organization; not revaccinated upon arrival despite vaccination policy for young dogs	(Rebellato et al., 2022)
Oct 2022	Morocco to France	4 years		Bit several people; imported to animal shelter	(Bacigalupo et al., 2022)

2.5.3 Mode of entry and border control measures

The most common form of movement leading to incursions was over land (56.4% or 66/117), followed by air (23/117 or 15.6%) then water (13/117 or 11.1%), wherein animals were transported by humans via boat or crossed frozen surfaces on foot. 18/117 (15.4%) events involved a combination of at least two forms of movement. 18 events explicitly mentioned illegal importation of dogs, using fraudulent or incomplete documents (Table 2.2). In seven instances, no border control measures were observed or implemented. At least three wildlife incursions were directly attributed to stopping ORV along one or both sides of a border or limiting ORV to only borders, while two wildlife incursions were ascribed to weakened surveillance. One wildlife incursion occurred despite maintained ORV and one transboundary fox incursion was reportedly facilitated by a lack of natural barriers.

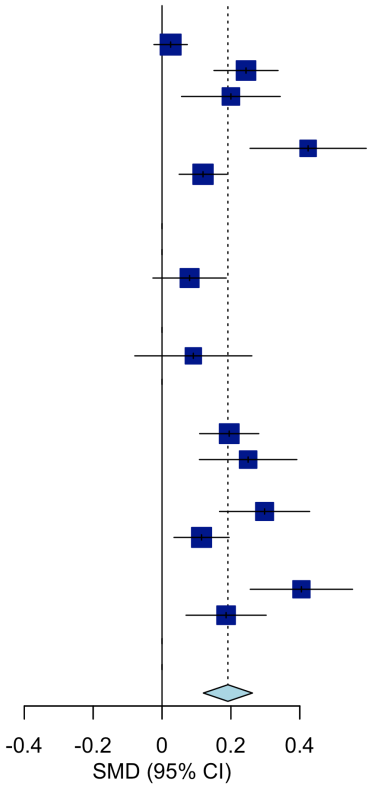
2.5.4 Outcomes

For 85 incursions, the case was contained (Table 2.1), with exposures of both people and other potential hosts not progressing to infections. Seven incursions led to secondary transmission, including four involving cross-species transmission (mainly to livestock): from a red fox to a cow in China (Liu et al., 2014), from a raccoon dog to a goat in China (Liu et al., 2014), from a jackal to multiple cows in India (Byrnes et al., 2017), and from a red fox to two dogs in Greece (Tsiodras et al., 2013). Three of the incursions with secondary transmission led to temporary loss of rabies-free status in France (February 2008 – February 2010), Belgium (Oct 2007 – Apr 2008) and Spain, respectively (Jun 2013 – Dec 2013) (Table 2.2). However, 25 (19.7%) incursions led to outbreaks (Table 2.1; Figure 2.4),

Of the 25 outbreaks, 16 were caused by dogs, five by foxes and the remaining by raccoons and a jackal. At least one outbreak was recorded in each of the five continents, but 13/25 outbreaks were in rabies-endemic countries in Africa or Asia. Just two of these outbreaks in Africa and Asia were caused by wildlife: a jackal in South Africa (Ngoepe et al., 2022) and a fox in Russia (Adelshin et al., 2012). Eight outbreaks, mostly wildlife, occurred in rabies-controlled countries where elimination in wildlife has not yet been achieved, so rabies freedom status was not impacted. An average of one outbreak was recorded annually, except between 2019 to 2022. Human rabies deaths were reported in 3/25 outbreaks, all involving domestic dogs. Cross-species transmission was detailed in eight of the outbreaks, five caused by dogs, which infected wildlife (Ethiopian wolves), livestock (pigs, sheep, cattle) and cats. Three spillover events involving dogs caused outbreaks in Ethiopian wolves, pigs and sheep, while an outbreak in Canada was caused by spillover from an arctic fox to dogs (Curry et al., 2016). Raccoon rabies outbreaks in Canada and the US affected dogs, cats and skunks.

A random-effects model was used to estimate outbreak risk, with pooled analyses indicating factors associated with outbreak occurrence (Figure 2.4). Predictor variables included the country of incursion's rabies status, type of incursion, and the infected animal's mode of travel, vaccination status, age, species, and borders crossed, with the response being whether an outbreak occurred. At least 14 outbreaks resulted from natural incursions (Standard Mean Difference [SMD] = 0.30, 95% CI 0.17 – 0.43), while seven were human-mediated translocations (SMD = 0.11, 95% CI 0.03 – 0.19). All eight outbreaks involving transboundary movement occurred between neighbouring countries, with the remaining 17 outbreaks occurring within countries. Outbreaks were more common through land movement (SMD = 0.24, 95% CI 0.15 – 0.34) relative to travel by air (2.5%) or water (13.3%); at least one resulted from a fox in Russia crossing frozen water (Adelshin et al., 2012) and two from ferry travel within Indonesia (Rupprecht et al., 2018; Ward & Brookes, 2021) and the Philippines (Tohma et al., 2016). Five outbreaks were resolved: three that were dog-mediated in the Philippines (Tohma et al., 2016), Brazil (Benavides et al., 2019), and on Pemba Island, Tanzania (Lushasi et al., 2023), respectively, and a 2013 – 2017 raccoon outbreak in the US (Ortiz et al., 2018), as well as an outbreak in Ethiopian wolves that spilled over from dogs (Laurenson et al., 2005). At least three dog-mediated outbreaks became endemic: in Bali, Indonesia (Rupprecht et al., 2018); Sarawak, Malaysia (Rupprecht et al., 2018) and Arequipa, Peru (Raynor et al., 2020). The outcomes of the other nine dog-mediated outbreaks were unclear, though recent situation reports indicate some were resolved (Acharya et al., 2021) and others are still circulating (World Organisation for Animal Health, 2022). Similarly, the outcomes of the other eight wildlife outbreaks were not reported. Outbreaks occurred in 36.4% of incursions in canine rabies-endemic countries (SMD = 0.42, 95% CI 0.26 – 0.59).

Category	Event Rate [95% CI]
Mode of travel	
By air	0.03 [-0.02; 0.07]
By land	0.24 [0.15; 0.34]
By water	0.20 [0.06; 0.34]
Rabies status	
Canine rabies-endemic	0.42 [0.26; 0.59]
Canine rabies-controlled	0.12 [0.05; 0.19]
Vaccination status	
Vaccinated	0.00
Recently vaccinated	0.00
Unvaccinated	0.08 [-0.03; 0.19]
Age	
3 months or less	0.00
Juvenile	0.09 [-0.08; 0.26]
Adult	0.00
Species	
Domestic (dog, cat)	0.20 [0.11; 0.28]
Wildlife	0.25 [0.11; 0.39]
Type of incursion	
Natural	0.30 [0.17; 0.43]
Human-mediated	0.11 [0.03; 0.19]
Borders crossed	
In-country	0.40 [0.26; 0.55]
Shared border	0.19 [0.07; 0.30]
International (no shared border)	0.00
Intercontinental (no shared border)	0.00
Total	0.19 [0.12; 0.26]



Heterogeneity: χ^2_{12} = 62.69 (P < .001), I^2 = 81%

Figure 2.4: Forest plot showing factors associated with the risk of incursions progressing to rabies outbreaks. SMD = standard mean difference.

2.5.5 Responses

The most common response was PEP, given to those exposed, commonly animal owners or bite victims, in at least 52 incursions including those that led to outbreaks. Contact tracing was done for 30 incursions to locate exposed persons and animals. Exposed vaccinated animals were quarantined following 15 incursions, while potentially exposed, unvaccinated animals were sacrificed following 15 incursions. MDV took place in three incursions that did not spread. In response to 11 wildlife incursions (foxes in Europe and raccoons in North America), ORV was either restarted, intensified (coverage expanded) or continued. However, ORV was explicitly not recommended for one fox incursion as it was seen as a waste of resources; enhanced surveillance (increased sampling) was conducted instead intending to detect further spread (Slate et al., 2008).

Enhanced surveillance was performed during three raccoon incursions and for one dog imported to Belgium (Table 2.2). The newly-adopted puppy contacted other animals at a dog park, resulting in six-month quarantines for exposed dogs, sacrifice of pets, recommended pet vaccination, active fox surveillance and mandatory dog leashing. Mandatory leashing was also initiated in Poland from a fox incursion, along with cancellation of all pet-centric events and a temporary hunting ban (Smreczak et al., 2023). Culling was initiated in two incursions without local transmission, following a dog imported from India to Bhutan (Townsend, Lembo, et al., 2013), and a dog imported from Morocco to France through Spain that contacted over 150 people (Table 2.2). Apart from culling free-roaming dogs, owned animals were monitored and a hotline established as part of contact tracing. Restricted movement of all pets within the affected area was conducted in three instances, in response to two illegally imported dogs (Table 2.2), and one imported cat that escaped its home (Ribadeau-Dumas et al., 2016). Catching of stray animals was also conducted in France following an incursion that contacted another dog (Alvarez et al., 2022). Sensitization efforts were performed in Israel (David and Yakobson 2011), Poland (Smreczak et al., 2023) and the US (Brunt et al., 2020), each after an incursion which did not lead to local transmission. In 2019, the importation of dogs into the US from Egypt (and subsequently, all canine rabies-endemic countries) was temporarily suspended after three rabid dogs were imported in 2015, 2017 and 2019 (Table 2.2).

Response measures were not reported for four of seven incursions involving local transmission without escalation into an outbreak. Vaccination of exposed dogs and sacrifice of exposed livestock was conducted to avert a dog outbreak in China (Zhang et al., 2014), contact tracing and PEP were done to prevent human infection by two infected rabid dogs in France (Table 2.2), and fox rabies spread was contained in Greece through ORV, improved passive surveillance, mandatory pet vaccination, and increased public awareness (Lojkić et al., 2021).

The most common responses to outbreaks were PEP and mass vaccination (mainly of dogs), initiated in 11 of 25 outbreaks. An outbreak in raccoons in the US also triggered dog vaccination, and enhanced surveillance (increasing testing of sick animals) and efforts to raise public awareness (Brunt et al., 2020). The dog incursion in Ethiopia that caused an outbreak in Ethiopian wolves was resolved through a trap-vaccinate-release program (Laurenson et al., 2005). ORV was conducted in response to six wildlife outbreaks (fox and raccoon). Dog culling was conducted during two outbreak responses in Indonesia (Cliquet & Wasniewski, 2018; Townsend, Lembo, et al., 2013), and in response to outbreaks in China (Zhang et al., 2014) and Peru (Raynor et al., 2020), after which rabies re-established, becoming endemic. Other outbreak response measures included quarantine of exposed animals, sacrifice of animals (unvaccinated dogs and sheep) and mandatory vaccination of pet dogs. A dog imported within Canada was found to have originated from Nunavut, Quebec, where a rabies outbreak was ongoing (Curry et al., 2016). After diagnosis, the dog's travel companions (its mother and littermates) were quarantined, exposed persons were given PEP, and one associated dog was euthanized at the request of its owner. However, no response measures were reported in the origin location of the incursions. Reports of four dog-driven outbreaks in rabies-endemic countries, two fox outbreaks in Russia (Adelshin et al., 2015), one jackal outbreak in South Africa (Ngoepe et al., 2022) and one raccoon outbreak in the US (Ortiz et al., 2018) did not specify any response measures.

Some studies specified causes of outbreak escalation resulting from insufficient response measures: low vaccination coverage or lapses in dog vaccination were cited as reasons for dog rabies outbreaks in South Africa (Ngoepe et al., 2022), Peru (Raynor et al., 2020) and Tanzania (Lushasi et al., 2023). Stray or free-roaming dogs, which are often unvaccinated, were cited as the main cause of an outbreak in India (Byrnes et al., 2017), and coupled with lack of control measures, were implicated in rapidly spreading outbreaks in China (Zhang et al., 2014; Zhu et al., 2011), Bhutan (Tenzin et al., 2017) and Malaysia (Rupprecht et al., 2018). There is also considerable history of unsuccessful culling in Indonesia resulting in outbreak escalation, as seen in Flores in 1998, where prioritization of culling as an initial response led to the elimination of >200,000 dogs but failed to prevent rabies from spreading island-wide (Windiyaningsih et al., 2004). The dog meat trade was stated as the cause of an outbreak in China (Zhang et al., 2014). Neglecting ORV and surveillance measures reportedly led to fox outbreaks in Italy (Lojkić et al., 2021) and Poland (Berg et al., 2015).

2.6 Discussion

The findings of this systematic review underline the frequency of incursions and outbreaks in rabies-free zones near to rabies-endemic areas, especially across shared borders, which are commonly facilitated by human-mediated transport. Free-roaming dogs remain the most common source of rabies outbreaks (Meslin & Briggs, 2013), and natural barriers may reduce incursion frequency by curtailing their natural movement (Smith et al., 2002; Russell et al., 2005). However, natural barriers are often overcome by human-mediated transport, which enables long-distance travel. Measures to prevent entry of diseased animals include border controls, which are weak and largely focused on trade diseases within and between Low- or Middle-Income Countries (LMICs). In LMICs, surveillance gaps lead to underreporting with detection commonly unnoticed or retroactive, occurring after local transmission or outbreak escalation. This was seen in incursions of rabid dogs causing rabies outbreaks across Southeast Asia (Tohma et al., 2016; Ward & Brookes 2021), leading to formerly rabies-free areas becoming endemic. As for High-Income Countries (HICs), border control measures are semi-effective, but failures arise from non-cooperation or falsification, including shortcuts made for expediting travel.

The lack of land-based border controls between HICs, particularly within Europe, allow incursions to occur, with measures more focused on livestock diseases (European Food Safety Authority (EFSA) et al., 2023), and document verification procedures for rabies not routinely enforced. Incursions by air are more preventable due to enforced requirements (vaccination records, health certificates and serostatus) (Stokes & Wright, 2015) and traceable travel histories, but human-mediated incursions often stem from falsified documentation or short timeframes between vaccination and travel. Intercontinental adoption of dogs with no vaccination history, or only recent vaccinations (especially of puppies), occurs without ample time to develop an immune response, resulting in dogs manifesting rabies symptoms during transit or after arrival. To prevent this, quarantine is used in rabies-free countries such as Japan and Australia (Sparkes et al., 2015; Kamata et al., 2023), while the US bans dog importation from canine rabies-endemic countries (CDC, 2023) and enforces more rigorous entry conditions (including an age requirement of six months, a US-issued vaccination certificate and veterinary inspection upon arrival). In countries like the UK, relaxation of regulations amidst the global rise in adoptions from rabies-endemic countries now permits pet travel at any age without visual examination upon arrival, with pets no longer required to undergo mandatory quarantine and serology (Ogden, 2021). Though the UK has not seen any rabies incursions since 2020, our findings suggest that less stringent regulations coupled with high numbers of pet imports increase their likelihood. Currently, circumvention of rabies measures are tolerated in HICs, whose long-standing rabies-free status may have created a false sense of security. By focusing solely on tightening border controls, rabies-controlled countries prioritize preventing introductions rather than addressing their source which may be more economical and effective in reducing rabies risk long-term. Examples in France and Belgium show that even temporary loss of rabies freedom does not catalyse changes in rabies control strategies. Incursions involving overseas territories such as Svalbard (Norway), and Ceuta and Melilla (Spain) provide little incentive to eliminate rabies in those areas which do not "count" when qualifying for rabies freedom.

Rabies control remains an issue in source countries, particularly those endemic for dog-mediated rabies. The normalization of incursions in LMICs stems from poor detection and lack of resources (Knobel et al., 2005): weak surveillance fails to trace incursions before local spread, and financial constraints limit control measures, enabling further spread. The lack of international guidance for responding to rabies outbreaks likely contributes to the late, inconsistent and often ineffective outbreak responses reported. When left uncontrolled, local spread that has snowballed into an outbreak may culminate in the loss of local rabies-free zones. Alternatively, an incursion may turn out to be evidence that a seemingly rabies-free zone had endemic circulation at low levels but was previously undetected, as inferred for wildlife rabies in North America (Trewby et al., 2017). To determine whether rabies cases in LMICs are introductions, phylogenetic analysis has increasingly been used to deduce the origin of rabid animals. However, accuracy depends on available historical sequences, which are often lacking in LMICs where laboratory capacity is limited (Jaswant et al., 2024). Improvement of sequencing capacity would enhance countries' ability to distinguish whether rabies has been newly-introduced, or has circulated endemically unnoticed. Promotion and guidance on rapid diagnostic testing may also increase earlier detection and response in remote settings and where laboratory capacity is limited.

To resolve rabies outbreaks, MDV is effective in controlling dog rabies (Lushasi et al., 2023) while ORV has controlled wildlife rabies in foxes (Freuling et al., 2013) and raccoons (Slate et al., 2009). Evidence that rabies spills over constantly from peri-urban and rural areas into urban areas in Africa (Zinsstag et al., 2017), for example, illustrates source locations and susceptible pockets where MDV should be consistently maintained. Conversely, our data provide examples showing the ineffectiveness of culling as an outbreak response.

When conducted in several countries, culling did not control outbreaks, but instead led to endemicity (Nahata et al., 2021; Raynor et al., 2020; Suseno et al., 2019). Culling as a rabies control measure does not reduce rabies prevalence (Morters et al., 2013) and may cancel out effects of mass vaccination through removal of vaccinated dogs, while increasing animal movement due to owners wanting to spare or replace their pets (Bourhy et al., 2016; Townsend, Sumantra, et al., 2013). Instead, by tracing the source of incursions, MDV should be directed toward origin locations, consisting primarily of LMICs with low dog vaccination coverage, to avert similar incidents and control outbreaks before endemicity can re-establish. Plausible funders include WOAH (WHO et al., 2018) via its vaccine bank or charities (Worldwide Veterinary Service), while locally coordinated regional vaccine-sharing initiatives have also supported large-scale MDV (Yuson et al., 2024). ASEAN could establish mechanisms for vaccines as PAHO has done for rabies elimination in the Americas (Vigilato et al., 2013).

This systematic review is the first comprehensive analysis of global rabies incursions. By compiling literature spanning all terrestrial mammals, our analysis highlights the major role of dogs in LMICs in establishing local transmission over long distances and across shared borders into otherwise rabies-free areas. In addition, we explore key drivers behind outbreaks and pinpoint common patterns in responses that lead to endemicity. Our study's main limitation is the bias in data causing potential overrepresentation of incursions in primarily rabies-controlled countries. Better surveillance increases the likelihood of detection and reduces the risk of outbreaks. Since our review was restricted to English-language articles, we likely overlooked literature from non-English speaking countries, including many rabies-endemic countries where incursions and rabies cases in general are underreported, and any publications or government bulletins are likely to be posted in the country's native language. Therefore, such examples were not captured by our screening approach. We also note that lack of detailed reporting limited potential for inference on outbreak responses, the extent of secondary spread, and the resulting incursion/outbreak outcomes. Over 10% of the literature was grey literature, and and was only detected as part of the full article review, which suggests that outbreaks may also be missed if mentioned only in grey literature. Lastly, our screening failed to capture two articles that exclusively referred to rabies incursions using terms that are common in rabies-related articles (such as "transmission"), indicating the possibility of overlooking similar articles that allude to incursions without labeling them as such.

Most HICs do not share borders with rabies-endemic countries, and risks of Rabies tend to be ignored, in contrast to LMICs where outbreaks are often normalised. WHO's International Health Regulations provide a legal framework for coordinated responses to global health security threats (with emphasis on infectious diseases with the ability to cross borders), and have recently created emergency committees for Monkeypox and Poliovirus, which are currently emerging in HICs (World Health Organization, 2024; Nuzzo et al., 2022). Despite acknowledging the need to strengthen LMIC capacities to meet IHR commitments, international guidance for rabies outbreak responses is lacking. Multiple emergences in rabies-free areas (Farias et al., 2024) and a sharp increase in human rabies deaths post-SARS-CoV-2 pandemic (Alemayehu et al., 2024) have received little attention, sparse financial investment and minimal support. Despite major economic losses from rabies outbreaks (Hampson et al., 2015), and devastating impacts of deaths on communities,the status of rabies as a neglected endemic zoonosis is evident with how funding and control in LMICs instead prioritise diseases with perceived higher economic importance such as African Swine Fever (Gren et al., 2024) and Avian Influenza (Petersen et al., 2024). Recent pandemics (Micah et al., 2023) and the likelihood of more emerging zoonoses (Weiss & Sankaran, 2022) underscore the urgency of strengthening global health security through improving emergency preparedness. With data now showing continual incursions over two decades, rabies outbreaks are, in fact, frequent, especially in settings with inadequate resources for response. To prevent reintroductions (Bourhy et al., 2016) and control outbreaks before endemicity can re-establish, MDV should be directed toward origin locations, mainly in LMICs with low dog vaccination coverage. Improving sequencing capacity would enhance countries' abilities to detect rabies introductions (distinguishing them from ongoing circulation) and other emerging infectious disease threats. Recognizing that rabies is also an emerging infectious disease should lead to international cooperation to support LMICs to build One Health and outbreak response capacity. Establishment of internationally coordinated protocols, including provision of surveillance tools that can be rapidly mobilized in response to rabies emergence, could become a practice in preparedness for future emerging diseases and overcome the neglect that entrenches endemicity.

Chapter 3

Combining genomics and epidemiology to investigate a zoonotic outbreak of rabies in Romblon Province, Philippines

3.1 Author contributions

For this chapter, I trained the team of field researchers and local government staff in the methods to collect epidemiological data and then I coordinated and managed the data collection. I wrote and revised the manuscript (barring the sections related to phylogenetic analysis) and submitted the article for publication to Nature Communications.

3.2 Abstract

Rabies is a viral zoonosis that kills thousands of people annually in low- and middle-income countries across Africa and Asia where domestic dogs are the reservoir. 'Zero by 30', the global strategy to end dog-mediated human rabies, promotes a One Health approach underpinned by mass dog vaccination, post-exposure vaccination of bite victims, robust surveillance and community engagement. Using Integrated Bite Case Management (IBCM) and whole genome sequencing (WGS), we enhanced rabies surveillance to detect an outbreak in a formerly rabies-free island province in the Philippines. We inferred that the outbreak was seeded by at least three independent human-mediated introductions that were identified as coming from neighbouring rabies-endemic provinces. Considerable local transmission went undetected, and two human deaths occurred within six months of outbreak detection. Suspension of routine dog vaccination due to COVID-19 restrictions likely facilitated rabies spread from these introductions. Emergency response, consisting of awareness measures, and ring vaccination, were performed, but swifter and more widespread implementation is needed to contain and eliminate the outbreak and to secure rabies freedom. We conclude that strengthened surveillance making use of new tools such as IBCM, WGS, and rapid diagnostic tests can support One Health in action and progress towards the 'Zero by 30' goal.

3.3 Introduction

Neglected tropical diseases persist in low- and middle-income countries (LMICs), causing major economic losses, morbidity and mortality (WHO, 2021). Treatment and elimination prospects are limited by the inequitable allocation of financial resources, resulting in high morbidities affecting over one billion people worldwide. Economical strategies consisting of case-finding based on observed signs and history-taking, have been used for the epidemiological investigation of outbreaks of neglected tropical diseases including dengue fever (Wang et al., 2016) and leprosy (De Sousa et al., 2020). Genomic surveillance has also proven valuable for tackling zoonotic disease emergence, including its application to outbreaks of Ebola (Quick et al., 2016), Lassa fever (Kafetzopoulou et al., 2019), Influenza (Rambo-Martin et al., 2020), and Mpox (Isidro et al., 2022), providing insights into transmission dynamics and the impacts of interventions, and therefore informing more targeted control and prevention.

Rabies is an example of a neglected zoonotic disease caused by the rabies virus (RABV). It has long been a significant public health issue, and although the disease has been eliminated from several regions over the last century, rabies still kills thousands of people annually in Africa and Asia (Meslin & Briggs, 2013), where free-roaming dogs are common (Hampson et al., 2015). Despite being preventable through dog vaccination, rabies is re-emerging across much of Southeast Asia, including in Malaysia (Jeon et al., 2019), Indonesia (Putra et al., 2013), and Vietnam (Ward & Brookes, 2021). The historically rabies-free Timor-Leste reported its first human death due to rabies in early 2024, highlighting the ongoing challenge of spread across the region (Mali et al., 2024). Effective control of zoonoses like rabies requires a One Health approach with coordination between human and animal health sectors (Conrad et al., 2013).

Rabies is fatal once symptoms appear, but progression to disease can be prevented if immediate post-exposure prophylaxis (PEP) is given to bite victims after exposure. PEP, while highly effective, should be part of a broader rabies management strategy which includes educational campaigns to increase awareness, robust surveillance for case detection, and mass dog vaccination to interrupt dog-to-dog transmission, thereby reducing the risk of human exposures (WHO et al., 2018). Dog vaccination campaigns in the 20th century (Rupprecht, 2002) led to the elimination of dog-mediated rabies in North America, Western Europe, and parts of Asia, and dramatically reduced cases across Latin America (Wallace et al., 2017). Similar measures have been applied at the community level in some rabies-endemic countries, leading to local rabies-free zones like Pontianak City in

Indonesia (Aptriana et al., 2022) and N'Djaména in Chad (Léchenne et al., 2017). However, introductions and re-emergence of rabies through animal importations by humans (Pieracci et al., 2024) or from natural incursions across borders occur regularly worldwide (Lojkić et al., 2021; Lushasi et al., 2023; Al-Eitan et al., 2021; Tohma et al., 2016; Zinsstag et al., 2017; Trewby et al., 2017). Examples from the city of Arequipa in Peru (Castillo-Neyra et al., 2017), Sarawak in Malaysia (Jeon et al., 2019), and Mpumalanga province, South Africa (Mkhize et al., 2010), demonstrate how neglecting surveillance and dog vaccination can lead to rapid escalation from introductions in areas close to rabies-endemic zones. Inappropriate responses, such as dog culling, can also exacerbate spread, as seen in Indonesian islands Flores (Windiyaningsih et al., 2004) and Bali (Putra et al., 2013), where failure to contain the epidemic led to enzootic transmission.

The hallmark of effective rabies control is strong intersectoral collaboration to reduce human mortality risks and eliminate disease from reservoir populations, which is why a One Health approach is recommended (World Health Organization, 2018). Incorporating a One Health approach has been shown to address common gaps in rabies surveillance, such as poor case detection (Gibson et al., 2022). Tools like rapid diagnostic tests (RDTs) (Naïssengar et al., 2021; Mauti et al., 2020; Freuling et al., 2023), regular coordination between health workers from human and animal sectors through communication technologies (Schrodt et al., 2023; Mbaipago et al., 2020), IBCM (Lushasi et al., 2020; Etheart et al., 2017; Madjadinan et al., 2022; Ross et al., 2023) and genomic sequencing (Gigante et al., 2020; Zinsstag et al., 2017; Lushasi et al., 2023) are known to offset surveillance weaknesses, while strengthening health systems for outbreak preparedness. IBCM is a rabies surveillance strategy that directly links public health and veterinary workers to manage animal bite incidents and prevent rabies (Lushasi et al., 2020). It enhances surveillance through better case detection, improves patient care through more informed administration of PEP and can support better management of limited resources (Swedberg et al., 2022). Sequencing of rabies viruses has identified new virus reservoirs (Kotait et al., 2019), sources of introductions (Mollentze et al., 2013), and nearby populations that pose risks for re-emergence (Mahardika et al., 2014; Lushasi et al., 2023; Gibson et al., 2022) and more generally improved our understanding of virus dispersal dynamics (Dellicour et al., 2019; Layan et al., 2021; Nahata et al., 2021).

In 2015, the WHO launched the 'Zero by 30' global strategy to eliminate dog-mediated human rabies deaths by 2030 (WHO et al., 2018). However, achieving successful rabies control requires overcoming challenges such as limited human resources and cross-sectoral financing. Government priorities typically favour investment in animal diseases that have economic impacts such as African Swine Fever (ASF), whilst political and economic instability with frequent changes in governance make zoonotic disease control programmes difficult to maintain (Arias-Orozco et al., 2018). As a result, another major challenge to 'Zero By 30' is sustaining rabies freedom, as outbreaks reestablish due to lack of healthcare resources and siloing among health departments, undermining outbreak response.

Here, we report our learning from taking a One Health approach to tracking a rabies outbreak as it unfolded in a formerly rabies-free province in the Philippines. The investigation began with the initial detection of a rabid dog in 2022 on the island of Tablas, in Romblon Province (Fig. 3.1). The island had previously suffered from an incursion in 2011, and the ensuing outbreak caused 11 human fatalities (incidence of 3.48 deaths/100,000 persons/year) but no human or animal cases had been reported since 2012 (Tohma et al., 2016). Our cross-sectoral and multidisciplinary investigation used IBCM to enhance rabies surveillance as advocated by 'Zero by 30' (WHO et al., 2018) and deployed RDTs for early diagnosis. We further undertook WGS of rabies viruses from the outbreak to determine its probable origins and uncover the resulting spread.

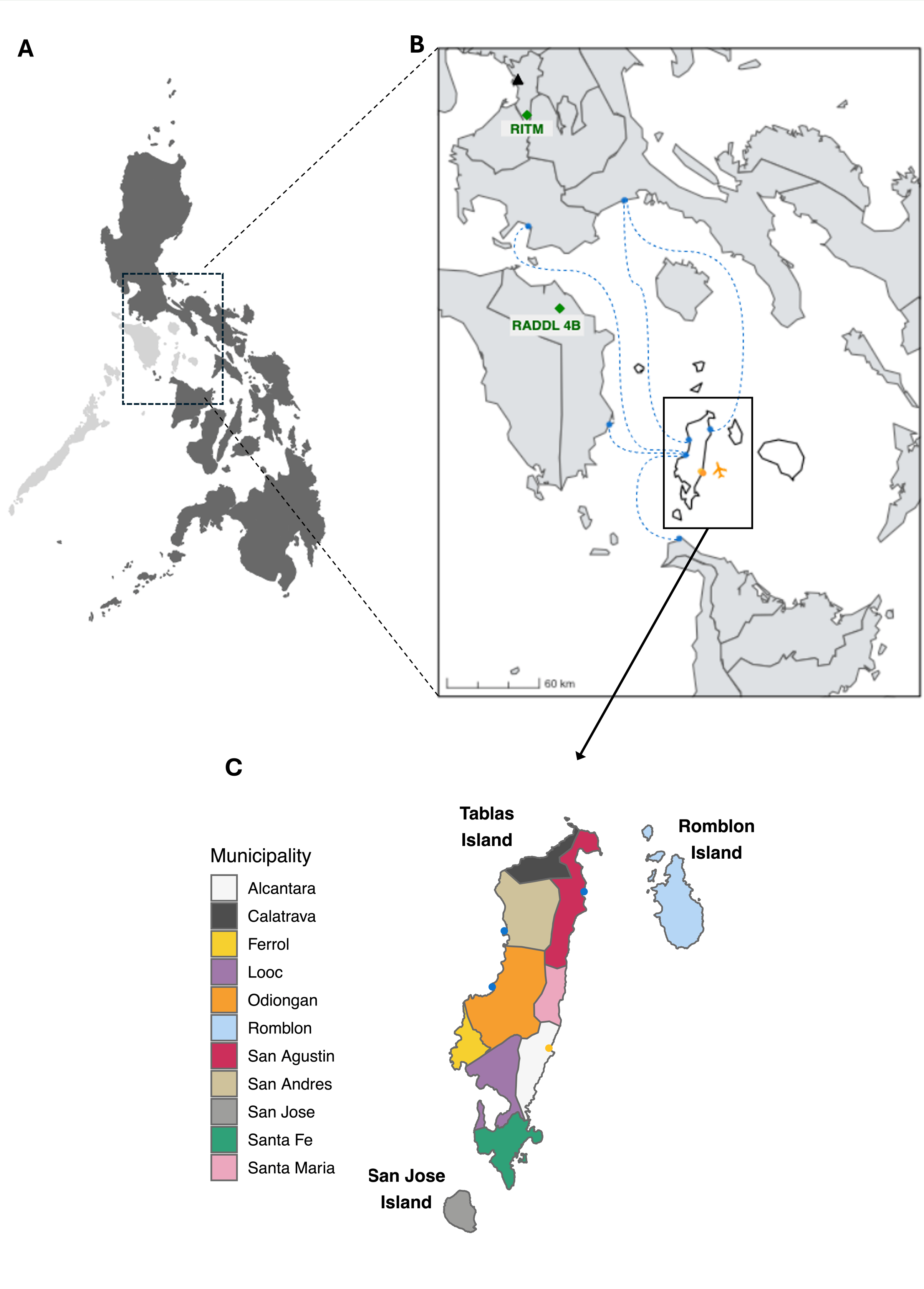


Figure 3.1: Outbreak location in the formerly rabies-free province of Romblon in the Philippines. A) Location of MIMAROPA region, also known as Region 4B (light grey) within the Philippines, with the inset B) of Romblon Province (white) showing the Regional Animal Disease Diagnostic Laboratory (RADDL) and the Research Institute of Tropical Medicine (RITM) as green diamonds. Manila is indicated as a black triangle. Major ports are indicated in blue, the airport in yellow, and dashed blue lines show the main ferry routes to/from Tablas. C) Tablas Island coloured by municipality, with the ports and airport coloured as above.

3.4 Methods

3.4.1 Study description

This study took place on Tablas Island, Romblon Province, MIMAROPA region of the Philippines. Tablas has a population of 174,447 (Philippine Statistics Authority, 2021) served by Odiongan, Santa Fe, and Calatrava ports, and Tugdan Airport in Alcantara (Fig. 3.1). The dog population is not known, but estimates of human:dog ratios in the Philippines suggest it is between 17,445 and 58,149 (Swedberg et al., 2023). Prior to 2020, dog vaccination coverage across the province ranged from 18.0–38.6% according to regional reports, and was self-reported by Romblon province from 2021 onwards as fluctuating between 0 and 24.2% (the number of vaccinated dogs per municipality can be seen in Supplementary Fig. S1). IBCM was introduced to Tablas in March 2020, but implementation and in-person training and support was constrained by COVID-19 restrictions enacted mid-way through initial training. Ethical review was secured from RITM ethical review board (2019–2023) and the University of Glasgow, Medical, Veterinary, and Life Sciences ethics committee (200190123).

3.4.2 Case finding and laboratory confirmation

As part of IBCM, Public Health Workers based in animal bite treatment centres (clinics in hospitals or health units that provide PEP to bite victims) reported 'high-risk' bites to animal health workers at the closest Municipal Agriculture Office (Fig. 3.2). Bites were classified as 'high-risk' if the biting animal died, was killed, showed signs of poor health, was suspicious for rabies, or disappeared (Wallace et al., 2015). Animal health workers investigated suspicious animals to confirm their health status. If they required assistance or were busy with other duties, a Disease Surveillance Officer would investigate on their behalf.

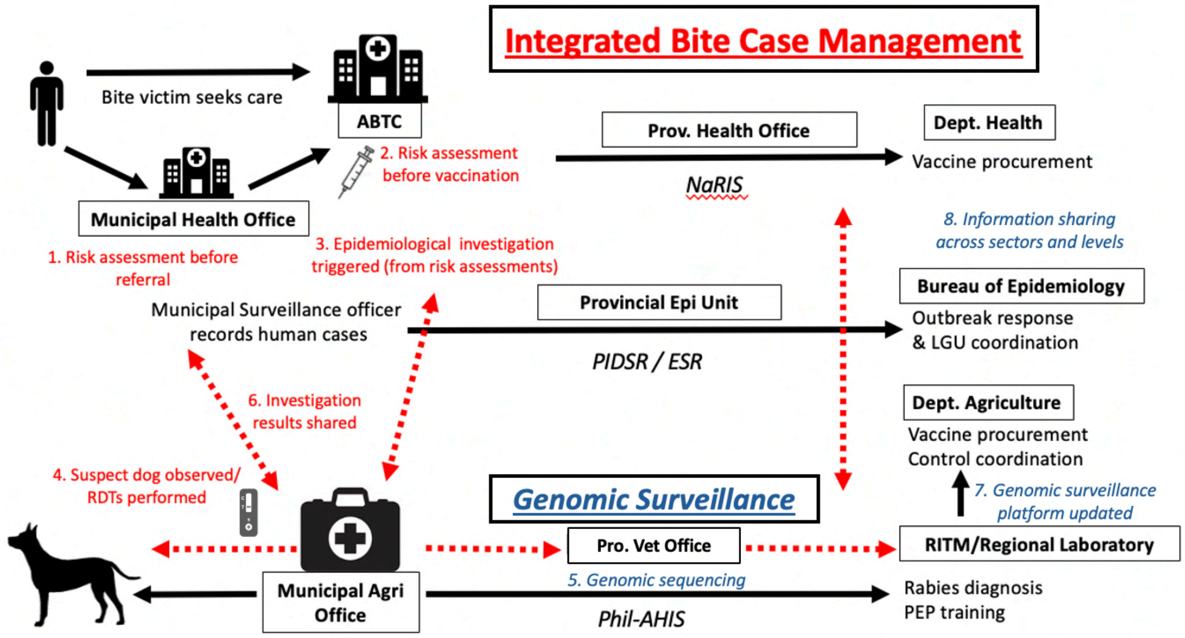


Figure 3.2: Diagram of the complete integrated bite case management (IBCM) process. Activities that enhance surveillance through IBCM shown in red, while genomic surveillance activities are shown in blue. ABTC Animal Bite Treatment Centre, LGU Local Government Unit, NaRIS National Rabies Information System, Phil-AHIS Philippine Animal Health Information System, PEP Post-exposure prophylaxis, PIDSR/ESR Philippines Integrated Disease Surveillance and Response/Event-based Surveillance and Response, RDT Rapid diagnostic test, RITM Research Institute for Tropical Medicine.

Animal investigations were initiated by phone or in-person to gather case details. Sick animals or animals presenting signs of rabies were quarantined at the owner's house, and their health monitored for 10 days (World Health Organization, 2013). Dead animals were subject to sample collection. Animal health workers retrieved brain tissue, the head, or whole carcass and initiated confirmatory testing in the field using a Bionote RDT (Léchenne et al., 2016; BIONOTE, 2023) if available, while packaging an additional sample for laboratory submission. If sample collection did not coincide with scheduled ferry trips, samples were temporarily stored frozen in the Provincial Veterinary Office, then sent to RADDL 4B for DFAT (Mayes & Rupprecht, 2015). As ferry trips were normally scheduled on weekends and outside office hours, one Provincial Veterinary Office staff delivered samples in batches, depending on their availability. When confirmatory testing was not possible at RADDL (fluorescent microscope was broken), samples were instead submitted to the RITM National Reference Laboratory in Manila (Fig. 3.1). Human samples from virus shedding secretions (saliva) and/or body parts (nuchal skin) were collected through minimally-invasive methods from suspected cases, whether pre- or post-mortem, and sent to RITM for confirmation through nested PCR (Fig. 3.2) (Dacheux & Bourhy, 2018). As part of routine procedures when handling a probable rabies patient, hospitals sought informed consent before conducting sample collection, with a statement clarifying that laboratory results were to be performed for surveillance purposes. Samples that were confirmed positive by DFAT or PCR were stored under cold chain.

3.4.3 Whole genome sequencing and phylogenetic analysis

Twenty-four out of 43 rabies-positive samples from the outbreak were sequenced, following a previously established protocol for whole-genome sequencing of RABV (Bautista et al., 2023) (Supplementary Table S2) to maximise reagent use, periodic sequencing was conducted, with 12–23 samples per run.

A Romblon-only phylogenetic tree was generated in IQtree and Romblon sequences were divided into phylogenetic lineages, for transmission tree inference (Magalis et al., 2024) (see next section). Lineages were defined through patristic distance clustering with the adegenet package (Jombart 2008) using a threshold of 0.0004, determined by comparing patristic distance clusters with phylogenetic trees and considering the RABV evolutionary rate (2×10^{-4} substitutions/site/year). A heatmap of patristic distances is available in Supplementary Fig. S3.

A large contextual dataset of partial and whole genome Philippine RABV sequences (n = 615) from the RABV-GLUE database (n = 694) (Campbell et al., 2022) was obtained for this study, with additional recently published whole genome sequences (WGS) (Bacus et al., 2021) (n = 49), and WGS from an ongoing Philippine RABV study (n = 4) and this outbreak (n = 24). The contextual data constituted RABV sequences with the Philippines as the country of origin, which belong exclusively to the Asian SEA4 clade, a phylogenetic clade associated with and almost entirely restricted to the Philippines (we did not include 11 sequences found in other countries). Associated metadata was prepared using custom R scripts to clean and standardise data from the different sources, including merging of sequences from different genes with the same isolate ID. Overall, this resulted in a dataset of 581 sequences. Metadata, sequences and code can be found in the GitHub repository. To prepare a sequence alignment, concatenated WGS (n = 79) were aligned using MAFFT (v7.520) (Katoh & Standley, 2013) with default parameters, then added to the RABV-GLUE downloaded alignment using MAFFT's functionality to add full-length sequences to an existing multiple sequence alignment with the keeplength option on. Each alignment was checked and edited manually as required (minor edits). Partial sequences with the same sample IDs (but submitted under different GenBank accession IDs) were merged using another custom R script.

Phylogenetic analysis including tree dating and ancestral character reconstruction was performed following the methods in ref. (Holtz et al., 2023). A maximum likelihood tree was constructed from the 581 Philippines RABV sequence data using FastTree v2.1.11 (Price et al., 2010) with a GTR+Gamma20 model. Using the sequence-associated dates, this tree was rooted according to the best root-to-tip correlation, by running the initRoot function in R package BactDating (https://github.com/xavierdidelot/BactDating). The rooted tree was pruned to WGS only using gotree (v0.4.5) and the evolutionary rate estimated using the R-wrapper for lsd2 (To et al., 2016) (Rlsd2) with a ZscoreOutlier of 3. This rate estimate was used as a prior to inform tree dating for the full 581 sequence RABV tree with a ZscoreOutlier of 5 and 1000 bootstraps to generate date CIs. PastML (Ishikawa et al., 2019) (v1.9.43) was used to perform ancestral character reconstructions on the dated tree using a marginal posterior probabilities approximation, with Philippines administrative divisions as traits (region and province). Subtrees including recent Romblon outbreak sequences and their 10 closest relatives were extracted from the larger contextual phylogeny for interpretation. Romblon phylogenetic lineages were defined according to a patristic distance threshold of 0.0004. Tree annotation and visualisation was performed in R with the ggtree package (Yu et al., 2017).

Outbreak spread between time of introduction (T_{int}) and first detection (otherwise known as time of observation or T_{obs}), was estimated using a branching process model, simulating the serial intervals and secondary cases probabilistically from lognormal (meanlog = 2.85, sdlog = 0.966) and negative binomial distributions (mean = 1.20, ($k = 1.33$), respectively, to generate descendents from the initial case (Townsend et al., 2013; Mancy et al., 2022). The interval between T_{int}, inferred via phylogenetic analysis, and (T_{obs}) was calculated—not accounting for the tMRCA (Time to Most Recent Common Ancestor) uncertainty—to determine simulation run time, conditioned on outbreak persistence until Tobs. 1000 outbreaks were simulated, and the median and 95% prediction intervals of undetected cases calculated. As this model assumes an infinite susceptible population, the median and prediction interval were calculated only from plausible outbreaks (incidence not exceeding 1% of Romblon's dog population).

3.4.4 Transmission tree inference

We probabilistically reconstructed transmission trees using the treerabid R package v1.0.1 that generates trees consistent with phylogenies (Rajeev, 2024) . Progenitors for each case were inferred from reference distributions of the rabies dispersal kernel and serial interval (Lognormal serial interval, meanlog 2.85, sdlog 0.966, and Weibull distance kernel, shape 0.698, scale 1263.461) (Mancy et al., 2022). We incorporated uncertainties into our bootstrapping procedure for dates of case onset and case locations, since the *barangay* (village) was recorded for each case but geolocations were not. Specifically, for each bootstrap, we assigned case onset dates by sampling uniformly from a 5-day window up to and including the date of the biting incident or sampling if this was reported, or a 15-day window up to and including the date of laboratory submission or testing otherwise. We selected plausible case localities by sampling from $100 \times 100\,\text{m}$ raster grid cells in proportion to population density according to unconstrained model data from worldpop (WorldPop, 2018).

We generated 1000 bootstrapped trees for each of 32 scenarios, corresponding to all combinations of the following: (i) case locations (*barangay* centroids versus locations sampled from the population density grid); (ii) use of genetic data for inference (yes/no); and (iii) inclusion of pruning steps to further resolve transmission chains (eight different combinations of cut-offs). In the scenarios using genetic data, transmission trees were first constructed using spatiotemporal data as described above, and then made consistent with phylogenetic lineage assignments by using a rewiring algorithm for cases assigned to incongruent lineages. In the phylogenetic lineage assignments, we interpolated the existence of an unsampled rabid dog at the time and location of the human exposure that developed rabies and for which a sequence was obtained, and assumed this case belonged to the designated lineage. In the scenarios with additional pruning steps, case pairs were filtered out where the time interval and/or distance exceeded specified percentiles of the serial interval and distance kernel distributions. Pruning options included no pruning, pruning by time only (cut-offs 0.95, 0.975, and 0.99), pruning by time and distance using the same cut-offs (0.95, 0.975, and 0.99) and one combination of differing cut-offs (time 0.975, distance 0.99). Without pruning or integration of phylogenetic information, tree reconstruction results in a single chain. The different scenarios were compared on the basis of their consensus trees.

3.5 Results

3.5.1 Rabies cases

Romblon province was considered rabies-free, with no cases recorded since 2012, until 2020 when two suspicious human deaths occurred in Romblon Island (Fig. 3.3). Prior to 2012, four human deaths were recorded in the province between 2003 and 2006 and an outbreak on Tablas Island in 2011 confirmed eight animal cases and 11 human deaths (Tohma et al., 2016). From 2017 to 2021, rabies sample submissions steadily declined from 39 specimens tested annually to zero tested during lockdown. In late 2022, the use of IBCM identified a cluster of bite cases leading to the detection of the first dog rabies cases on Tablas Island, Romblon Province, in over a decade.

The first detected rabies-positive case (November 21st, 2022) was a dog that was investigated three days after its involvement in a biting incident (November 18th) in Santa Maria municipality. This was the first sample from the province to have been tested for rabies since 2020, and the first local use of an RDT after being supplied for IBCM (training carried out in March 2020 just before COVID-19 restrictions were announced). Due to the absence of laboratory facilities in Romblon province and the fluorescent microscope being broken at the Regional Animal Disease Diagnostic Laboratory (RADDL 4B, Fig. 3.1), the sample was transported overnight to the National Reference Laboratory at the Research Institute for Tropical Medicine (RITM) in Manila. Here it was confirmed the next day (November 22nd) through direct fluorescent antibody testing (DFAT) and the positive result was immediately communicated to the local government, prompting increased sample collection, and in-field testing. That week two more samples collected from biting dogs in Odiongan and Alcantara municipalities were sent to RADDL 4B where they tested positive by RDT. Another biting dog from San Agustin municipality was classified as probable rabies after being killed and consumed without sample collection (Fig. 3.3).

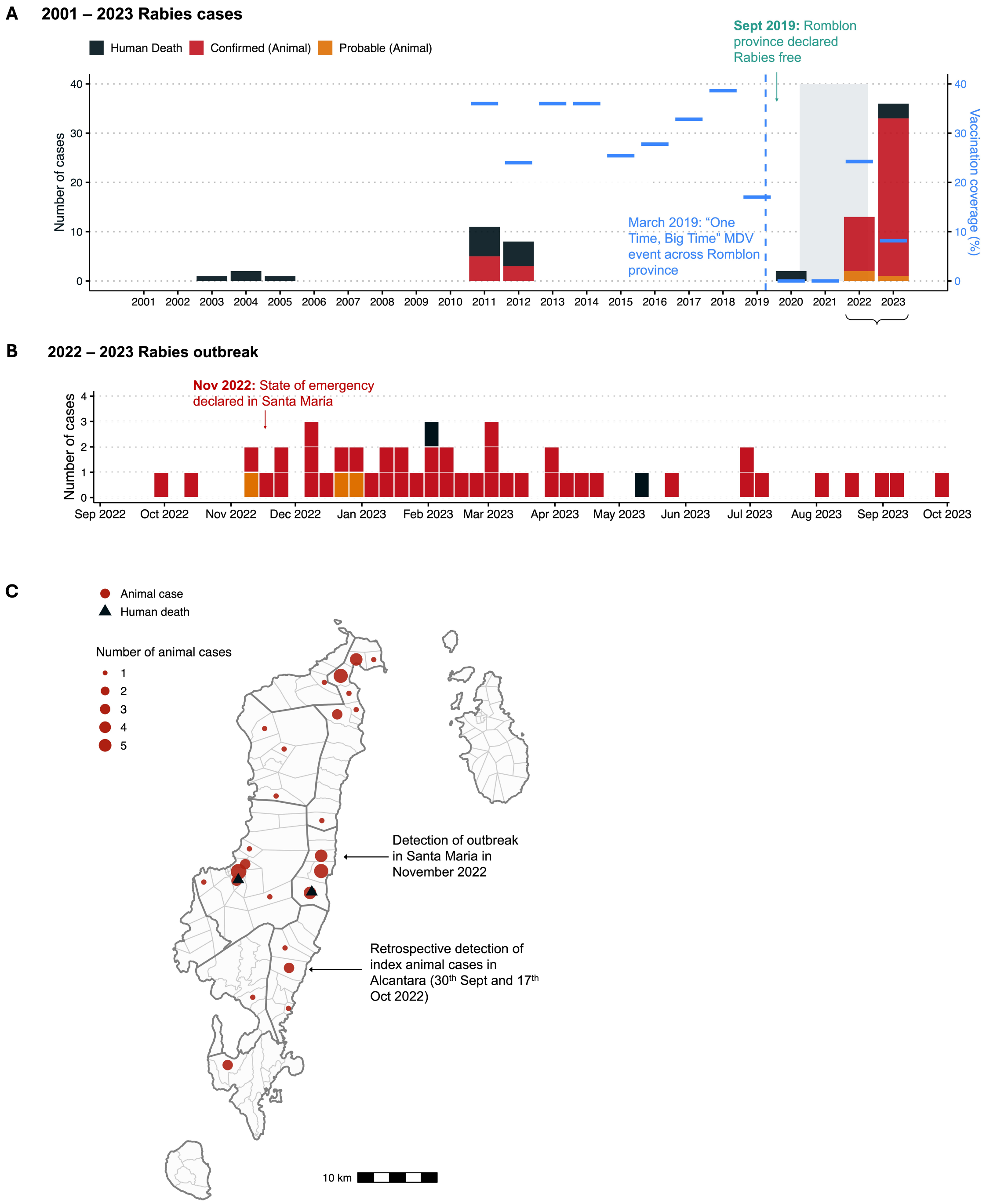


Figure 3.3: Rabies cases and control measures recorded in Romblon province since 2001. A) Human deaths and confirmed and probable animal cases recorded annually between 2001 and September 2023; this includes two human deaths from Romblon Island in 2020 that were diagnosed based on clinical signs but not confirmed so were not included in official government statistics, and two human deaths in 2023 that were laboratory confirmed following implementation of genomic surveillance. The estimated percentage of dogs vaccinated each year is shown as blue horizontal bars. The shaded area represents the COVID-19 lockdown period. B) Human deaths, confirmed and probable animal cases recorded during the outbreak between September 2022 and September 2023. Human cases are dated by month of death while animal cases are dated by month of biting incident (if known); otherwise, sample collection date is used (22/43 cases). C) Animal cases (red circles, scaled by number) and human deaths (black triangles) in Romblon between September 2022 and September 2023. Grey polygons indicate municipalities and cases detected early in the outbreak are annotated.

Positive confirmation of the first case in Santa Maria municipality prompted the sending of two frozen dog heads collected from Alcantara municipality in September and October 2022 to RITM in early December 2022. Both tested positive via DFAT, thus marking the index case of the outbreak as September 30th, 2022 (Fig. 3.3).

Between September 2022 and September 2023, a total of 43 animal rabies cases and two human deaths were confirmed in eight out of the nine municipalities in Tablas Island (Fig. 3.3). Additionally, three biting dogs were classified as probable cases, based on clinical signs (World Health Organization 2018) and progressive fatal outcomes consistent with those reported in literature (Ma et al., 2020; Medley et al., 2017), but without diagnostic confirmation due to lack of sample collection. The One Health link between public health and veterinary workers operationalized through IBCM was critical to identifying many of the rabid dogs (n = 25). Conversations on the IBCM peer support chat also disseminated information about rabid dogs that were investigated directly because of their strange behaviour (i.e. not because of biting a person). The Disease Surveillance Officer (appointed to coordinate IBCM across the provinces) facilitated resource sharing between sectors by transporting supplies, case reports and vehicles so that investigations were conducted within 1–2 days of an animal death, before samples decomposed or became unfit for testing.

Of the submitted samples, 71.7% (43/60) tested positive for DFAT (all dogs). Only 3.3% (2/60) of submitted samples were from cats and both were negative. RDTs were used for initial screening of 51.7% (32/60) of samples. All RDT-positive samples were confirmed by DFAT. The RDT specificity was 100%, while sensitivity was 95.5%, with one initially negative RDT sample later confirmed positive by DFAT. Most positive cases were detected in San Agustin municipality (n = 13/43, 30.2%) where one of Tablas' ports is located (Fig. 3.1). San Agustin had the highest sample submission rate, followed by Odiongan municipality, which accounted for 25.6% (11/43) of positive cases. No samples were collected from Ferrol municipality, nor were any probable rabid animals reported there. Most rabies-positive dogs were owned, while no owner could be identified for 32.6% of rabies-positive dogs (14/43). Twenty three point five percent (4/17) of rabies-negative dogs had a history of vaccination, while 13.6% (6/43) of rabies-positive dogs had reportedly been vaccinated, although the vaccination year and the type of vaccine were unspecified, except for one of the dogs that became ill and died shortly after vaccination in 2023. Rabies-positive animals were either killed (27.9%), found dead (23.3%), died while under observation (41.9%), or had unspecified outcomes (7%).

Two human rabies deaths were identified in 2023: one in February (39 days after the bite in December 2022) and another in May (131 days after the bite) (Fig. 3.3). The victims, a child from Santa Maria municipality and an older person from Odiongan municipality, were bitten by dogs and did not receive PEP. Initially, they sought treatment from local faith healers (‘*tandok*’), as encouraged by their families and were hospitalised only when symptoms worsened.

On average, the delay between exposure and PEP in treated patients was 1.8 days (95% CI: 0.14–3.36 days; median of 0 days; n = 12). The mean delay between a biting incident and dog death in confirmed cases was 2.1 days (95% Confidence Interval (CI): 0.7–3.5 days), with a median delay of 1 day.

3.5.2 Rabies control and prevention

Since 2000, rabies control in Romblon Province has primarily involved yearly mass dog vaccinations, with estimated coverage never exceeding 40% (Fig. 3.3). During the COVID-19 pandemic, dog vaccination campaigns were suspended due to social distancing restrictions and resource reallocation leading to a decline in coverage (Fig. 3.3). Air travel to and from Tablas Island was suspended from March 2020 to December 2022, but inter-island ferries continued routes via rabies-endemic provinces of Oriental Mindoro, Quezon, and Batangas to ports on Tablas Island in Odiongan, San Agustin, and Calatrava municipalities (Fig. 3.1). While pets are allowed on ferries with a health certificate and proof of rabies vaccination, in practice, checks at public ports are rare. Additionally, private pump boats frequently used by fishermen, tourists and visiting families do not subject companion animals to regulatory procedures.

The confirmation of the positive animal rabies case in Santa Maria municipality in November 2022 prompted an immediate state of emergency declaration by the municipal mayor (Fig. 3.2). Contact tracing identified humans and animals exposed to the rabid dog, and mandatory ring vaccination was conducted, for owned dogs living in residences that were located nearest to the index case's burial location. The available vaccine supply was sufficient to support the vaccination of 66 dogs in total. Municipality-wide dog vaccination was not carried out due to limited human resources and vaccines. In March 2023, after the first human rabies case, an 'Information, Education and Communication' (IEC) activity, consisting of lectures on rabies prevention, was held in the victim's *barangay*. That same month, the governor of Romblon Province instructed all municipalities' mayors on Tablas Island to enforce Republic Act No. 9482 (Anti-Rabies Act of 2007), requiring local government units to allocate funds toward dog vaccination (Government of the Philippines, 2007). Subsequent dog vaccinations were both limited and heterogeneous across the island. While some municipalities restarted vaccination campaigns in 2022, at least three did not conduct large-scale dog vaccinations in 2022 or 2023 (Supplementary Fig. S1). As a result the proportion of the dog population vaccinated declined, from 24.2% vaccinated in 2022, to just 8.2% in 2023. A regional workshop held in early 2024 has since catalysed more concerted vaccination that was completed in May 2024 (12,792 dogs vaccinated).

Bite patients are generally administered PEP on presentation to animal bite treatment centres. However, following the release of positive DFAT results, there was an increase in the patients presenting that underwent IBCM risk assessments, with bite victims duly encouraged to complete PEP regimens. Additional contact tracing was conducted but no other bite victims were identified. No human fatalities were attributed to laboratory-confirmed rabies cases. Delays in DFAT results were circumvented, with RDT results used to reinforce tracing of bite victims. However, lack of official recognition of RDTs at national level was seen as an obstacle that prevented regional and provincial managers from declaring cases and a status based on clinical suspicion was presumed to not carry the same weight as the confirmatory test (DFAT). Contact tracing and PEP were also incomplete for some people exposed to one of the probable cases; they had consumed the dog and were hesitant to come forward, fearing repercussions since dog consumption is illegal.

Details of ongoing cases and updates to the epidemiological situation are maintained on the dashboard: https://boydorr.gla.ac.uk/rabies/SPEEDIER/

3.5.3 Phylogenetic inference

During the outbreak investigation, periodic genomic sequencing was carried out from December 2022 to March 2023. At this time, 96.15% (25/26) of the confirmed positive samples were sequenced. Genome coverage of one out of the 25 sequenced samples was too low for analysis. DFAT confirmed animal brain samples (23/25) had genome coverage of 90–99% while a lower coverage of 88% was achieved for the human skin biopsy sample that was confirmed by nested PCR.

The first sequencing run in December included the first three positive samples from November 2022. The second run on March 2nd, 2023 sequenced the remaining cases from 2022 (including the two earlier cases from Alcantara municipality since sent to RITM), and the first human case. A third run on March 8th, 2023 included the remaining 14 samples up to the most recent at that time (March 1st, 2023) although three prior samples were subsequently traced to the Provincial Veterinary Office. Each run sequenced 12–23 samples, including additional contextual samples from other parts of the Philippines.

A maximum likelihood tree constructed from publicly available sequences from the Philippines (n = 664, reducing to 553 after excluding duplicates and consolidating genes from the same sample) plus 28 sequences from this study (24 outbreak cases, 4 isolated from nearby provinces) provided temporal and geographic context for the outbreak sequences. These 581 unique sequences were collected from 1998 to 2023 from different regions in the country and were of varying length (211 to 11,797 bp), covering different regions of the genome (further details provided in the Github repository, see methods). Both time-scaled and substitution-scaled trees for these 581 sequences are shown in Supplementary Fig. S2. Examining the sequences from the current outbreak in the larger contextual phylogeny showed at least three independent introductions to Tablas Island (Supplementary Fig. S2). The largest cluster of cases (n = 20) subdivides into three identifiable genetic lineages (1, 4, and 5) based on a patristic distance threshold of 0.0004 (Supplementary Fig. S3 shows a heatmap of patristic distances between the outbreak sequences). These lineages may have been due to either a single introduction or multiple introductions from a single foci over a short period. The second (n = 1) and third clusters (n = 3) represent another two introductions, each comprising single genetic lineages (2 and 3 respectively, Fig. 3.4).

The first and largest cluster shares a historical ancestor with sequences from the previous Tablas outbreak (2011–2012). However, ancestral character reconstruction (ACR) determined the earlier and current outbreaks to have emerged from different geographic sources, specifically Pangasinan and Bulacan provinces, respectively, with their time to the most recent common ancestor (tMRCA) estimated as 2010 (Fig. 3.4). This first cluster shows several polytomies, each with ‘star-like’ bursts, indicative of an introduction from a common source, succeeded by multiple local transmission chains. The star-like signatures signify rapid dissemination within a naive population (Volz et al., 2013), making it highly unlikely that these cases resulted from sustained cryptic circulation on Tablas island from the previous 2011 outbreak. Based on the clusters tMRCA, we estimate an introduction around July 2021 (95%CI: Jul 2020–Jun 2022), prior to divergence into three sampled genetic lineages (Fig. 3.4). The resulting cases are most closely related

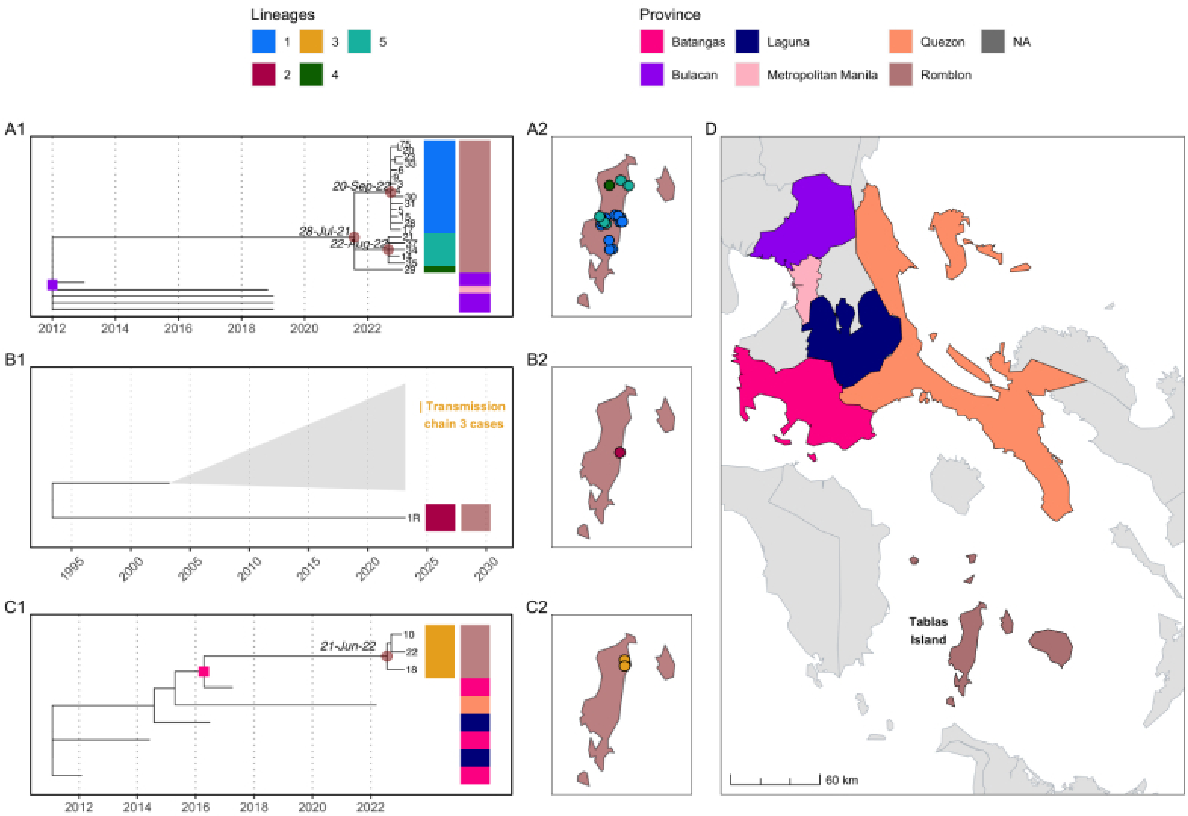


Figure 3.4: Time-scaled phylogenetic subtrees from the current outbreak. The source of introductions was inferred by ancestral character reconstruction (ACR). A1–C1) Subtrees corresponding to each inferred introduction, with colourstrips indicating lineages (colours match Fig. 3.5) identified from clustering by patristic distance (Supplementary Fig. S4) and sequenced case locations (province-level) to match (D). Internal nodes mark the tMRCA of each cluster and lineage (circles) and inferred province-level ACR location (squares) for each cluster's ancestral node coloured accordingly. A2–C2) Locations of sequences from Tablas (with points jittered) coloured by lineage and D provinces in the Philippines coloured according to ACR.

to sequences from Central Luzon and National Capital Region i.e. municipalities within Metropolitan Manila, and Bulacan province is the inferred ancestral location (marginal probability of 100%). If the different lineages were from multiple introductions, they all likely arose from Bulacan province.

The second cluster comprised just one case (the sequenced human case with 88% genome coverage), which lies on a distinct outlier branch in the phylogeny (Fig. 3.4). It was ancestral to a large cluster of sequences ($n = 167$) from a mixture of geographic regions, including cases from the third cluster (collapsed clade, Fig. 3.4), with tMRCA estimated as Oct 1990 (95% CI: Sep 1985–Jul 1994). The geographic source that led to this human case and the time of the lineage introduction, however, could not be pinpointed, likely due to undersampled diversity in this part of the phylogeny. We estimate that the third cluster resulted from an introduction in late June 2022 (95% CI: Aug 2021–Dec 2022) and was most closely related to sequences from neighbouring provinces within the Calabarzon region, with Batangas province the inferred ancestral location (marginal probability of 97.7%) (Fig. 3.4).

From simulating a branching process using epidemiological parameters (R0 and serial interval) for rabies viruses, we estimated possible cases resulting from each initial unobserved introduction to Tablas Island. Using the estimated introduction dates for two clusters (1 and 3), we calculated detection delays of 429 days for cluster 1 (from 28/7/2021 to 30/9/2022), and 141 days for cluster 3 (from 28/6/2022 to 14/11/2022). Simulations with realistic incidence suggest a median of 149 undetected cases (95% prediction interval (95%PIE): 14—355) for cluster 1 and 30 (95%PI: 2–180) for cluster 3 before detection. However, if cluster 1 resulted from multiple introductions (estimated around 24/9/2022 and 26/8/2022), leading to lineages 1 and 5, we calculate detection delays of 6 and 121 days respectively, suggesting a median of 1 (95%PI: 1—3) and 20 (95%PI: 1—114.1) undetected cases. Since lineage 4 is represented by a singleton, we presume that it emerged after July 2021.

Transmission trees constructed solely from epidemiological data (dates and locations) were deemed not phylogenetically consistent as virus spread did not match inferences based on genetic data, highlighting the enhanced resolution provided by viral genomes (Supplementary Fig. S4). Following rewiring for phylogenetic consistency with the five differentiated genetic lineages, pruning by serial interval distribution percentiles (95th, 97.5th, and 99th) resulted in negligible tree configuration changes. Further pruning by distance kernel percentiles led to orphaned cases and short unsampled transmission chains, indicative of either undetected cases in areas with ongoing transmission, or of long-distance human-mediated translocations. Transmission trees inferred using *barangay* centroids versus simulated locations (in proportion to population density) were broadly similar. Using the 99th pruning percentiles split the 5 lineages into 7 transmission chains as indicated by colour in Fig. 3.5. Lineage 1 split into two transmission chains; lineage 2 linked the biting dog responsible for the first human death with an unsampled dog; lineage 3 remained as one chain and lineage 4 as a singleton; while lineage 5 split into two chains (Fig. 3.5).

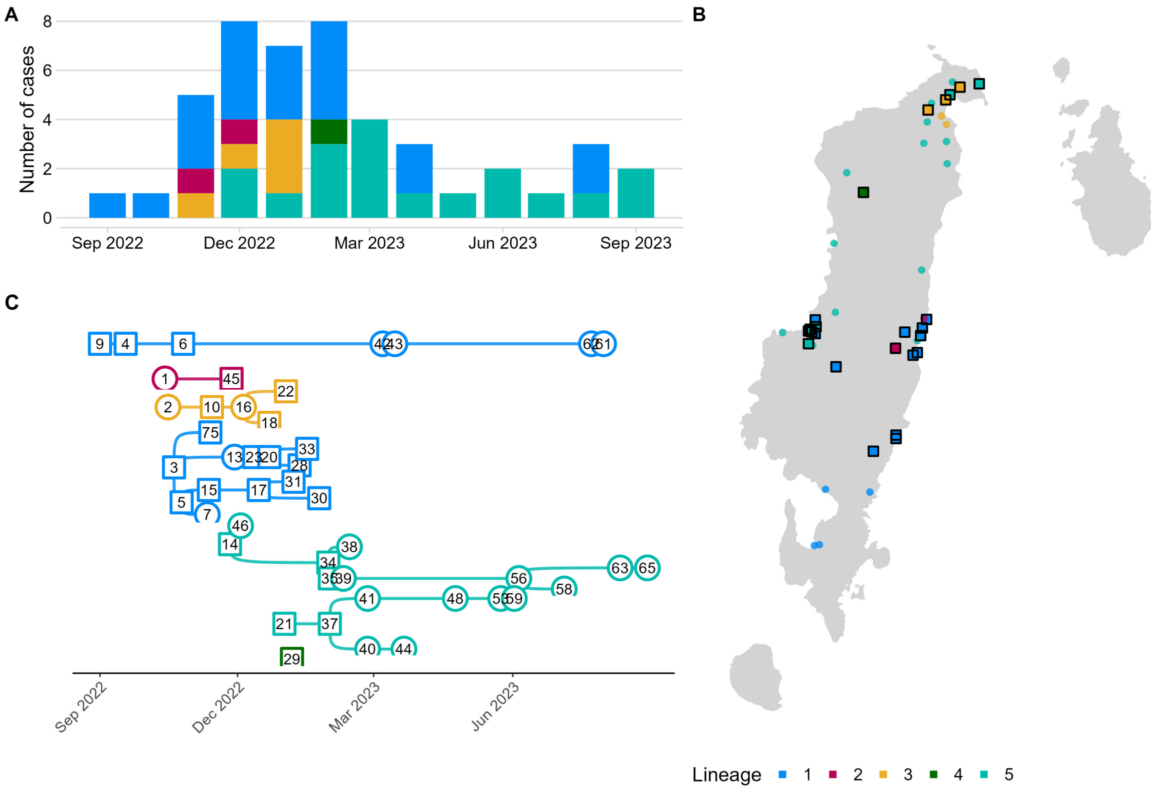


Figure 3.5: Inferred transmission chains from the outbreak. A Monthly confirmed and probable dog cases; B mapped dog case locations all coloured by lineage (as per Fig. 4). Squares represent sequenced cases, and circles unsequenced (unsampled) cases, except for case 45, which was not sequenced, but assigned to lineage 2 based on its epidemiological link to the sequenced human case (not shown) and C reconstructed transmission chains. The illustrated chains are from the consensus transmission tree with case locations simulated in proportion to human population density and pruning by the 99th percentiles of the serial interval and dispersal kernel. The effects of pruning assumptions and uncertainties on reconstructed transmission chains are shown in Supplementary Fig. S4.

3.6 Discussion

From investigating this outbreak in a formerly rabies-free province, we identified at least three independent introductions that led to rapid island-wide spread. Although 46 animal cases and two confirmed human deaths were detected over the first 12 months, our inference suggests considerable transmission occurred prior to outbreak detection. Long-distance human-mediated translocations and low dog vaccination coverage likely increased the likelihood of both rabies introductions and spread.

Each year, around 200–300 people die of rabies in the Philippines (Department of Health, 2019). Mass dog vaccination is effective for rabies control, and has been employed nationwide at varying consistencies. One successful local example is Bohol Province's intersectoral elimination programme, which achieved 70% coverage (as recommended by WHO) through "catch-up" vaccination following mass campaigns (Lapiz et al., 2012). Models predict that vaccinating at least 60–70% of dogs should substantially reduce cases (Cleaveland et al., 2003), but if coverage is heterogeneous, time to elimination increases, while the probability of elimination decreases (Ferguson et al., 2015). Prior to 2020, vaccination coverage never exceeded 40% in Romblon due to budget and labour shortages, while poor coordination between municipalities led to patchy campaigns that lacked island-wide coverage. Suspension of vaccinations due to COVID-19 lockdowns in 2020 and 2021 resulted in lower herd immunity across Romblon and much of the country, as evidenced by the subsequent nationwide increase in human rabies deaths, which peaked at 382 in 2023 (Tejano, 2024) (the highest recorded since 2008).

Our work supports previous findings that incursions occur frequently, with genomic surveillance revealing higher rates than expected (Volz et al., 2013). Many introductions fail to take off due to stochasticity in rabies transmission (Volz et al., 2013). However, recent outbreaks in other provinces such as Ilocos, as well as the formerly rabies-free island Marinduque, suggest large-scale re-emergence in the aftermath of COVID-19. The third cluster in Romblon was detected in a municipality with a ferry port, possibly linked to an increase in inter-island introductions as travel heightened and restrictions relaxed. The Philippines' archipelagic nature may generally limit incursions in geographically isolated islands, and residual vaccination coverage reduces the chances of secondary cases. However, accessibility to nearby rabies-endemic provinces, coupled with poor vaccination coverage, likely contributed to the outbreak spread.

Prior to the pandemic, gaps in the province's surveillance were apparent: few samples were submitted annually, as storage in the Provincial Veterinary Office and transport by ferry were necessary for confirmation. With staff shortages, timely transfer to the regional laboratory was further impacted by the infrequency of ferry trips due to inclement weather. Apart from causing the suspension of vaccinations, which left dog populations vulnerable, COVID-19 restrictions hindered surveillance, delaying outbreak detection, and possibly leaving earlier outbreaks undetected. Social distancing and prioritised pandemic response impeded investigation of two suspect deaths on Romblon Island in 2020. Samples from animals involved in high-risk bites were mostly not collected prior to the first RDT-positive case, but the result sparked multiple investigations, leading to increased sample collection and RDT use. News of the case result also catalysed testing of two samples that had been stored for over a month. These laboratory-confirmed cases proved that rabies had been circulating earlier than initially presumed.

Between 2017 and 2019, all submitted animal specimens from Romblon tested negative for rabies and no human deaths were reported, reaffirming the province's rabies-free status. Three and zero submissions in 2020 and 2021, respectively, were attributed to lockdown restrictions, while increased case detection and real-time investigation of the outbreak from 2022 onward were enabled by IBCM. Improved communication between animal and human sectors led to identification of most cases, through animal investigations that were triggered by bite victim reports. Use of RDTs may have compelled speedier investigations, since dissemination of positive RDT results increased awareness, which spurred immediate follow up of animals involved in biting incidents (Léchenne et al., 2016; Cruz et al., 2023;

Yale et al., 2019; Tenzin et al., 2020). Through these timely investigations, animal health workers collected suspicious animals that had died, and the upsurge in testing produced more confirmed cases. To compensate for Romblon's lack of laboratory facilities, multi-sectoral inter-island collaboration between provinces streamlined the sample transport process for confirmatory testing and subsequent sequencing. But the volume of samples highlighted challenges, exceeding available resources required to send them individually. Thus, all samples, whether untested, RDT-positive or RDT-negative, were forwarded in weekly batches for laboratory confirmation. When the regional laboratory could not perform DFAT, RDTs were performed instead, before transfer to a third location–the national laboratory (RITM)–for DFAT confirmation and sequencing, requiring additional travel time and exacerbating delays to result reporting.

Sequencing has played a crucial role in informing sources of rabies introductions (Sabeta et al., 2013; Mahardika et al., 2014; Trewby et al., 2017) and mobilising vaccination responses (Bourhy et al., 2016; Zinsstag et al., 2017). Integrating genomic data with epidemiological data from IBCM enhanced understanding of the outbreak spread and identified possible points of introduction, also suggesting the need for preventive vaccination, targeting dog vaccination towards source endemic areas. The benefits of genomic surveillance, as evidenced during the COVID-19 pandemic, require that expertise and skills be maintained in-country (Lee et al., 2022).

Veterinary capacity remains limited across much of Southeast Asia. In Tablas, few staff had to contend with the rapidly evolving public health emergency. The concurrent emergence of ASF prompted government-mandated enhanced surveillance across several provinces, including testing, culling, and banning importation of pork products from affected islands. In comparison, rabies outbreak response was decentralised, fragmented, differing between municipalities, and limited in scale. Prioritisation of ASF by the animal health sector set back investigations, and case confirmation delays slowed the public health response. No formal declaration of an island-wide outbreak was made, and while a few municipalities declared a state of emergency, rabies control efforts were limited. With insufficient dog vaccines and vaccinators, reactive coverage through ring vaccinations of <100 dogs following case confirmation may have provided a small radius of immunity but did little to contain the outbreak, as cases in neighbouring villages showed that transmission was already occurring across shared borders by the time of detection. Moreover, small-scale vaccination is known to be ineffective when only a proportion of cases are detected (Cleaveland et al., 2003). Contact tracing and PEP prevented human deaths from confirmed animal cases, but poor awareness constrained contact tracing for probable animal cases, as evidenced by refusal to seek PEP among those involved in consuming dog meat, out of fear of prosecution. The local IEC activity held following a rabies-positive case had limited effects on PEP-seeking and reporting of suspicious animals, as a human death occurred just two months later. Both human cases reportedly resorted to tandok instead of PEP, and caretakers only sought medical care after symptoms manifested. Arguably, these deaths could have been averted had communities been sensitised about the rapid rabies spread evident by December 2022. That local response intensified only after a human case, and island-wide dog vaccination was only restarted in 2024, two years after the outbreak's detection, shows how reliance on primarily reactive strategies in health care remains a major One Health challenge.

Our study had several limitations, beginning with IBCM training and support being compromised by COVID-19 restrictions. Despite triggering the outbreak investigation, RDTs were challenging to incorporate into case finding, for several reasons. There was a two-year gap between RDT training and field deployment. Romblon's rabies-free status may have also created a false sense of security, explaining the lack of immediacy in testing suspicious animals. Lack of practice and confidence were reflected in samples that were stored post-collection, with the expectation that the regional laboratory would handle testing. Furthermore, positive RDTs were not considered valid unless matched by DFAT, so there was little incentive to use RDTs as they didn't 'count' as a diagnostic method, even if waiting for laboratory confirmation delayed information dissemination. National authorization for the use of RDTs and release of official diagnostic results could have expedited early outbreak detection, and if RDTs were recommended internationally, this could perhaps hasten implementation of control measures. Though it must be noted that laboratory confirmation still did not spur outbreak response in several municipalities until a human case was reported.

Genomic surveillance revealed insights not possible from the epidemiological data alone, but were not definitive. For example, the human case sequence points to a second introduction from an unknown source that we were unable to pinpoint, due to undersampled diversity in the phylogeny. As this sample type (skin) and extraction kit was not ideal (sequencing approaches have been optimised for brain tissue), this sample could be revisited to generate better sequence coverage and depth. Moreover, not all positive samples were sequenced, with only 24/43 early samples sequenced to date. Sequences from samples taken later in the outbreak could reveal which lineages have persisted and if further introductions have occurred. The largest cluster likely resulted from a single introduction from Bulacan province that diverged into three genetic lineages, but it could have resulted from multiple introductions. However, without more sequences from this period and from Bulacan province, we are unable to distinguish these scenarios. Our inference of orphaned cases and short transmission chains indicate either locations with undetected transmission, or long-distance (human-mediated) translocations. Longer delays make our branching process approximation less accurate for estimating undetected transmission, as observed for the largest cluster associated with the initial outbreak detection. Further methodological development could refine these estimates, including accounting for uncertainty in the timing of introductions and for residual vaccination coverage.

Free-roaming dog populations sustain rabies outbreaks worldwide, as seen in Romblon, where most cases were from owned dogs that were unleashed and unsupervised. It is a cultural practice in some LMICs to let dogs wander, and despite local ordinances in the Philippines prohibiting non-leashed dogs in public, these are not easily implemented due to insufficient resources for dog-catching and impounding. Therefore, the burden must also be shared with dog owners to take responsibility for ensuring that their pets are vaccinated and not inconveniencing others.

Achieving vaccination coverage of 70% remains the most important rabies control method. Dog vaccination coverage estimates fluctuated from year to year, ranging between 18–38.6% pre-pandemic and 0–24.2% post-pandemic, hence their limited impact on rabies transmission. Lack of standardised monitoring of coverage meant these estimates were extrapolated from different sources, potentially explaining inconsistencies (Fig. 3.3). More generally, heterogeneous coverage in the Philippines is evidenced by lack of coordination among municipalities, even during a deadly outbreak on a small island. If one municipality achieves sufficient coverage, it is still vulnerable to incursions from neighbouring municipalities, highlighting the value of cross-border coordination between local government units. This principle also applies to provinces, as reflected in the increasing number of rabies cases detected post-pandemic (even in provinces lacking IBCM). Henceforth, focus must be placed on proximate control measures in nearby rabies-endemic islands if the ‘Zero by 30’ goal is to be achieved.

3.6.1 Conclusion and recommendations

This investigation demonstrates the value of combining epidemiological and genomic data for inferring the source and spread of rabies outbreaks. Enhanced surveillance through IBCM coupled with genomic surveillance proved essential in case-finding and tracking, while simultaneously highlighting the challenges of outbreak detection and response in rural archipelagic settings. The immediacy of RDT results illustrate their potential to inform timely outbreak declaration and response, but lack of international guidance on their use remains an obstacle.

Despite belying the One Health approach, control measures driven solely by human deaths are unfortunately common in LMICs, with dog rabies cases often not taken seriously. Lessons should be taken from Romblon on RDTs and laboratory-confirmed animal cases acting as triggers for outbreak response. The Philippines has previously demonstrated rabies control capacity, but since its economic impact is negligible compared to ASF (even despite human fatalities), routine surveillance remains neglected and current border control measures at local ports of entry (Department of Health, 2019) have not been strengthened amidst disease re-emergence. Delayed public health responses that included small-scale ring vaccinations were inadequate, emphasising the need for dog vaccination to be sufficiently large-scale and sustained; in this situation, island-wide at a target coverage of 70% over several years to achieve elimination, as seen in the Pemba Island outbreak in Tanzania (Lushasi et al., 2022). Genomic surveillance is beneficial for determining the source of incursions, and can also target preventative vaccination toward rabies-endemic areas. Additionally, sustaining genomic capacity can benefit investigations of other infectious diseases in human and animal populations, with rabies serving as a marker of government response proficiency.

Globally, lessons from this outbreak include proven benefits of the One Health approach in enhancing surveillance, the limitations of short-term control measures, and the importance of routine surveillance in maintaining capacity for responding to potential re-emergence.

Chapter 4

A feasibility study to examine the potential of collar use to enhance mass dog vaccination in the Philippines

4.1 Author contributions

I designed the study reported in this chapter, which included designing semi-structured interview questions and questionnaires. I recruited participants, conducted observations and and interviews, participated in transect surveys (training the other enumerators who undertook the rest of the transect surveys), and distributed questionnaires. I also translated and transcribed interviews, analysed qualitative and quantitative data, wrote the manuscript and created the figures used in this work.

4.2 Abstract

Rabies results in >250 human deaths in the Philippines yearly. To eliminate dog-mediated human deaths, WHO and partners recommend achieving dog vaccination coverage of 70%. Although local coverage often remains insufficient, effective and acceptable methods to visually identify the vaccination status of dogs could provide numerous benefits to rabies vaccination programmes. In Puerto Galera, a rabies-endemic municipality, we collected data by conducting observations during the three-day vaccination campaign and interviewed participants who applied the collars We also conducted a community survey to assess peoples' attitudes toward collars and collared dogs, and conducted transect surveys of dogs to observe the rate of collar loss in free-roaming dogs. We used Normalisation Process Theory as a theoretical framework to analyse interviews, questionnaires and surveys. Our analysis shows that minimal training is required to understand the purpose and process of applying collars to dogs. Applying collars did not significantly increase time spent vaccinating each dog (<5 minutes), although aggressive dogs were more difficult and time-consuming to collar. Collars were not evenly distributed due to coordination and supply issues. Questionnaire answers from residents showed an understanding of the collars despite lack of community sensitization prior and during the vaccination, although human behavior was unchanged and community misconceptions about rabies suggests that understanding about the disease and vaccination is weak. Collar loss was high (89.5% lost at 3 months post-vaccination). Collar application is easy to adapt, and does not reduce the number of dogs vaccinated nor require prolonging MDVs, although collars should be tested for more durable yet still cost-effective materials. Our study identified no behaviour changes toward dogs despite the presence of dog collars as well as concerning misunderstandings about rabies in communities, which underscores the value of increasing rabies awareness.

4.3 Introduction

Rabies, a viral disease primarily spread through dog bites, kills over 59,000 people annually (Hampson et al., 2015), with 99% of human deaths occurring in Africa and Asia (Lembo et al., 2010). Historically, dog-mediated rabies was eliminated in many countries through mass dog vaccination, supported by provision of post-exposure prophylaxis (PEP) to bite victims, dog population control and strictly enforced pet ownership laws (Schneider et al., 2007). The global strategic plan to end human deaths from dog-mediated rabies by 2030 ('Zero by 30') advocates for sustained vaccination of 70% of dogs (WHO et al., 2018).

Large-scale mass dog vaccination (MDV) programs have been initiated in low-and-middle-income countries (LMICs), such as the Philippines (Valenzuela et al., 2017), South Africa (LeRoux et al., 2018) and Tanzania (Lushasi et al., 2022), leading to the decline of rabies cases in local areas and establishment of rabies-free zones. Common vaccination campaign approaches in LMICs include central point vaccination (Léchenne et al., 2016), wherein multiple vaccination stations are designated where residents can deliver their dogs for immunization, or door-to-door vaccination (Gibson et al., 2016) (sometimes referred to as "house-to-house" vaccination), involving vaccination teams visiting dog owners at their residence. Alternative methods to vaccinate free-roaming dogs, which are permitted to wander in public and may be more difficult to restrain, include oral rabies vaccination through bait (Chanachai et al., 2021) and the more time-consuming and labor-intensive capture-vaccinate-release method for each dog (Gibson et al., 2020), but the additional expense and implementation challenges of these approaches require careful consideration.

Since 2022, over 350 human rabies deaths have been reported in the Philippines annually (Republic of the Philippines Department of Health, 2024). Puerto Galera, a municipality in the rabies-endemic province of Oriental Mindoro, recorded four canine rabies cases alone in 2023 (Swedberg et al., 2023). Receiving 20,000 visitors per month, Puerto Galera also had to contend with increasing complaints about free-roaming dogs on beaches (Aparato, 2023). In collaboration with Boehringer-Ingelheim (BI), manufacturer of the animal rabies vaccine Rabisin, a three-year mass vaccination program was initiated by the Puerto Galera Municipal Agriculture Office (MAO) starting in 2022, wherein >2,000 animals were planned to be vaccinated annually. For 2023's MDV campaign, yellow collars made of polythene and propylene were incorporated into the Puerto Galera vaccination campaign and to serve as a semi-permanent marker for immunized dogs. Markers such as paint or dye and collars have previously been incorporated into MDVs to distinguish free-roaming vaccinated dogs from non-vaccinated ones (Conan et al., 2015). See Supplementary Table S4 for a full description of the intervention using the Template for Intervention Description and Replication for population health and policy interventions checklist (TIDieR-PHP) (Campbell et al., 2018).

Implementation research has supported improved delivery of immunization programs in LMICs like Nigeria (Akwataghibe, 2024) and Ethiopia (Drown et al., 2024). It has also been applied to dog vaccination campaigns (Castillo-Neyra et al., 2025; Duamor et al., 2023), as they are complex activities requiring multisectoral coordination, private and government support, and cooperation of human and animal health sectors, but there remains a lack of evidence-based, systematic and well-designed approaches to improve the sustainable and effective delivery of MDV campaigns. Using new and untested technologies like semi-permanent collars in the Philippines entails interaction between several components, including development of required skills for those vaccinating and applying collars, and targeted human-dog behaviours among community members. Therefore, we approached the use of collars in MDVs as a complex intervention, as UK Medical Research Council guidance was relevant to our study (Skivington et al., 2021). In collaboration with campaign organizers, we developed a Theory of Change for use of collars in Puerto Galera's vaccination campaign to guide the intervention's perceived impacts in comparison to previous campaigns and to determine its feasibility for future use in MDVs

(Fig. 4.2). Our objectives were to explore whether: (a) local field staff and community members find collars acceptable and appropriate, (b) how attitudes toward collared dogs compared to those without, and (c) to determine collar durability and therefore value as a visible marker of vaccination status.

4.4 Methods

4.4.1 Study setting

The study was conducted in the Philippine municipality of Puerto Galera (population 42,301), one of 14 municipalities in Oriental Mindoro province (population 919,504) (Philippine Statistics Authority, 2025), from June 2023 to June 2024. Puerto Galera consists of 13 *barangays* (the Philippine equivalent of villages) located encapsulating mountains, forests and/or coastlines (Fig. 4.1). One barangay, San Isidro, is the location of White Beach, which is one of several well-known attractions that drives Puerto Galera's tourism-dependent economy and serves as the home of a free-roaming dog population that has been the main subject of complaints by tourists.

4.4.2 Study intervention

Plastic yellow collars were designed and mass-produced by BI and distributed to countries including the Philippines, Bangladesh and Tanzania for use on free-roaming dogs during MDVs, as semi-permanent visual markers of their vaccination status for residents and vaccinators. Vaccination and collaring were intended to be yearly (with different collar colors per year). For our study, referred to as the 'collaring feasibility study', a three-day MDV was coordinated between BI and the Puerto Galera MAO to take place in

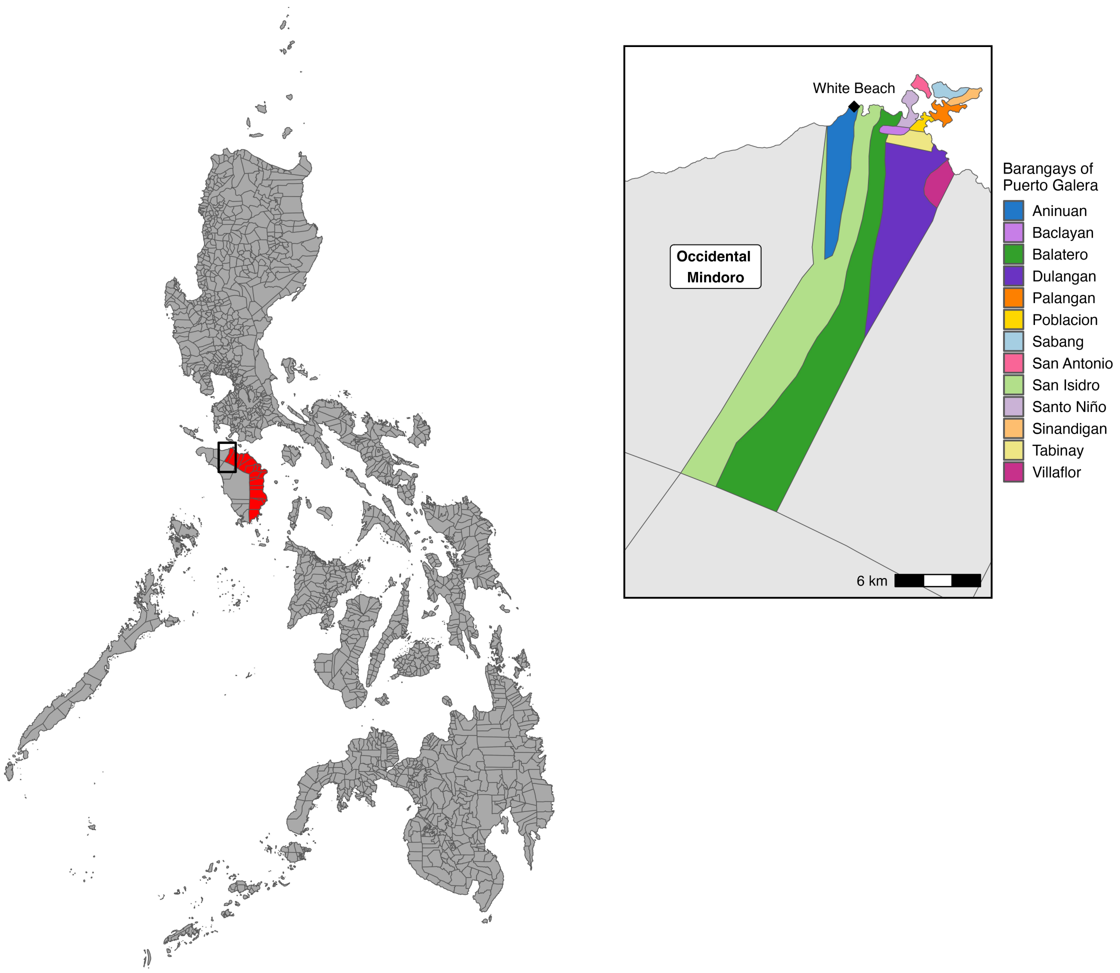


Figure 4.1: Map of the Philippines with Oriental Mindoro province highlighted (red). In-set map shows Puerto Galera municipality's 13 barangays and White Beach, which is located in Barangay San Isidro.

September 2023, the second year (of a planned three-year initiative). BI provided financial and logistical support for the MDV and study, staff for MDV implementation, and directly contributed to the development of the study design and formulation of objectives and desired outcomes, which included continued widespread use of collars in subsequent years, fewer rabies cases in Puerto Galera and changes in human behavior toward collared dogs compared to non-collared dogs. The Puerto Galera MAO provided administrative support, staff and transportation for the MDV and data collection. Preparation meetings included discussion of vaccination campaign activities and expected outcomes for the event, which were co-developed into a Theory of Change to highlight specific aims that, once achieved, could be transformed into long-term outcomes (Fig. 4.2).

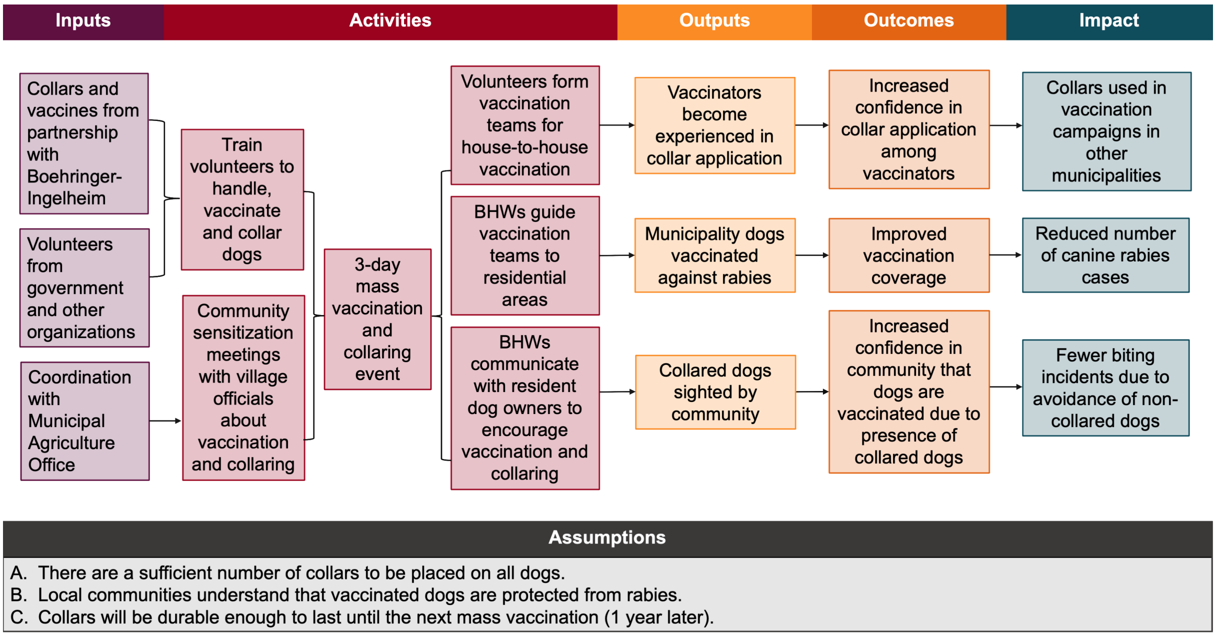


Figure 4.2: Theory of Change to incorporate collars in mass dog vaccination.

Practitioners hailing from private and public sectors joined vaccination teams serving as either vaccinators, responsible for restraining, vaccinating and collaring dogs, or recorders, who manually listed dogs and their owners' details. Vaccinators consisted primarily of government staff volunteers at the municipal, provincial, regional and national levels, and volunteer veterinarians, most with previous experience handling and vaccinating dogs from at least one previous vaccination event. All 13 barangays in Puerto Galera were covered by multiple vaccination teams, with the number of teams per barangay varying based on the barangay's area size. Every vaccination team consisted of at least one vaccinator and one recorder. Teams in all barangays were assigned to conduct house-to-house vaccination, unlike the previous year's central point vaccination. Barangay health workers (BHWs) assisted vaccination teams by acting as guides in local areas, identifying dog-owning households and communicating information to pet owners. BI provided collars, vaccination supplies, and transportation. Before the event started, representatives of BI held a brief demonstration to show the collar application process, which was to be performed on every adult dog following administration of the rabies vaccine. Vaccination teams carried their own equipment, which included an ice box containing vaccines, and additional bags containing syringes, water bottles, collars, writing materials and personal protective equipment. Supplies were replenished and brought to barangay halls by vans. A dog behaviorist accompanied one vaccination team in White Beach, San Isidro as vaccination and collaring were targeted toward free-roaming dogs there specifically.

4.4.3 Data collection

Between October 2023 and May 2024, four sources of data were collected for the feasibility study: (a) observations, (b) semi-structured interviews, (c) questionnaires and (d) transect surveys. Observations were recorded during and after the MDV campaign by research team members who supported vaccination teams.

Post-MDV, we conducted one-on-one semi-structured interviews with practitioners involved in implementing the vaccination campaign. See Supplementary Table S5 for topic guide. Semi-structured interviewees consisted of 11 practitioners: seven vaccinators (two veterinarians in private practice and five government employees), two recorders (volunteers from the private sector) and two BHWs were interviewed. Interviewees were selected to represent the different roles (vaccinator, recorder and BHW guide) within vaccination teams and consent was collected before interviews were conducted in English/Tagalog (depending on the interviewee's preference). Nine interviews were conducted in-person, while the remaining two were conducted by phone. A topic guide was used for all interviewees, with questions centred on their experiences during the mass vaccination event and collar application. Each interview was audio-recorded and transcribed, with Filipino sections translated into English, then pseudonymized. All transcripts were uploaded to NVivo 14 (Lumivero, 2023).

We also administered questionnaires to 60 community members living in, or working in Barangay San Isidro (Fig. 4.2), which was the barangay with the highest rates of collar uptake. Consent was sought from each respondent, who were lent a smartphone to answer a short (5-10 minutes) digital questionnaire hosted on KoboToolbox (KoboToolbox, 2023), a tool for digital data collection. Each questionnaire was given in-person, and surveyors clarified any questions on the respondent's behalf. The questions had five categories: personal information, dog ownership, experience with dogs, perception of collars and understanding of rabies.

Following the MDV, we conducted surveys of free-roaming dogs along White Beach in Barangay San Isidro. These dogs were specifically targeted during the campaign, and were vaccinated and collared with the aid of a dog behaviourist. Free-roaming dogs are regularly observed in White Beach by visiting tourists and residents, and are constantly exposed to natural elements such as sand, saltwater, sunlight/rain and wind, as well as other dogs and people. Surveys were conducted to assess collar durability. Each sighted dog was photographed and its descriptive characteristics, including the presence or absence of a collar, were recorded using the WVS App (Gibson et al., 2015). Five transect surveys were performed between June 2023 and March 2024 along the 2-km coastline.

4.4.4 Data analysis

To analyze the transcribed semi-structured interviews, a descriptive codebook was developed with inductive codes generated to categorize answers based on commonly discussed topics (such as community feedback, understanding of rabies, issues during the event). Research team members (MY and TA) then used thematic analysis combined with Normalisation Process Theory (NPT) to classify quotes deductively under four core constructs, with any conflicts resolved through discussion.

NPT is a tool for understanding how new healthcare technologies become routinely embedded in practice (Murray et al., 2010). By providing a framework through which an implementation can be reviewed, NPT is a sociological theory that explains how new practices, interventions, or technologies become routinely embedded ("normalized") in everyday work, especially in healthcare and organizational settings. As it focuses on the collective work people do to implement, embed, and sustain innovations in practice, NPT has been used in qualitative research to evaluate public health interventions, including new approaches to vaccination campaigns (Lillvis et al., 2020, Laing et al., 2022) and dog rabies control measures (Duamor et al., 2023). Integration of collars into the Puerto Galera vaccination campaign was the first time the intervention was delivered and evaluated in the Philippines. Thus, the feasibility of collars in becoming routinised in mass dog vaccinations was understood using the sixteen sub-components of NPT (See Supplementary Table 4.2 for summarised results and Table S7 for full results with example quotes). These are constitutive of the top four main NPT components: coherence, cognitive participation, collective action, and reflexive monitoring. The aforementioned components assessed how implementers and community members understood the use of collars, their willingness to engage others in using collars on dogs, their ability to apply collars and modify collar application, respectively. Additional components that enabled or challenged the successful integration of collars into MDVs were examined from practitioner responses.

Encoded answers from the questionnaires were anonymized and tabulated to determine prevailing attitudes towards dogs, collars and rabies. Variation in perceptions was assessed qualitatively by comparing them with results from observation notes and semi-structured interviews. For the dog surveys, percentages of sighted dogs wearing collars were used to calculate the rate of collar loss over time. Observations of dog activity during surveys and signs of collar wear and tear were also noted.

4.4.5 Ethics approval and consent to participate

Research Ethics were secured from the University of Glasgow [#200220420] and the Research Institute for Tropical Medicine – Department of Health [IRB No. 2023-26]. MDV practitioners and community members were provided information sheets detailing the purpose of the study, and written consent was obtained from all participants prior to interviews and questionnaires.

4.5 Results

Observations during the MDV provided evidence of practitioners applying collars with minimal difficulty, and acceptance of collars among dog owners. Interviewed practitioners believed that the collar application was a success and can be expanded to other Philippine settings. They highlighted positive reception from dog owners as evidence of the collars' benefits among the local community. Community members who answered questionnaires consisted mainly of San Isidro residents, majority of which were dog owners (Table 4.1). Most knew that the presence of collar on dogs indicated that it was vaccinated, but their attitudes and behaviors toward dogs were ambivalent regardless of whether the dog was collared or not. Summarized findings exploring the feasibility of collar use in MDVs based on observations, semi-structured interviews and questionnaires were categorized under the four constructs of NPT (with four sub-domains each) within Table 4.2. Transect surveys showed substantial collar loss among free-roaming dogs in White Beach, Puerto Galera, within four months.

Table 4.1: Summary table of questionnaire respondent characteristics. Community members living or working in Barangay San Isidro were administered questionnaires for assessing their attitudes toward dogs, post-vaccination collars and rabies.

Community member responses		**Frequency (%)** (*n = 60*)
Age	18-25 years old	2 (3.3%)
	26-40 years old	19 (31.7%)
	41-60 years old	30 (50.0%)
	Over 60 years old	9 (15.0%)
Sex	Male	22 (36.7%)
	Female	38 (63.3%)
Job or profession	Tourism-related	28 (46.7%)
	Transportation-related	8 (13.3%)
	None	17 (28.3%)
	Other	7 (11.7%)
	Shop	4 (6.7%)
	Barangay official	1 (1.7%)
	Laundry services	1 (1.7%)
	Fisherman	1 (1.7%)
Barangay of residence	San Isidro	54 (90.0%)
	Other	6 (10.0%)
Number of owned dogs	None	17 (28.3%)
	One only	26 (43.3%)
	More than one	17 (28.3%)
Dog vaccination status	Recent (<1 year ago)	30 (69.8%)
	Not recent (>1 year ago/never)	13 (30.2%)

4.5.1 Coherence

Coherence refers to practitioners' (vaccinators, recorders and BHWs) and community members' understanding of collars and what they did to achieve that level of comprehension. Questionnaires with community members provided useful information on the degree to which the use of collars during the MDV was understood. 43/60 (71.2%) of community members who answered the questionnaire were familiar with collars and 23/43 (54.8%) believed other residents knew what collars signified, but 8/47 (17%) did not correctly identify collars as markers for rabies vaccination. One owner removed the collar, claiming they were advised to do so by practitioners, while another only kept the collar until the New Year for their dog to remain leashed during festivities.

Meanwhile, all interviewed practitioners during the mass vaccination and collaring understood the significance of collars as markers of vaccination status.

> *"If you see the collar, and your kid gets bitten, you feel at ease because the dog was vaccinated."* –Barangay Health Worker-1

Those with previous vaccination experience demonstrated 'Differentiation', understanding of how the intervention differs from usual practice: they realized that the additional task of collaring necessitated that slightly more time was spent with each individual dog. Notably, they emphasized that this did not lead to fewer dogs vaccinated, as the number of total vaccinated dogs was higher compared to the previous year's MDV.

> *"The nice thing about the collars is that they are a regular reminder to those that encounter, or were given collars for their animals, that they're vaccinated and that they were given proper attention by the team that volunteered here in Puerto Galera led by BI, with the collaboration of the LGU [local government unit]."* –Government Staff Member-1

Practitioners recounted their 'Communal Specifications' (shared understanding of how to successfully implement collars), emphasizing the intersectoral coordination that was essential for MDV. This consisted of meetings and discussions with multiple volunteers, partners and stakeholders leading up to the event, and teamwork between vaccinators, recorders and BHWs in ensuring dog vaccination and collaring. They were fully aware of their 'Individual Specifications' (actions that helped them understand their specific responsibilities): vaccinators handled dogs, recorders collected demographic data and BHWs guided the team and communicated with dog owners for consent to vaccinate and collar their pets.

Understanding of collar benefits differed based on practitioners' roles: government staff viewed the collars as evidence that community dogs are well-cared for by the municipality, while non-government practitioners mentioned that collars highlight dogs that are safe to interact with, which can improve tourist perception of Puerto Galera. All practitioners collectively recognized the benefits that collars provided to tourists and visitors, exhibiting

‘Internalisation’ or understanding of the intervention’s value, as they felt appreciation from the community for the increased level of care given to dogs, which therefore inspired them to continue MDV. Questionnaire results showed that highlighted that among community members, 37/42 (81%) believed collared dogs could still get rabies and for those asked whether they would seek PEP if bitten by a dog, 39/43 (90.7%) of respondents said yes regardless of the presence or absence of a collar; the most common reason for seeking PEP was because they believed that the collared dog could still be rabid, while some would seek PEP “to be safe/sure”. Remaining respondents said that they would seek PEP because they can’t tell if the dog has rabies, they don’t trust the owner, or because a doctor previously told them that even vaccinated dogs can spread rabies. In addition, some residents answered that they would seek *tandok* (treatment by a local faith healer), and one explained that they would kill the biting dog despite the presence of a collar.

Table 4.2: Results of normalization of collars using the four main constructs of NPT, further subdivided into 16 secondary sub-constructs.

Coherence (sense making work)	**Cognitive participation** (relational work)	**Collective action** (operational work)	**Reflexive monitoring** (appraisal work)
Differentiation Practitioners recognized the differences in applying collars compared to a traditional dog mass vaccination are minimal, just additional time (<1-10 minutes) needed for collar application. Sometimes dogs would have to be restrained twice for collar application which was seen as time-consuming, but worth it for its long-term effects.	*Initiation* Practitioners understood that applying collars requires the cooperation of stakeholders and community members: stakeholders include government and non-government organizations who are trained in vaccination, and are willing to provide funds, resources and/or volunteers. BHWs were viewed as essential because of their knowledge of communities. Community members were willing to have their dog vaccinated and collared, and were able to collar the dog themselves if the dog was difficult to restrain.	*Interactional workability* Practitioners were able to conduct the mass vaccination normally as there aren't many changes needed to incorporate collars. Despite minimal training, vaccinators quickly became proficient in the act of applying collars.	*Systematization* Practitioners believed that collars should be used in other places in the Philippines due to the number of free-roaming dogs.
Communal specification Practitioners believed that their understanding of the purpose and benefits of collars was shared by colleagues and the community, and that collars are meant to signify that dogs are vaccinated to provide a sense of safety to community members and tourists.	*Enrolment* Practitioners planned the mass vaccination and collaring almost one year in advance, and regularly communicated with stakeholders to ensure successful implementation. One BHW took the initiative to inform residents of the upcoming vaccination, so they could prepare their dogs (by tying them) in advance.	*Relational integration* According to practitioners, the new approach was trusted because it was introduced by a collaborator from the previous mass vaccination (Boehringer-Ingelheim). Relationships with the community improved due to free collars and because no negative impacts on owners or dogs were seen.	*Communal appraisal* Practitioners received good feedback from community members and fellow colleagues, with no one reported as having refused the collars. There was positive appraisal from practitioners but while community members appreciated the collars, there were clear misunderstandings, suggesting that collar use would not translate into desired changes.

Individual specification Practitioners understood how to complete specifically assigned tasks and responsibilities related to collar application (vaccinating, collaring, guiding, encoding). One said some vaccinators were unfamiliar with handling collars initially, and had to develop practice in applying them.	*Legitimation* All practitioners believed that applying collars was part of their role in the mass vaccination and that it would help the community. MAOs have continued those roles in the following weeks for community members who missed the event but requested follow-up vaccination for their dogs. BHWs believed their role was essential to bridging the gap between practitioners and dogs and that the community must be covered as much as possible. Vaccination teams would double back to areas which were previously neglected upon owners' request.	*Skill set workability* Practitioners showed that they had the skills and training to deliver the new approach. The only exceptions involved dogs that were too difficult to restrain, owners would volunteer to collar the dog instead. In two barangays, collar implementation was limited due to lack of supplies and lack of manpower.	*Individual appraisal* Practitioners said that collars did not impact on their day-to-day activities following the mass vaccination, except for MAOs, who performed follow-up visits and vaccination. Although they believed that the community was satisfied with the collars and understood their meaning, some residents failed to notice collars or were unaware of what collars signified. Majority who answered the questionnaire expressed lack of interest in changing behaviors toward collared dogs and do not consider vaccinated dogs protected against rabies.
Internalisation Practitioners saw the benefits of applying collars: to show community members that the dog is vaccinated, and to serve as a souvenir of owners' participation in the event.	*Activation* Practitioners understood the process of applying collars: suppliers were prepared, a brief orientation was given to volunteers, and the MDV commenced. For each dog, collars were explained to the owner, then the dog was vaccinated and collared. Practitioners encouraged the use of collars in future vaccinations.	*Contextual integration* The new approach was fully supported by the municipality of Puerto Galera, as well as volunteers from the barangay, provincial, regional and national levels. Supplies (vaccines, collars, food, PPE) were provided by Boehringer-Ingelheim, with additional augmentation by the Provincial Veterinary Office.	*Reconfiguration* All practitioners believed that feedback regarding collars can be used to improve future mass vaccinations. They were free to modify how they worked with collars, and would do so in real-time, with some using scissors to help lock the collar and others having owners collar their dogs if there were signs of aggression. Some left the collars with owners for later use. They suggested improving collar understanding among community members by distributing pamphlets or increasing manpower.

4.5.2 Cognitive participation

'Initiation' is a component under the cognitive participation NPT construct that identifies key individuals who drive the intervention forward and are essential to its success. This was shown in interviews with practitioners who praised BHWs, in particular, highlighting them as instrumental to MDV and collar application as they utilized their knowledge of local areas and communities to ensure access to as many dogs as possible:

> *"We were familiar with the area since we normally do rounds in these areas. Therefore, we knew what routes to use."* –Government Staff Member-3

It was explicitly stated by several practitioners that the absence of BHWs in one barangay resulted in a much lower vaccination coverage and collar uptake, as unfamiliar teams experienced difficulty in finding dog-owning households. One practitioner acknowledged that, compared to owners who present their animals to the clinic for vaccination, some community members were less rabies-aware, with some even unwilling to have their dog vaccinated because they saw the vaccine as harmful or causing changes in dog behaviour. BHWs admitted helping convince community members to allow vaccination and collaring of their dogs. When answering the questionnaire, owners who did not have their dogs vaccinated were not able to do so often due to logistical reasons (difficulty in transporting dog, event too far or set at an inconvenient time) but wanted to do so. The presence of dog owners was viewed as essential for vaccinators as they were requested to restrain their own pets. Occasionally, owners were taught on-the-spot how to collar the dog themselves if the vaccinator considered the dog too difficult to handle. Based on the questionnaire, at least one owner was given a collar but could not apply it.

> "*There were those who volunteered [to put the collars], especially when we couldn't get close to their pets, since they were familiar with and 'friends' of those free-roaming dogs.*" –Government Staff Member-2

All practitioners demonstrated ‘Legitimation’ by viewing collar application as a legitimate aspect of their role. In terms of ‘Enrolment’ (changing relationships to accommodate collaring), they recounted their willingness to engage with others to vaccinate and collar as many dogs as possible: practitioners would return to households upon the request of owners despite the additional time and effort needed, and BHWs informed residents in advance so that owners could leash dogs in preparation, thereby reducing the time spent locating and restraining the dog. ‘Activation’ (ability to define the procedure for successful collaring) was demonstrated by vaccinators in particular, who found the demonstration session on collars held by BI to be fulfilling. Their confidence increased from practicing their skills at dog handling, vaccinating and collaring, allowing them to sustain the activity and remain involved for all three days of the MDV:

> “*It was just a matter of talking to the owner civilly about what it was for. And so that we could learn to apply [the collar] quickly, we tested it first to see how it locked in place. We got it immediately.*” –Government Staff Member-2

4.5.3 Collective action

Practitioners considered the ‘Interactional Workability’ (activities done together to integrate collars into MDV) easy, and reported no issues. They received no complaints or refusals from community members, indicating that the collars were acceptable. One practitioner added that owners were satisfied to know that their dog was protected against rabies for at least one year, expressing increased sense of safety among the local community. Applying collars did not significantly increase the time spent vaccinating individual dogs; each dog required between one and five minutes to vaccinate and collar, with the duration determined by the dog’s level of calmness.

> “*When putting on the collar, it was really easy, around five minutes or less. Not more than that, as long as the dog wasn’t going wild. When it came to vaccinating, it was also easy, mere seconds. But there were times that the animal couldn’t be injected or the owner couldn’t secure the pet, which would take long.*” –Government Staff Member-4

> "*No one protested. In fact, they liked it. A souvenir for their dog.*" –Government Staff Member-3

Practitioners highly recommended collar use in more widespread mass vaccinations in the future, specifying that the colours used should remain consistent for each year to avoid confusion across communities. They understood that government support is necessary for continuing collar application:

> "*I think if there's enough budget from the government or from those willing to support it, like NGOs, it would be nice for [the collars] to be recommended to other LGUs so that people would be more informed as to what this program's purpose.*" –Government Staff Member-5

Advantages and difficulties using the house-to-house approach to MDV were described, with practitioners acknowledging that any MDV challenges affect collar application by default. Therefore, the success of collaring across barangays hinged on whether house-to-house vaccination was performed efficiently by the vaccination teams assigned to cover them. One vaccinator noted that house-to-house vaccination reduced injuries among dogs:

> "*It's bad to gather in one spot. The dogs start fighting.*" –Government Staff Member-3

According to one practitioner, their team managed to visit 60 households within three hours. A practitioner who had informed residents of the impending mass vaccination reported a proactive response from the local community, wherein owners bathed and tied their dogs in preparation. Another practitioner reported that, although they informed residents of the MDV in their local group chat, some community members claimed that they were not visited or informed (which was reiterated by one resident during the questionnaire). While there were practitioners who declared that they had covered all households in their assigned area, some admitted that it wasn't possible to visit houses that were less accessible (as they could only be reached by climbing, or had no paved paths leading to them) due to time constraints:

> "*[We need] more vaccinators, to cover more – so that we can do it house-to-house again. Increase the number to a lot more, to make sure that more houses are visited. Especially in places like ours, which are deeper in the forest, and are more elevated. Those weren't fully covered.*" –Barangay Health Worker-2

> "*There were some areas we couldn't get to because they were too remote. [...] especially those in the mountains. They said they weren't visited. [...] Maybe it's because the routes to get there are difficult to traverse. The roads aren't as accessible.*" –Government Staff Member-3

In one barangay, few BHWs were available to assist vaccinators on the day of the scheduled vaccination. Without local guides, practitioners reported having difficulties navigating the barangay, searching for dogs to vaccinate, resulting in low numbers of vaccinated and collared dogs compared to other barangays. BHWs' knowledge of the local area ensured accessibility to owned dogs for successful house-to-house vaccination:

> "*When you went to an area, you had a guide so that you wouldn't get lost, so I think it was well-planned and well-coordinated with the LGUs.*" –Volunteer Recorder-2

All vaccinators achieved 'Relational Integration' (knowledge that allowed them to maintain confidence in collaring) as they were resolute in each other's abilities to apply collars despite minimal training, although one suggested using a practical demonstration involving real dogs when teaching less experienced vaccinators in the future. Some commented on the varying quality of collars, as certain collars were stiffer than others, which made locking them more difficult. Vaccinators developed their own individual techniques for applying the collars:

> "*We'd use the end of a [pair of] scissors to lock it.*" –Government Staff Member-4

Vaccinators relayed instances of owners requesting them to double back to a house that had been missed due to the owner's absence at the time. However, in one barangay, a practitioner reported the delayed arrival by a vaccination team from a previous barangay, where they had taken longer to finish vaccinating and collaring. While some residents waited and expressed their gratitude at being provided veterinary services and collars for

Figure 4.3: A team of two vaccinators and one recorder collaring a dog. Consent was obtained from all individuals in the photo.

free, showing confidence in practitioners to vaccinate and collar their dogs despite delays, feedback was less positive from residents who claimed they had not been told of the event in advance. These complaints were refuted by BHWs. Other practitioners reported that some BHWs were more compelled to guide vaccination teams toward their own residences, due to their greater familiarity with those areas.

'Skill set workability', or allocation of roles for vaccination and collaring, were clearly defined. Practitioners acknowledged that each role (vaccinator, recorder and BHW) within a vaccination team had the sufficient skills to complete their assigned tasks (Fig. 4.3). Vaccinators noted that BHWs used long-standing relationships with communities to encourage residents to take a more active role in rabies control, as following the event, more people have reported suspicious animals for sample collection and testing. Veterinarians also provided pet ownership guidance to residents:

> "*It played a big part to have vets who accompanied us and explained the purpose of this, and they were able to express their concerns about their pets, so generally, the feedback was very positive. And there was overwhelming support from the community.*" –Government Staff Member-5

'Contextual Integration' or management of resources and procedures related to collars was facilitated by advanced and comprehensive planning in collaboration with private organizations/NGOs and government departments on all levels (barangay, municipal, provincial, regional and national), through which volunteers and vehicles were sourced. Approval and support from the mayor enabled coordination on a community-level with barangay officials and the use of vehicles for transporting practitioners between barangays. Collar quality and ease of application were praised by a practitioner who had experienced a previous vaccination and collaring event in 2014, where collars had been made of different material, which greatly increased the time spent on applying them to dogs:

> "*The material was different. It wasn't like this one. So, it was somewhat harder and more durable [before], I would say, because it was made of wire. [...] But it took longer to attach. So the material used now is good, because it's easier to apply, relatively, and then it's a nice material anyway, unlike the snap-ons, wherein one tug and it's easy to remove.*" –Volunteer Recorder-1

However, some practitioners faced resource challenges, having been impacted by insufficient manpower, collars and vaccines in areas where demand was underestimated. With only a limited number of volunteers, practitioners relied on community members to help restrain dogs, although two owners admitted that their dogs were too difficult to restrain.

> "*When it comes to vaccination, it was relatively challenging. There were a lot of us, but the problem is that it took place on three consecutive days, so it was quite tiring, because of the intense heat. And concerning the collar application, sometimes it was better for us and the owner if they applied the collar. But with free-roaming dogs, there were a number that we couldn't collar. We were able to collar some that were friendly to certain humans who could restrain them. The ones that weren't collared were the ones that were just too difficult to handle.*" –Government Staff Member-2

Since the event was limited to three days, fewer than 100 vaccinators were tasked to cover all 13 barangays within that timespan, leading to fatigue, injury and heatstroke, which caused at least one practitioner to stop vaccinating. Another practitioner was unaware of the possibility of traversing rocky terrain, and was therefore dressed inappropriately, which hampered mobility. Teams were assigned to two barangays per day, and were expected to transfer to the next barangay at a scheduled time regardless of whether they had fully covered the first barangay. Some teams delayed their departure to complete their tasks, and would arrive at the next barangay at a later time:

> "*Yes, we were told it wouldn't push through at the scheduled time. We would do it in the afternoon instead because our companions hadn't finished vaccinating [other areas] yet.*" –Barangay Health Worker-1

> "*There were some places that weren't visited. Next time, if it's going to be done house-to-house again, there should be more vaccinators.*" –Barangay Health Worker-2

Miscommunication, at one point, caused an overlap of vaccination teams in the same area, for which one practitioner recommended the use of walkie-talkies. Practitioners were also limited on how many collars to bring, dependent on how many they could physically carry. There were instances wherein the number of collars was insufficient, requiring delivery of a new shipment on the second day of the event:

> "*I'd just estimate how many [collars] I expected to use, which was difficult. I was basing it on the estimated dog population in that area, how many should I bring. Sometimes, it wasn't enough.*" –Government Staff Member-3

> "*What happened was, the other collars arrived rather late, since we realized that the volume of dogs vaccinated was much higher than anticipated, so many more collars were needed.*" –Government Staff Member-2

4.5.4 Reflexive monitoring

Effects of collars on community members on their dogs was evaluated by practitioners solely through informal 'Systematization' (feedback collection), in which responses by dog owners after vaccination of their pets were noted. Lack of complaints, sightings of collared dogs and requests for repeat visits were interpreted as positive reception. Practitioners believed that collars benefited dog owners, tourists and children, and predicted that human-dog relationships were predicted to improve. One practitioner specified that collared dogs would be less likely to be killed after biting a human due to their known vaccination status.

> "*The dog owners became more responsible when it came to pet ownership. Also, the barangays realised that control, not just vaccination, is very much needed for their local dog populations. And public safety, especially for tourists and locals, is very important. So the community was enlightened with regards to the mass vaccination we're doing."* –Government Staff Member-5

Practitioners reported 'Community and Individual Appraisal', wherein they evaluated the collars' impacts as groups and as individuals, by comparing the MDV to the previous year's. They described positive outcomes from working with a dog behavioural expert to catch free-roaming dogs, instead of using nets (which was deemed time-consuming and ineffective, and received negatively by the community last year). By nearly doubling the number of dogs vaccinated in the previous year, and receiving gratitude from residents for using a house-to-house vaccination approach, practitioners admitted to placing more value on collaring despite the increased physical exhaustion.

> "*I think it's much better to do it house-to-house to be able to visit all dog owners. Because that's really what the people want. Others don't really want to have to transport their dog, such as those in our area, because they're free-roaming.*" –Barangay Health Worker-1

Some practitioners observed fewer numbers of free-roaming dogs following the event, likely because some owners specifically asked for collars to make it easier to leash their dogs. While dogs seemed comfortable wearing the collars and there were no reports of dogs suffering adverse effects, one practitioner expressed concerns:

> "*Long-term use of the collar may result in contact dermatitis, especially in dogs that are not regularly bathed by their owners. But on that note, [collars] benefit dogs on a societal level because of the community acceptance gained from wearing the collar.*" –Volunteer Veterinarian-1

Meanwhile, some community members believed their dogs were not comfortable with collars as they became targets for biting from other dogs. At least five owners whose dogs lost collars admitted that the collars were bitten off, while three said the collar broke on its own or fell off. Among dogs that were observed with collars during transects conducted after the MDV (n = 38), only four were seen collared three months later during the repeat transect, and this halved to two after one month. From over half of dogs sighted wearing collars originally, less than 5% of dogs still wore collars four months post-vaccination, indicating a 44.5% collar loss rate per month. Observations during transect surveys more than one month after the collaring event revealed multiple instances of collar damage (Fig. 4.4). While there was collective agreement among practitioners on the usefulness of feedback for future implementation in MDV, 'Reconfiguration', or modifying the practice of collar application based on assessments, was suggested but not to increase durability. Practitioners had presumed that collars would be long-lasting, as noted in the Theory of Change (Fig. 4.2). Different collar colours were recommended for use in following years, as well as modification of collar material for easier application:

> "*The collar was too rigid. It was too stiff... [...] Maybe the material should be changed to rubber instead, but it might get too brittle when it's hot. [...] Something like rubber, or leather. [...] Something that's easier to fasten. But then again, it might not be able to withstand the heat or rain.*" –Government Staff Member-3

One practitioner recommended collaring cats as well while another suggested the use of muzzles for aggressive dogs to protect the owner while the pet is restrained. Several practitioners suggested distribution of written materials that provide information on collars, as well as heavier targeting of free-roaming dogs, which would require training in free-roaming dog vaccination to augment the use of a dog behavioural expert for approaching free-roaming dogs.

Figure 4.4: Examples of collar outcomes: (A) Collar removal through biting, with the dog in the background, reported by owner. (B) Various examples of collar damage. (C) Two remaining collared dogs sighted in White Beach, five months post-vaccination.

4.6 Discussion

The learnings from this feasibility study highlight the varying impacts of collar use in dog vaccination, with the greatest positive effect seen on vaccination teams, whose confidence and valuation of work increased from the ease and speed of application. According to practitioners, this led to achieving a high number of vaccinated dogs and acceptance by residents, although the positive effects were likely confounded by the use of house-to-house vaccination over central point vaccination. Practitioners' assumption that communities understood vaccination's protective effect on dogs (as noted in the Theory of Change) was contradicted by community member responses to the questionnaires. Community members' perception of collars was skewed by lack of rabies knowledge, and although the majority were aware of the collar's meaning, behaviour toward collared dogs was unchanged due to the incorrect assumption that even vaccinated dogs can become rabid. Dogs were not adversely affected by collars, but owner observations and surveys revealed that collars were not long-lasting (despite previous expectations outlined in the Theory of Change) as they are easily susceptible to damage by dogs and natural elements.

Despite the incorporation of temporary collars for mark resight surveys in past dog population and vaccination coverage studies (Childs et al., 1998), there remains a notable knowledge gap with regards to the effect of collar application in mass vaccination and how it impacts practitioner efficiency and community member behavior around dogs, including after dog bites. Apart from our findings, there is currently no literature centred on the longevity of collars when worn by dogs, although one study does note that up to 40% of collars were lost over a four-day study period (Cleaton et al., 2019). The collars used were also made of plastic, and advertised to last for up to three months (TabBand, 2025). Thus far, only two studies have analysed the effect of vaccination collars on community perceptions toward dogs (Minyoo et al., 2015; Omar et al., 2023).

4.6.1 Practitioner outlook on acceptability and appropriateness of collars

Vaccination teams deemed the collars useful and appropriate, as collaring provided more meaning for their work and served as a visible marker and reminder to community members of their efforts. As one of the goals of the vaccination campaign was to improve vaccine coverage in Puerto Galera (see Fig. 4.2), the increased number of vaccinated dogs compared to the previous year, and the depletion of vaccine and collar stocks (requiring a second round of replenishment) were considered evidence of successful vaccination and collaring. Unlike in previous years, there were no reports of owners refusing vaccines (which occurred occasionally due to fears of negative side effects). However, the change of vaccination method from central point vaccination to house-to-house vaccination is likely to have played a significant role in increased vaccination and collaring uptake, as widespread collar acceptance as noted by practitioners was attributed to vaccination teams visiting owners at their homes, with collars viewed by owners as an additional perk, souvenir or "freebie". Notably, some residents approached practitioners to request for collars for younger dogs or cats. But because collaring was performed in all barangays, no direct comparisons of vaccination coverage and collar acceptance can be made to barangays without collars, and this would require further study. It is therefore difficult to determine whether the inclusion of collars in particular improved vaccination acceptance among dog owners.

While the additional task of collaring made the MDV more time-consuming and fatigue-inducing, vaccinators were able to deliver the intervention with minimal training (with most being self-taught), and viewed collar application as a manageable task that helped increase their confidence in dog handling and vaccinating. Owners of aggressive dogs were trained on the spot to apply collars if the vaccinator was unable, with no reports of refusal or injuries. Practitioners understood the value of the practice as they anticipated positive effects on dogs, residents and tourists, and therefore believed that collar use should be sustained in Puerto Galera in following years. There were also recommendations that collaring should be expanded to other Philippine municipalities, and long-term benefits for the community were expected, including a decrease in biting incidents and rabies-positive dogs.

Collar shortages in one barangay did not negatively impact vaccination coverage, but challenged one assumption in the Theory of Change that collar supply was sufficient for the number of vaccinated dogs. Miscommunication impeded house-to-house vaccination in a separate barangay–as BHWs were not available to guide vaccination teams to dog-owning households–which led to markedly decreased vaccination coverage and collar uptake. This showed that the role of community leaders is severely understated in house-to-house vaccination: BHWs were essential in informing the community in advance, and closer ties to the community indicated better outcomes for vaccination coverage, and therefore, collaring. As highlighted by practitioners, success of collaring was directly proportional to the effectiveness of house-to-house vaccination, as central point vaccination had previously led to community member complaints, fewer vaccinated dogs and spatial gaps in vaccination coverage resulting in animal rabies cases. However, house-to-house vaccination requires far more resources (including vehicles, manpower and vaccines), which are procured through LGU partnerships with corporations like BI. Without a sponsor, it is more difficult for municipalities to deliver an intervention such as collars due to the limited budget allotted toward rabies control.

4.6.2 Community attitudes toward collars

Feedback from community members in the previous year consisted of complaints regarding difficulty reaching vaccination sites and follow-up visits to government staff, requesting visitation of owners' homes to vaccinate their dogs. This year, evaluation of community response to collars was not planned (although support was readily provided to fulfill the aims of this study). BHWs, who recounted the complaints of some dog owners during and after the collaring, had no further communication with practitioners after the event and therefore did not share the feedback received from their community or their own personal assessments of the event. Instead, the lack of immediate negative reception regarding collars reaffirmed the intervention's success for practitioners.

While the meaning of collars was understood by majority of residents, including non-dog owners, some questionnaire participant responses were contrary to practitioner assumptions that the purpose of collars (as semi-permanent signifiers of rabies vaccination status) was sufficiently explained. Some owners professed to removing collars due to misunderstandings or did not apply them despite promising to. This could have been prevented through prior community sensitization instead of introducing and explaining collars verbally on-the-spot, as previous complex interventions have shown how effective engagement of communities for MDVs enhances coherence to ensure full benefit of the intervention (Duamor et al., 2023). Furthermore, pre-existing misconceptions about rabies indicated that community behavior toward dogs remained mostly indifferent. Similar results were seen from collar use in Tanzania, where most respondents knew the collars' purpose, but only half expressed their willingness to interact with collared dogs (Omar et al., 2023). It should be noted, however, that our questionnaire specifically included questions about respondents' understanding of rabies and probable actions in cases wherein collared dogs are aggressors, which were not asked in Tanzania. Most community members believed that dogs are susceptible to rabies infection even when vaccinated, confiding that they would exhibit similar health-seeking behaviour regardless of whether the biting dog was collared (vaccinated) or not (unvaccinated).

Although few community members were willing to interact with an unfamiliar dog in the first place, common health-seeking behaviours after biting incidents include pursuing ineffective traditional medicine such as *tandok*, which is often substituted for PEP and has enabled human rabies deaths within the region (Yuson et al., 2024). It has been noted that continued practice of *tandok* in the present day stems from a reliance on indigenous knowledge when accessibility to education and healthcare are limited (Alfonso, 2023). During an educational campaign coinciding with the MDV, collaborating partners hosted lectures about rabies for middle school students. While this is expected to increase rabies awareness in children, community member responses indicate that the lack of rabies knowledge among adults should also be addressed as these beliefs continue to be enforced on children, who typically make up almost half of bite patients (Swedberg et al., 2023).

4.6.3 Assessing collar longevity

Collars displayed limited durability, and instances of collar damage and loss were observed within one month of the vaccination event. Dog owners observed instances of collars breaking or getting bitten off by dogs. Collared, free-roaming dogs observed on White Beach gradually lost their collars within three months of application, and notable signs of damage such as dirt/sand, tears, cracks (due to exposure to natural elements) and bite marks (due to other dogs) were observed in collared dogs that would eventually be seen collar-less a month later. It is notable that, of the two dogs whose collars remained after five months, one of them was a free-roaming dog that spent majority of its time in the premises of a roofed cafeteria and did not seek interaction with other dogs. That collars were lost soon after vaccination prevented any possibility of long-term benefits for the community. Collars were therefore not included in the following year's MDV. Plastic collars used in two other studies were not intended for long-term use, with one of the studies reporting a 6.8% collar loss within two days (Léchenne et al., 2016; Sambo et al., 2022). A more durable material would be appropriate for a collar meant to be long-lasting, but the cost of production would most likely exceed the current value of €0.10 per collar.

4.6.4 Strengths and limitations

Implementation research was useful in this study as it developed the programme theory of the intervention (as visualised in the Theory of Change), thus defining the intervention's expected outcomes and impacts and clarifying underlying assumptions. We used different sources of data collected via several methods (observations, interviews, questionnaires) to examine practitioner and community perspectives, which helped in assessing the extent to which outcomes were met and if assumptions were reasonable. We were therefore able to identify challenges in collar application and its benefits in relation to house-to-house vaccination, which are not present in other literature. Recognizing these immediate effects and projected outcomes allowed us to suggest modifications for collar use in future MDVs, namely that collars should be durable, fast and easy to apply (particularly on free-roaming dogs), and transportable in large quantities when traveling on foot. Further research and development should be conducted to develop alternatives to collars and other interventions that can address human-dog behaviours that reduce rabies risk. Communities should be consulted on a larger scale before and after the intervention, as collar acceptance was only assessed in this study by collecting feedback from a small subgroup of residents. Our study on collars as a complex intervention can serve as an example for better-designed interventions in the future, so that potential challenges and oversights may be avoided in developing an intervention that is meaningful, sustainable and rigorous.

By focusing on residents in White Beach, San Isidro, we were not able to fully explore other sociocultural factors (such as religion, education and socioeconomic status) affecting community perspectives on collar and rabies. Therefore, certain findings may not collectively represent some communities in Puerto Galera, including Muslims, to whom dogs are not typically kept as pets due to their perceived impurity (Berglund, 2014), and Mangyans, indigenous communities in Oriental Mindoro whose perspectives have yet to be studied.

4.6.5 Conclusion

Practitioners easily integrated collars into dog vaccination as they viewed the activity as meaningful due to its perceived benefits for the community. In turn, increased confidence in vaccinating and collaring led to higher efficiency, resulting in higher vaccination coverage. Challenges to conducting house-to-house vaccination, which included depletion of supplies, difficulty accessing rural areas and aggressive dogs were found to have negatively impacted collar uptake in areas where fewer dogs were vaccinated. Although practitioners were willing to sustain collaring the following year (which was also originally intended by the collar provider), evidence from dog sightings and community response shows that the collars are extremely vulnerable to environmental and dog damage, with most lost within four months of the intervention. Collar quality should be improved, with more robust materials used to better withstand dog bites and natural elements, if collars are to be adopted and sustained in future mass vaccinations. In potential studies, tourist perceptions on collars would be useful in measuring collars' impacts on a subgroup that is mainly affected by the proliferation of free-roaming dogs. Lastly, our findings show that collars did not have a significant effect on human attitudes toward dogs, but informed us that local emphasis currently needs to be placed on improving community knowledge, awareness and engagement regarding rabies rather than investing in expensive technology. While integration of collars is well-understood by practitioners, the gap with communities about the meaning of collars and how MDV provides protection is a key barrier to obtaining benefits such as improved vaccination coverage from increased vaccine acceptance and fewer bite incidents from community avoidance of non-collared dogs.

Chapter 5

Estimating vaccination coverage in free-roaming dogs using collars

5.1 Author contributions

I designed the study reported in this chapter. Specifically, I designed the transect surveys, trained the enumerators and also participated in the data collection, performed the statistical analysis and modelling, created the figures, and wrote the manuscript.

5.2 Abstract

Free-roaming dogs are common in rabies-endemic countries in Africa and Asia, including the Philippines, where over 300 human rabies deaths yearly are caused by dog bites. According to WHO and partners' global strategy "Zero By Thirty", dog-mediated human rabies deaths can be eliminated by sustaining a dog vaccination coverage of 70%. Following a mass dog vaccination, we conducted transect surveys of dogs throughout Puerto Galera municipality in Oriental Mindoro province, Philippines to determine vac-

cination coverage based on the presence of collars that were applied to vaccinated dogs. Comparison of various approaches to estimating dog populations revealed that the number of free-roaming dogs is severely underestimated in the Philippines. With vaccination geared primarily toward owned dogs, our findings showed that only 17.4% of free-roaming dogs and 26.4% of restrained dogs were vaccinated, indicating a low vaccination coverage overall. In one village where free-roaming dogs were specifically targeted, the vaccination coverage achieved was estimated to be higher (38.5%). By targeting free-roaming dogs during vaccination campaigns, coverage would increase and significant progress would be made towards achieving the "Zero By Thirty" goal.

5.3 Introduction

Rabies is a viral, zoonotic disease that is most commonly transmitted to humans via dog bites. Free-roaming dog populations are sources of dog-to-human transmission in rabies-endemic countries (Conan et al., 2015; Rahaman, 2017; Acharya et al., 2012), causing thousands of human rabies deaths per year in Africa and Asia. While free-roaming dogs are sometimes referred to as stray, feral, community or street dogs, not all free-roaming dogs are ownerless. Free-roaming dogs have owners in some countries, and may visit familiar homes for feeding, but otherwise have unfettered access to public spaces, whereas a subset of free-roaming dogs consists of unowned strays or feral dogs which may interact with the community but are otherwise unclaimed as no resident takes charge of their care (Arluke & Atema, 2015). The lines of ownership are often blurred, as reflected in various dog population studies—in Bali, >80% of free-roaming dogs are considered owned (Morters et al., 2014), whereas high numbers of free-roaming dogs in India are actually unowned (Belsare & Gompper, 2013). The existence of such dogs makes dog population estimation challenging due to their exclusion from household surveys and high population turnover, which can lead to underestimations or overestimations of rabies vaccination coverage (Meunier et al., 2019).

Dog populations are generally estimated using household surveys or transect (mark resight) surveys (Minyoo et al., 2015). When calculating vaccination coverage, mark resight surveys entail marking newly-vaccinated dogs with paint (dye), ear tags or collars. Paintsticks, sprays and wax have been used in mass dog vaccination (MDV) as they are quick and easy to apply, but are temporary (lasting up to two weeks but typically only a few days), less visible on darker-coloured dogs, and require mark resight surveys to be conducted immediately post-vaccination (Undurraga et al., 2017). Ear tags are a semi-permanent marking method that are scarcely used due to the time and difficulty of application and required use of anaesthesia (Czupryna et al., 2023). Collars are low-cost, easy to apply, and can be semi-permanent depending on the material used. They have been used in MDVs to measure dog population density in the Philippines (Childs et al., 1998), calculate vaccination coverage in Haiti (Cleaton et al., 2019) and assess human behaviour toward dogs in Tanzania (Omar et al., 2023).

In the Philippines, a study assessed rural dog population density using transect surveys in 1998 (Childs et al., 1998). Recent local studies have largely focused on estimating owned dog populations through household surveys conducted in various towns or cities, which show that in rural settings, up to 84.5% of owners do not keep their dogs confined or restrained (Valenzuela et al., 2017; Chaudhari et al., 2022). But other than this work, data on unowned free-roaming dogs in the Philippines is scarce. Similar to other low-and-middle-income countries (LMICs), resources for rabies control have historically been limited in the Philippines, so in lieu of surveys, official government guidelines recommend calculating dog vaccination supply based on a Human:dog ratio (HDR) of 10:1 and using this ratio to also estimate vaccination coverage (Department of Health, Philippines, 2012). Recent household surveys in Bulacan province within the Philippines estimated an HDR of 3.7:1 (Dizon et al., 2022). According to the WHO, a 70% sustained vaccination coverage would lead to elimination of dog-mediated human rabies deaths (WHO et al., 2018). However, even when estimated using the 10:1 HDR, vaccination coverages in the Philippines are markedly heterogeneous, ranging from 20% to 80% across regions from 2015 to 2018; all declined sharply when MDVs were suspended nationwide in 2020 and

2021 in accordance with COVID-19 social distancing rules (Yuson et al., 2024). As MDVs resumed in 2022, Boehringer-Ingelheim (BI), manufacturer of rabies vaccine Rabisin for dogs and cats, supported three annual MDV campaigns in Puerto Galera municipality in the Philippines province of Oriental Mindoro. Collars were incorporated in the 2023 campaign to aid in dog population estimation and vaccination coverage calculation. With our findings, we aimed to update dog population and vaccination coverage estimates for Puerto Galera to guide future MDVs, and develop a better understanding of owned and unowned dog population dynamics in the Philippines.

5.4 Methods

5.4.1 Study setting

Puerto Galera (population 42,301) is one of 14 municipalities in Oriental Mindoro, a rabies-endemic Philippine island province (Philippine Statistics Authority, 2025). From 28-30 Sept, 2023 a MDV campaign in Puerto Galera was conducted, during which yellow collars made of polythene and propylene plastic were applied to vaccinated dogs. Between April and October 2023, data was collected from six out of Puerto Galera's 13 *barangays* (villages) (Fig. 5.1). Two barangays were purposely selected: Poblacion, which houses the municipal administrative headquarters, and San Isidro, a popular tourist destination known for its beaches. Four other barangays (Palangan, Santo Niño, Sinandigan and Tabinay) were chosen randomly, and were considered sufficiently representative of all residential barangays in Puerto Galera due to their similar sociodemographic characteristics.

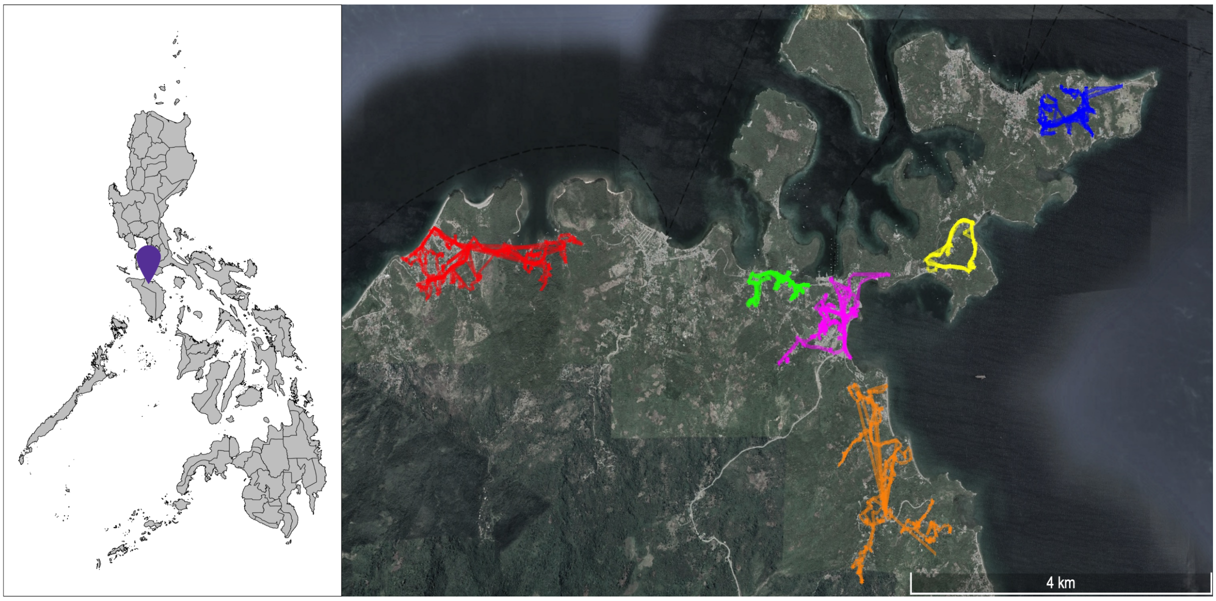


Figure 5.1: Map of the Philippines with Puerto Galera's location designated with a violet marker. Surveys were conducted in six barangays, with each track represented by a different color: San Isidro (red), Santo Niño (green), Poblacion (pink), Tabinay (orange), Palangan (yellow) and Sinandigan (blue). Maps and satellite imagery were provided by Google and Maxar Technologies.

5.4.2 Data collection

Quantitative data in the form of previous 2022 Puerto Galera dog population estimates based on household survey data, and total dogs vaccinated against rabies during MDVs in 2022 and 2023, were provided by the Puerto Galera Municipal Agriculture Office (MAO) and BI, respectively.

Transect surveys of dogs were initially conducted in April of 2023 (five months pre-MDV) during the Philippines' 'dry season', to reduce the likelihood of rainy weather that would have hindered data collection. In total, eleven survey tracks were developed by local community representatives that pass through residential and urban areas where dogs are known to frequent: two each for five barangays, and one for Barangay Palangan, which, due to its small size, could be fully explored with one survey track. Each of these eleven tracks were walked four times in total over two consecutive days (Fig. 5.1). Two survey teams traversed separate tracks in the mornings (8:00 – 10:00 AM) and afternoons (4:00 – 6:00 PM) when free-roaming dogs were most active (with the exception of Palangan, wherein one team completed one track). A few days after the MDV was held from September 28-30 of 2023, the transect surveys were repeated following the same approach.

Survey teams, consisting of one guide and one recorder, were assigned to one survey track per barangay and traveled on foot, following a predetermined route. The guide ensured that the survey track was followed, while the recorder used a smartphone with the WVS App (https://www.wvsapp.org/) installed. The WVS App is a data collection tool that enables the recorder to input individual dog sightings, characteristics and an uploaded picture of the dog. Each dog was photographed and its characteristics (sex, age class, colour, type of collar, new sighting or resight, roaming status) were recorded. A dog was considered a resight if it had been recorded one or more times in previous surveys. For roaming status, dogs that were leashed, tied, in a cage, or behind a fence were considered restrained, and those that were not were classified as free-roaming.

5.4.3 Data analysis

An estimate of each barangays 2022's vaccination coverage was made by dividing the number of vaccinated dogs in each barangay by the estimated dog population based on the household survey data. The household population was divided by the estimated dog population to produce HDR per barangay.

The transect data were used to obtain alternative estimates of the dog population and vaccination coverage, based on mark-recapture methods. For transect survey data, photographs of dogs from the same barangay were examined to verify resights and distinguish them from unique sightings, as both are commonly used parameters in population estimation methods. Upon review, if a dog was found to have been sighted twice or more, but had been mistakenly categorized as a new sighting, all subsequent sightings were reclassified as resights. Estimation of the free-roaming dog population was done using an online Application SuperDuplicates (AS) shinyapp tool (https://Chao.shinyapps.io/SuperDuplicates/) developed by Chao et al. (Chao et al., 2017). AS originally applied the Good-Turning theory frequency formula to assess species richness using only the following parameters: total number of sightings, number of unique sightings and number of surveys. It has since been adapted to estimate dog population size (Tiwari et al., 2018) and was chosen for this study as it is comparably most accurate with least effort, and has been validated in a different population by the same authors (Tiwari et al., 2019). We also estimated the population size using the same data but applying the Chapman estimator, which is a more commonly used mark-recapture method (Chapman, 1951). It has been previously used to estimate dog populations from transects (Meunier et al., 2019), and provided a comparison population estimate for each barangay, which we calculated using the recapr package (Tyers, 2021) in R (R Core Team, 2021). Then, our third population estimation approach consisted of fitting the survey data to a modified Bayesian model (Gsell et al., 2012) that was originally developed to estimate dog population and vaccination coverage in N'Djaména, Chad (Kayali et al., 2003). After using the Petersen-Bailey formula to estimate the owned dog population, we calculated the proportion of owned dogs and incorporated the results together with survey data on numbers of collared (marked) and non-collared (unmarked) dogs into the model. Afterward, we estimated the parameters of the Bayesian model using Markov Chain Monte Carlo simulation conducted through the rjags package (Plummer, 2025) in R (R Core Team, 2021). Since Bayesian inference involves updating prior information with observed data, prior probabilities (including confinement and recapture probabilities) were derived from household survey data and other Philippine-centric literature (Chaudhari et al., 2022), and then used as additional model parameters. Parameter details are available in Supplementary Table S8.

Vaccination coverage was then calculated in several ways, in addition to the estimates based on the household survey dog population estimates and the numbers of dogs vaccinated. We directly estimated of coverage based on observed restrained and free-roaming dogs with and without collars as a marker of vaccination. We also used the sum of our free-roaming and restrained dog population estimates (using the AS and Chapman methods, and Bayesian model) as denominators, and numbers of dogs vaccinated as numerators. We compared all our estimates, including those specific to just free-roaming and restrained dogs.

5.5 Results

Based on household surveys conducted door-to-door in 2022, the mean dog population per barangay was 394 (95% Confidence Interval [CI]: 379.5 – 408.5). Estimated vaccination coverages ranged from 26.5% in Tabinay, to 119.2% in Poblacion, with a mean coverage of 63.7% (95% CI: 56.2 – 71.3). The HDR ranged from 4.4:1 to 18.5:1, and the mean HDR was 9.4:1 (95% CI: 6.3:1 – 12.4:1). On average, 217 (95% CI 210.8 – 232.2) dogs were vaccinated in each barangay in 2022, compared to 369.8 (355.6 – 384.1) dogs per barangay in 2023, with a mean increase of 152.8 (95% CI 132.0 – 173.6) dogs vaccinated. In total, the number of vaccinated animals was 5,289 in 2023, a 119% increase over the previous year's (2,414 animals). Each barangay experienced an increase in the number of vaccinated dogs except Palangan, where there were eight fewer vaccinated dogs compared to 2022. The number of vaccinated dogs in 2023 across barangays ranged from 145 to 583, with a mean of 369.8 vaccinated dogs per barangay (95% CI: 365.6 – 384.1). Dogs vaccinated in 2022 and 2023 consisted primarily of owned dogs due to the presence of an owner who assisted in their capture and restraint. In 2022, plans to vaccinate unowned, free-roaming dogs using nets were canceled due to the excess time required per dog, negative community response and high noise levels from initial captured dogs that caused other free-roaming

Table 5.1: Household survey and vaccination data across six barangays in Puerto Galera.

		Palangan	Poblacion	Santo Niño	Sinandigan	San Isidro	Tabinay
2022	Dog population (household survey)	297	250	297	531	354	635
	No. of vaccinated dogs	173	298	205	212	246	168
	Human population	1,637	5,112	2,838	4,907	5,224	4,069
	Human-to-dog ratio (HDR)	5.5:1	20.4:1	9.6:1	9.2:1	14.8:1	6.4:1
2023	No. of vaccinated dogs	145	314	396	446	583	335

dogs to flee and evade capture. Whereas in 2023, a dog behaviourist assisted vaccination teams in White Beach, San Isidro in the capture of unowned free-roaming dogs. In all other barangays, unowned free-roaming dogs were not similarly targeted. Dog population and vaccination data per barangay are summarized in Table 5.1.

A total of 2,196 unique dogs were observed in the six barangays from the pre-vaccination transects, ranging from 163 dogs in Palangan to 568 dogs in Tabinay; all dogs referred to from here after are considered unique dogs unless otherwise stated to be resights. In Poblacion, Santo Niño and San Isidro, the number of dogs surpassed the dog population reported in household surveys carried out the previous year. Palangan had the least number of dogs observed (n = 163), while Tabinay had the most (n = 568) (Table 5.2). Restrained dogs comprised 44.7% of identified dogs, but were more commonly observed than free-roaming dogs in Palangan and Poblacion. However, in other barangays, free-roaming dogs outnumbered restrained dogs, particularly in San Isidro, where 62.3% (n = 174) of observed dogs were free-roaming (Fig. 5.2). An average of 202.8 (95% CI: 191.6 – 214.1) free-roaming dogs per barangay were identified, compared to 163.2 (95% CI: 153.4 – 172.9) restrained dogs.

The average number of resighted dogs pre-vaccination was 63.3 (95% CI 47.9 – 78.8), with as few as five resighted dogs identified in Tabinay. Using the AS method to estimate the number of free-roaming dogs resulted in a mean adjusted free-roaming dog population of 1,398.3 (95% CI 1,292.4 - 1,504.2) per barangay, although dog population estimates per barangay ranged between 145.1 and 5,662.6 (Table 5.2).

Table 5.2: Pre- and post-vaccination transect data of dogs.

		Palangan	Poblacion	Santo Niño	Sinandigan	San Isidro	Tabinay
Pre-MDV (Apr-Jun 2023)	No. of identified dogs [resights]	163 [67]	369 [52]	311 [190]	323 [33]	462 [33]	568 [5]
	Restrained dogs (%)	96 (58.9%)	185 (50.1%)	150 (48.2%)	99 (30.7%)	174 (37.7%)	275 (48.4%)
	Free-roaming dogs (%)	67 (41.1%)	184 (49.9%)	161 (51.8%)	224 (69.3%)	288 (62.3%)	293 (51.6%)
	Adjusted free-roaming dog population	145.1 (112.6 – 217.1)	444.7 (366.7 – 564.9)	326.9 (291.4 – 381.1)	842.3 (570.3 – 1,342.0)	968.0 (751.4 – 1,293.4)	5,662.6 (1,531.0 – 23,627.0)
Post-MDV (Nov-Oct 2023)	No. of identified dogs [resights]	221 [29]	314 [26]	396 [125]	446 [124]	583 [122]	335 [17]
	Restrained dogs (collars: no collars)	107 (0:107)	199 (54:145)	147 (54:93)	50 (24:26)	213 (83:130)	111 (3:108)
	Free-roaming dogs (collars: no collars)	114 (1:113)	211 (32:179)	174 (24:150)	174 (34:140)	286 (110:176)	270 (13:257)
	Adjusted free-roaming dog population	360.1 (234.7 – 632.9)	922.6 (532.4 – 1,811.7)	491.1 (366.3 – 710.0)	351.4 (326.3 – 390.1)	619.5 (542.1 – 731.0)	1,800.8 (2,033.8 – 3,349.9)
	Chapman estimate of free-roaming dogs	558.7 (407.7 – 709.6)	2,472.3 (1,654.0 – 3,290.6)	550.4 (508.5 – 592.3)	624.8 (575.2 – 674.4)	1,361.7 (1,200.6 – 1,522.8)	5,057.7 (2,919.6 – 7,195.8)
	Bayesian estimate of free-roaming dogs	958 (311 – 2,105)	302 (191 – 449)	427 (244 – 674)	592 (293 – 1,012)	537 (369 – 741)	881 (341 – 1,677)

A follow-up transect survey conducted shortly after the MDV and collar application showed an increase in identified dogs in all barangays except Poblacion, where 314 dogs were observed compared to 369 pre-vaccination, and Tabinay, where 381 dogs were identified compared to 658 previously (Table 5.2). Slightly higher numbers of free-roaming dogs were observed during the post-vaccination surveys (n = 1,229, 59.8%) compared to pre-vaccination (n = 1,217, 55.4%), but fewer dogs were sighted in total (2,056 compared to 2,196). An average of 73.8 dogs (95% CI 61.8 to 85.8) per barangay were resighted post-vaccination. The adjusted free-roaming dog population from use of the AS method ranged from 360.1 to 1,800.8 across barangays, with a mean of 757.6 (95% CI 719.9 – 795.3) free-roaming dogs per barangay. Based on those results, the transect survey failed to detect 3,316.5 or 73.0% of free-roaming dogs. Using the Chapman estimator produced a comparatively higher mean of 1,770.9 (95% CI 1,691.9 – 1,850.0) free-roaming dogs per barangay, while Bayesian estimates resulted in a much lower mean of 616.3 (95% CI 227.4 - 1,549.7) dogs.

Figure 5.2: Group of free-roaming dogs in Barangay San Isidro, pictured during a transect survey.

In terms of vaccination coverage, 21.0% (432/2,295) of total identified dogs were collared, with an average of 72 collared dogs identified per barangay (95% CI: 56.9 – 87.1). Out of 2,219 vaccinated dogs overall, at least 19.5% were seen collared during the transect survey. Notably, only one collared dog (0.5%) was observed in Palangan, with low collar coverage reported in the barangay due to collar supply shortages in that area during the MDV. In addition, low collar coverage was also reported in Tabinay, where only 16 (4.2%) collared dogs were identified, owing to lower vaccination coverage attributed to insufficient manpower (Fig. 5.3). San Isidro, where targeted vaccination of free-roaming dogs took place, had the highest number of observed collared dogs at 193 (38.7%) (Fig. 5.4). 26.4% (218/827) of total observed restrained dogs were collared, compared to 17.4% (214/1,229) of observed free-roaming dogs.

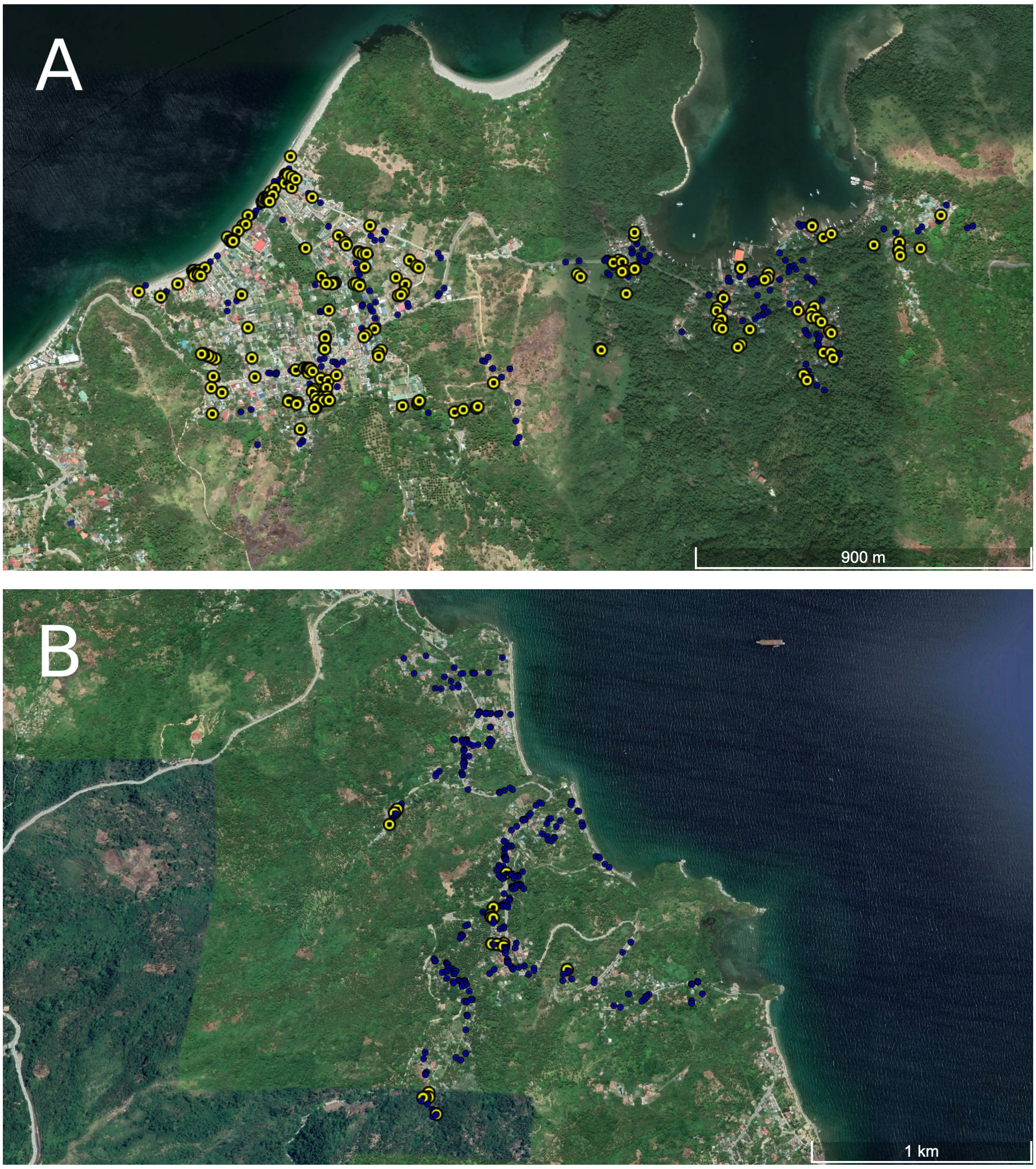


Figure 5.3: Maps of Puerto Galera barangays (A) San Isidro including the coastline of White Beach, and (B) Tabinay, with dots representing non-collared dogs (blue) and collared dogs (yellow). Maps of other barangays are provided in Supplementary Fig. S5.

Figure 5.4: Examples of collared and non-collared free-roaming dogs identified during a post-vaccination transect survey in White Beach, San Isidro.

Vaccination coverage calculated using AS-adjusted free-roaming dog population ranged from 34.0 to 126.9% across different barangays, with a mean of 65.8% (95% CI 56.1 – 75.4%) per barangay. In comparison, using the proportion of free-roaming dogs observed with collars produced coverages of 4.8 to 38.5, with a mean of 18.4% (95% CI 13.0 – 23.6%), although no direct coverage estimate is available for Palangan as its result was not meaningful. Mean coverage for restrained dogs was 30.7% (95% CI 24.9 – 36.5%)

compared to 22.8% (95% CI 18.0 – 27.7%) overall coverage. While mean vaccination coverage based on household survey data was 107.4% (95% CI 98.9 – 115.8%), Chapman estimates produced a mean coverage of 38.6% (95% CI 29.9 – 47.2) and Bayesian estimates produced a lower mean coverage of 8.9% (95% CI 0.4 - 19.0%) (Table 5.3).

Table 5.3: Comparison of several vaccination coverage (%) estimates.

	Palangan	Poblacion	Santo Niño	Sinandigan	San Isidro	Tabinay
Household survey	48.8	125.6	133.3	119.1	164.7	52.8
Collared proportion						
Free-roaming	–	15.2	13.8	19.5	38.5	4.8
Restrained	–	27.1	36.7	48.0	39.0	2.7
Total	–	21.0	24.3	25.9	38.7	4.2
AS estimate	40.3	34.0	80.6	126.9	94.1	18.6
(95% CI)	(22.9 – 61.8)	(17.3 – 59.0)	(55.8 – 108.1)	(114.3 – 136.7)	(79.8 – 107.5)	(10.0 – 16.5)
Chapman estimate	26.0	12.7	71.9	71.4	42.8	6.6
(95% CI)	(20.4 – 35.6)	(9.5 – 19.0)	(66.9 – 77.9)	(66.1 – 77.5)	(38.3 – 48.6)	(4.7 – 11.5)
Bayesian estimate	0.2	10.4	10.8	10.4	20.2	1.5
(95% CI)	(0.1 - 0.4)	(8.1 - 12.9)	(8.1 - 13.8)	(7.3 - 14.0)	(16.2 - 24.1)	(0.9 - 2.2)

5.6 Discussion

Our research findings reflect the challenges in estimating dog population, and consequently, rabies vaccination coverage in the Philippines due to the presence of free-roaming dogs, whose ownership status is often unclear. We find that high numbers of free-roaming dogs result in dog population underestimation and overestimated vaccination coverage, which can cause insufficient vaccine supply. Calculated vaccination coverages based on population estimators were generally lower, with these discrepancies demonstrating how factors such as inconsistent post-vaccination marking and survey track design can skew estimates especially if insufficient effort leads to a small number of resights. These issues may lead to a false sense of security regarding vaccination coverage achieved and therefore progress toward rabies elimination in local areas.

5.6.1 Comparing household survey and vaccination data

Dog population estimates based on a constant HDR value of 10:1 are still widely used in Philippine rabies control programs, despite evidence that dog populations vary depending on the size and type of community (urban, semi-urban, rural) (Moran et al., 2022). Sociodemographic factors such as poverty and religion also impact heterogeneity of dog ownership and HDR across communities (Wallace et al., 2017). Most free-roaming dogs in rabies-endemic countries such as Tanzania (Czupryna et al., 2016) and Indonesia (Morters et al., 2014) are owned, whereas in countries like India, the majority are considered feral or stray (Evans et al., 2022). The existence of these free-roaming dogs has shaped rabies control programs to include unique strategies for targeted vaccination, for example catch-neuter-vaccinate-release (Smith et al., 2025) and oral rabies vaccination (Chanachai et al., 2021). However, neither of these approaches have been performed in the Philippines on a regular basis apart from field trials (Estrada et al., 2001). The question of whether most Philippine free-roaming dogs are owned or unowned was unexplored prior to this study.

To account for variation across barangays, household surveys are sometimes used for dog population estimation but notably exclude unowned dogs (Sambo et al., 2018). Underestimation of dog populations can result in misleading expectations regarding vaccination coverage, which was evident in Puerto Galera in 2022, as the number of vaccinated dogs exceeded the reported numbers of owned dogs in several barangays. The survey results exposed an oversight of informal household surveys conducted in municipalities, in that volunteer community representatives responsible for data collection would tally numbers based on residents' answers to one question only (how many dogs they owned). The answer depended on whether the owner personally considered a free-roaming dog 'theirs'.

Surveyors reported difficulties assigning an ownership status as some free-roaming dogs would voluntarily enter a resident's property, only for the resident to deny being the dog's owner. Additional vaccinated dogs were therefore most likely free-roaming dogs that were not declared by owners during the household survey.

Vaccination data from the previous year (2022) informed the supply of rabies vaccines supplied to Puerto Galera in 2023, but assumptions that the previous vaccination coverage was sufficient for estimated dog populations led to depletion of vaccine stocks on the first day of the MDV. This necessitated delivery of an additional batch of rabies vaccines to Puerto Galera. Although MDV progress was not impeded due to swift response by the organizers, nearly doubling the number of dogs vaccinated from the previous year further highlighted the inaccuracy of household survey-based vaccination coverages. Low HDRs in some barangays, despite the exclusion of unowned dogs in surveys, further emphasized the unreliability of the government-recommended 10:1 estimate. The increase of over 100% in the number of dogs vaccinated in San Isidro can be attributed to purposeful targeting of free-roaming dogs in that area, while conversely, the increase in vaccinated dogs in Tabinay occurred despite limited manpower, underscoring how using previous vaccination data could also lead to population underestimation for the next MDV.

5.6.2 Transect surveys for adjusting dog population estimates

Philippine owners of multiple dogs typically use varying forms of restraint for individual dogs that are determined by aggression level, size, breed or type of human settlement (Chaudhari et al., 2022). It is therefore common to see some dogs restrained outside, others kept inside while the remaining dogs are permitted to free-roam, all within the same household. These ownership patterns were difficult to capture using transect surveys, as they fail to include dogs kept exclusively indoors or in unseen private spaces (Meunier et al., 2019). Fortunately, transect surveys helped fill in the blanks left by household surveys by providing estimations of free-roaming dog populations in Puerto Galera. Overall, that

>1,200 free-roaming dogs—nearly equivalent to the total number of dogs vaccinated there in 2022—were identified across six barangays suggests that they are a much larger part of the dog demographic structure in the Philippines despite being largely ignored in local rabies control programs.

Total dog population estimates that were adjusted using the AS method indicated the presence of at least 3,000 undetected free-roaming dogs, compared to the Chapman estimate of more than 9,000 dogs. While both estimates are highly uncertain, it is clear that substantially more support for vaccination programs is required. Increasing vaccine stocks, manpower and time would necessitate external partnerships for their procurement in low-resourced municipalities in the Philippines, as government support for rabies control measures is typically insufficient (Miranda & Miranda, 2020). Notably, although the mean number of dogs across barangays was not wholly meaningful, Bayesian estimates yielded much fewer dogs per barangay and the lowest overall mean of free-roaming dogs compared to other methods, indicating a reductive effect when confinement probability is taken into account, as fewer available sighted dogs implies a smaller population. Free-roaming dog population estimation through the AS methods produced wide CIs for barangays wherein numbers of resighted dogs were low. A similar pattern was seen from estimations using Chapman's method, which produced much higher estimates in some barangays. The effect of few resights was observably larger compared to the AS method because in closed-population mark-recapture, the precision is driven mostly by the number of recaptures. Hence, higher numbers of resighted dogs are required to get reasonably tight CIs for abundance. Resights were uncommon in sprawling barangays, where clusters of houses are spread out from each other, requiring considerable time and effort to reach. Houses situated in these rural areas were only accessible through narrow, winding paths that are sometimes steep and require climbing. Exact repetition of survey tracks was made difficult by the lack of paved roads in these sectors, which, coupled with expansive forest coverage that provide dogs with large space to roam unseen, could explain why many of them were only seen once. The differences between estimates pre- and post-vaccination highlight the inconsistency in some barangays, which reinforces that more effort is needed to pin down estimates.

5.6.3 Calculating vaccination coverage

Household surveys, while easy to perform in low-resourced areas, vastly overestimate vaccination coverage achieved in comparison to other approaches. In Puerto Galera, Household surveys were done informally, through casual conservations with residents, which may explain inaccurate findings. These led to multiple >100% coverage estimates which indicate owners presenting more dogs for vaccination than what they initially declared. In other studies, household survey data were collected using best practices and methodological approaches, which included detailed questions concerning dog ownership (such as how many dogs are permitted to free-roam vs how many are restrained) (Dizon et al., 2022). If implemented in Puerto Galera in the same manner, population and coverage estimates may improve assuming that most free-roaming dogs are owned.

For the mark-resight survey, few sightings of collared free-roaming and restrained dogs compared to non-collared dogs indicated low vaccination coverage for both groups. Despite hugely increased coverage compared to the previous year, many restrained dogs in particular were seen non-collared, and thus presumed unvaccinated. At least 1,015 or majority of free-roaming dogs seen were similarly collar-less, with San Isidro as the only barangay where coverage in both free-roaming and restrained dogs was observed to be nearly equal (almost 40%). Targeted vaccination of unowned, free-roaming dogs in White Beach, San Isidro produced a substantially higher vaccination coverage compared to other barangays, exemplifying the advantage of including unowned dogs in MDVs. Compared to other methods used in this study, estimating coverage with marks is unique as it makes overestimation unlikely. However, underestimation is possible if not all vaccinated dogs are marked, which occurred in some areas in Puerto Galera. Because applying collars is more difficult compared to other markers like paint, there were instances wherein collars were left for owners to apply to dogs that were too difficult to handle. It is therefore possible not all owners used the collars as intended. In addition, markers can easily be lost despite short time frames between vaccination and transect surveys, which has been observed in previous studies (Cleaton et al., 2019; Tazawa et al., 2024).

Calculating vaccination coverage using the AS-adjusted free-roaming dog population produced overestimations in barangays where there were few free-roaming dog sightings compared to the number of vaccinated dogs. Collar coverage results provided further evidence that restrained dogs comprised most of the vaccinated dogs in those barangays, and therefore true coverage for free-roaming dogs is expectedly lower. Similarly high coverage in the same barangays resulted from Chapman's estimates, probably for the same reasons. However, between the two methods, coverage from the Chapman method more closely aligned with collar coverage among free-roaming dogs in multiple barangays. The AS method was used in India to estimate the number of free-roaming dogs for calculating desired coverage and was recommended over the Chapman method for that purpose (Tiwari et al., 2018). In Bhutan, the Chapman method was considered a suitable approach for estimating free-roaming dogs (Tenzin et al., 2015). Meanwhile, our findings show that although both the AS and the Chapman methods require few surveys and resources to conduct, both produced overestimated coverages in some barangays. However, estimates from the Chapman method were more reasonable, and mark-recapture data allowed us to directly compare proportions of vaccinated free-roaming and restrained dogs. Bayesian estimates produced the lowest overall coverages. The results likely stemmed from low numbers of collared dogs sighted, which are attributable to a high confinement probability for collared (marked) dogs. Taking into account prior probabilities reduces bias in estimation, but as such parameters greatly impact the proportion of marked, vaccinated dogs to unmarked, unvaccinated dogs, information collected prior should be accurate to optimize parameters and produce a robust model.

5.6.4 Strengths and limitations

The use of collars with a distinct appearance was beneficial to our study, as it was an easily distinguishable mark that was visible from a distance. Resights were easy to verify through comparison of high-quality digital images. However, resource challenges during the MDV prevented collaring of some vaccinated dogs. As such, future MDVs should ensure that marks are applied to all vaccinated dogs for more accurate post-vaccination coverage assessments. Puerto Galera's geography, which includes coastlines, forests and mountains, posed challenges for conducting transect surveys. As there are no clear borders between barangays, dogs can move between them freely; verification of resights was done per barangay, making it possible for a dog to accidentally be misidentified as two separate dogs if it traveled to and was observed in different barangays. Furthermore, similar free-roaming dog surveys in India were conducted using motorcycles (Gibson et al., 2015; Tiwari et al., 2018; 2019), which is not feasible in some Philippine settings due to residences that are only accessible on foot. Survey tracks focused on residential areas also potentially prevented sightings of free-roaming dogs who, according to reports by residents, primarily reside in forests and have little interaction with the community. The biggest limitation was that resightings (that were made to enable accurate population estimates) were insufficient in some barangays, suggesting considerably more effort would be needed for future surveys. Detailed estimates of dog population size, particularly the proportions of confined to free-roaming dogs and owned versus unowned dogs would be beneficial for planning and monitoring MDVs (Kayali et al., 2003).

5.6.5 Conclusion

Household surveys and generalized HDRs, despite overestimating vaccination coverage, are still widely used for dog population estimation in the Philippines. We conducted the first transect surveys of dogs in Puerto Galera, and our findings together with previous vaccination data revealed that the local dog population, including both free-roaming and restrained dogs, is much higher than previously suggested. Calculating vaccination coverage using Bayesian modelling and, alternatively, using proportions of dogs observed with collars immediately post-vaccination, were the only methods that did not consistently produce inflated estimates. While Chapman's method produced similar results in several barangays, increased survey effort is needed to to achieve robust estimates. Mark-recapture surveys showed that, overall, only a small proportion of free-roaming and restrained dogs were vaccinated in Puerto Galera despite an increase in vaccine supply compared to the previous year. Poor collar coverage especially, among free-roaming dogs, illustrates their reduced accessibility for MDV. One barangay that targeted free-roaming dogs had a notably higher vaccination coverage compared to others. This practice should be emulated in future MDVs to achieve a 70% vaccination coverage and hasten progress toward rabies elimination.

Chapter 6

General discussion

Despite over a century of rabies control efforts and initiatives, rabies is still a neglected zoonosis in many countries in Africa and Asia (Swedberg et al., 2024), and recent resurgence and outbreaks in formerly local rabies-free zones continue to hamper progress toward elimination of human-mediated rabies deaths by 2030. If rabies isn't controlled in endemic settings, incursions are likely—particularly in neighbouring areas, as evidenced by the recent Timor-Leste introduction from Southeast Asia (Ward & Brookes, 2021)—and will inevitably lead to outbreaks if preparedness is not sufficient. Although rabies elimination has been achieved in many countries through maintained dog vaccine coverage, this is difficult to sustain in LMICs because of more limited resources, lack of political will and unnecessarily high expenses for the procurement and importation of biological tools (vaccines, reagents and tests for surveillance) in LMICs with the exception of India.

Furthermore, inadequate rabies surveillance makes it difficult to appreciate the true burden of rabies and detect rabies cases in LMICs, often resulting in catastrophic outbreaks that are only reported after considerable spread has already occurred (Suseno et al., 2019). Through our research, we sought to evaluate the effectiveness of rabies control measures that have been implemented in LMICs, determining which methods have helped make major strides toward achieving rabies elimination. Through our findings, we also explored ways to improve rabies surveillance that can be successfully adapted to local settings.

6.1 Summary findings

After compiling literature on reported rabies incursions worldwide that have occurred in the past 20 years, we pinpointed common factors enabling them, as well as those that led to their escalation into outbreaks (Chapter 2). In Chapter 3, we tracked an outbreak in an LMIC (Romblon province in the Philippines), studied epidemiological and genomic data of human and animal rabies cases and assessed local public health response (Yuson et al., 2024). Finally, we reviewed the use of collars in a mass dog vaccination in Puerta Galera, a municipality of Oriental Mindoro province in the Philippines, in Chapters 4 and 5. We evaluated the implementation process, collar durability, change in human behaviours toward dogs and use of collars in surveys for estimating dog population and vaccination coverage. This thesis highlights rabies control measures that prevent reincursions, or avert local transmission and outbreaks, which pose a more substantive risk in LMICs. Through our work in Romblon, we traced the origins of the outbreak and determined ways in which emergency response should be improved to hasten case detection, prevent dog-to-human transmission and resolve the outbreak. Our research in Puerta Galera informed whether collars could be used in dog vaccination, and the benefits gained from successful integration.

From conducting a systematic review on rabies incursions, our findings show that they often recur under remarkably similar, but preventable, circumstances. In HICs, importation of adopted pets from rabies-endemic countries was a common scenario, and in wildlife, incursions occurred between border-sharing countries if rabies vaccine coverage was not maintained on both sides. For LMICs, free-roaming dogs triggered incursions from natural movement or human-mediated travel to local rabies-free areas. Incursions in rabies-controlled countries had very different outcomes from incursions in rabies-endemic countries, which were more likely to snowball into outbreaks without detection. Geography had a significant impact on incursion risk, as proximity to rabies-endemic countries or areas heightened the likelihood of incursions. Countries' rabies response differed greatly, with immediate action typically performed in North America and Europe that successfully preventing outbreaks. Meanwhile, weaker surveillance in LMICs was congruent with delayed or neglected public health response. For outbreaks that were widespread, few were resolved as the control efforts used were delayed, limited, hindered by lack of budget, or involved strategies with proven ineffectiveness (such as culling). As illustrated by the Pemba Island outbreak in Tanzania, few detected cases in villages initially led to a "single-pulse" vaccination campaign in affected areas, which were insufficient to stop the outbreak as further incursions to other villages had continued undetected (Lushasi et al, 2022). The outbreak had spread throughout Pemba Island and was ultimately only resolved through island-wide vaccination.

In the Philippines, my colleagues and I tracked the Romblon outbreak in real-time, from the very first case that was detected in November, 2022. We analysed various methods undertaken to surmount the challenges of tackling rabies in this low-resourced community. Case confirmations were delayed by storms affecting inter-island transport to laboratory facilities, lack of supplies and limited manpower for conducting investigations of animals that were suspicious for rabies. Integrated Bite Case Management (IBCM) was instrumental in detecting the outbreak, but public health response was only triggered once a human rabies case was detected. A mass dog vaccination was initiated in 2024, and while the number of cases has reduced since then (Fig. 6.1), rabid dogs are still being detected. This shows the dire need for sustaining yearly vaccination to eliminate local transmission and prevent rabies reintroductions.

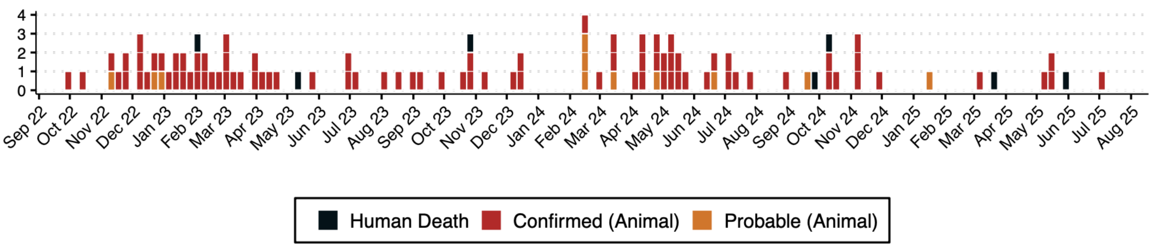


Figure 6.1: Monthly rabies cases in Romblon from 2022 to 2025.

Observations from the mass dog vaccination and collaring show the difficulties in enacting various rabies control measures in an LMIC. Any approach must be low-cost, given that resources are scarce, particularly in more rural areas, but as a result, this could compromise the effectiveness of the approach. The collars were cheap to produce and easy to apply, but were not durable enough to be considered 'long-lasting' in a tropical environment. Although collars were easily integrated into the mass vaccination, limited manpower and time resulted in fatigue for vaccinators, who were then unable to reach more remote or marginalized communities (particularly those within Geographically Isolated and Disadvantaged Areas or GIDAs), which caused gaps in vaccination coverage. Areas with lower vaccination coverage that are further from municipal centres have historically experienced higher rabies incidence (Rysava et al., 2022). As observed during transect surveys, unowned free-roaming dogs comprise a large portion of the dog population, with most not vaccinated or collared because of a lack of owner to restrain them. Meanwhile, misconceptions among the local community about rabies indicate apathy toward collared, free-roaming dogs among residents, as they believe vaccinated dogs are susceptible to rabies infection. Thus, improving the quality of collars for extended durability may be too costly to implement in the Philippines, as gains would be minimal as long as free-roaming dogs are not collared and rabies awareness is not improved.

6.2 Unique challenges in LMICs: a Philippine example

Filipinos' history with dogs dates back to over 2000 years ago, as evidenced by discoveries of ancient human and canine skeletons found side-by-side (Alfonso, 2023). The dog was often used as a hunting companion, to the extent that the Filipino word for hunting, *'pangangaso'*, stems from the root word *'aso'* (dog). Since the Spanish colonization era in the 16th century, free-roaming dogs have been depicted in Philippine-set art, with corresponding literature referring to native dogs as "Philippine edible dogs" as they were considered a delicacy by locals. Early candid photographs in Manila frequently featured at least one dog loitering on the street. Rabies in the Philippines was first reported in 1791, and phylogeographic analyses have traced earliest strains to China (Tohma et al., 2014), which spread across the country through repeat incursions (Saito et al., 2013; Zhang et al., 2025). Although the Philippines' relationship with dogs has been considerably transformed by improvements in animal welfare and veterinary care, and increasing social acceptance, rabies has maintained its endemicity, and continues to be neglected by the government and general public despite being a problem that urgently needs addressing.

As dog adoption massively increased worldwide during the COVID-19 pandemic (Morgan et al., 2020), the Philippines was listed as one of the top countries exhibiting increased interest in pet adoption (Ho et al., 2021). As I discussed in Chapter 2, international pet adoption has become a common source of rabies incursions, and in several cases, animal rescue groups shipping animals in large quantities inadvertently caused rabies exposures in other animals and humans. In Chapter 5, community response presented a snapshot of Filipino perceptions of dogs: while some dogs are provided proper food and shelter, free-roaming dogs are often dismissed as an everyday, unavoidable nuisance.

There are clear distinctions between pet dogs and free-roaming dogs. Pet dogs are often purebred and are well-cared for, are given food and attention, but are confined inside the house, or in the yard if appointed as guard dogs. Generally, pet dogs exhibit more domesticated behaviour because of their familiarity with humans. Free-roaming dogs, which are almost always *aspins* (Philippine native dogs), subsist off leftovers given by residents, but otherwise fend for themselves and spend the majority of their time outside. However, some owners have reported keeping free-roaming dogs as part-time pets, confining them during the day and releasing them at night. While free-roaming dogs may eventually be adopted and treated as pet dogs, it is rare to see purebred pet dogs that are free-roaming; this is ill-advised as they would most likely be stolen. It should therefore be unsurprising that, during household surveys, a resident who is asked how many dogs they own is likely to answer with the number of pet dogs kept indoors, while potentially excluding the free-roaming dog(s) that spends majority of its time right outside the house, waiting for its next meal. As Chapter 6 shows, the ratio of free-roaming dogs to pet dogs can vary even across neighbouring *barangays* (villages). During the dog vaccination and collaring event, high numbers of pet dogs were vaccinated and collared, but free-roaming dogs, despite having preferred persons, weren't always amenable and would become aggressive, hence their lack of collars. During transect surveys in Puerto Galera, I visited GIDAs where expensive purebred dogs—Siberian Huskies, Chow Chows, German shepherds—were kept and cared for, and in front of the same house, free-roaming dogs with poor body conditions (visible ribs) wandered freely, sharing food scraps given by charitable residents.

Ultimately, the nature of Filipinos' relationships with dogs cannot be generalized because of the unique roles free-roaming dogs play in society. Cultural traditions, such as the practice of allowing dogs to roam to begin with, have persisted in the Philippines for centuries, despite repeated legislative measures to stamp them out. In 1875, a governor of then- Manila released a *bando* (notice) banning free-roaming dogs in an attempt to combat rabies outbreaks, but it was ultimately ineffective (Alfonso, 2023). The Anti-Rabies Act of 2007 was established, and required dogs in public to be leashed and vaccinated, as well as the enforcement the Animal Welfare Act of 1998 (Supreme Court E-Library, 1998), which forbids the killing of dogs for consumption (Supreme Court E-Library, 2008). However, both Acts remain largely unenforced due to lack of funding and political will. Local customs involving free-roaming dogs have managed to coexist alongside ever-evolving notions of dog ownership, which may explain why Filipinos exhibit seemingly contradictory beliefs regarding dogs. Thus, while a resident may feel affection for the free-roaming dog they frequently interact with, free-roaming dogs in general are viewed with indifference (Fig. 6.2). Treatment of free-roaming dogs is largely consistent with Filipino cultural traditions of the distant past, wherein free-roaming dogs were deemed independent, and so diseases, including rabies, are simply a natural consequence of that independence.

Figure 6.2: Free-roaming dogs and tourists in White Beach, Puerto Galera, a municipality of Oriental Mindoro province.

Although animal welfare has improved considerably in the Philippines, progress toward rabies elimination has been minimal based on the consistently rising number of human rabies deaths seen in recent years (Republic of the Philippines Department of Health, 2025; 2024). In 2024, one specific news story received nationwide attention: a pet golden retriever had escaped from its home and was later found dead in a sack, after which closed circuit television (CCTV) footage was released showing a *barangay tanod*—a locally appointed neighbourhood watchman—beating the dog (Laqui, 2024). A criminal complaint was filed against the tanod, accusing him of killing the dog for consumption, but he admitted to doing so based on suspicions that the dog had been rabid. An image of the dog wearing a tuxedo on its birthday, complete with streamers, banners and a custom cake, went viral together with the story, as animal welfare groups rallied alongside the owner in calling for justice for the dog. The dog then tested positive for rabies, a result that a prominent animal welfare group claimed "may not be accurate" (Acebuche, 2024). Additional CCTV footage later showed how the dog had escaped its home and bit an elderly person (GMA Public Affairs, 2024). The owner confessed that she did not have her dog vaccinated against rabies, but that her sister, a nurse, purportedly vaccinated it at home (One News PH, 2024).

The incident illustrates the conflicting, and often contradictory attitudes toward dogs and rabies in the Philippines, caused by the interplay of cultural, political, social and technological influences. According to the Anti-Rabies Act, the barangay tanod is a representative of the local government unit (LGU), and was therefore within his rights to impound and euthanize the dog because it was considered dangerous. Nevertheless, he was condemned by politicians and animal welfare groups for demonstrating cruelty to animals. Despite the positive rabies diagnosis, he continued to be vilified on social media for an act that could very well have saved lives. The Philippines has been dubbed the social media capital of the world due to Filipinos, on average, spending more than four hours a day on associated phone applications (Uy-Tioco & Cabañes, 2021). Allured by the picture of a cute dog having a birthday party, social media users had much less criticism against the owner than they did against the tanod, even though the owner did not have her dog vaccinated against rabies (which would have cost marginally less than a birthday celebration).

Pets featured on social media have influenced owners into acquiring certain dog breeds (Maclennan & Smith, 2019), and although the Philippines entered a new age of 'pet parenting'—where dogs are now allowed in shopping malls, and can often be seen in strollers in public, looking well-groomed and wearing clothes—luxurious pet ownership has not translated to more responsible pet ownership. When I was a practicing clinic veterinarian from 2015 to 2018, I dealt with owners who could not afford treatment for their pet, but readily availed of pet funeral services when the pet died. Pet funeral services often include simulation of a wake, wherein dead dogs can be displayed on a bed of flowers then photographed, so that the pictures can be posted on social media. Meanwhile, the majority of Filipinos, especially in rural areas, do not know of the existence of the Anti-Rabies Act (Jose et al., 2019). This ignorance was further exemplified when the tanod in the rabid dog incident was reportedly indicted even after the dog tested positive for rabies. Although animal rescue groups aim to reduce the number of free-roaming dogs by encouraging adoption and sterilization (The Philippine Animal Welfare Society, 2022), frequent clashes with LGU personnel have been reported in municipalities and cities that try to implement dog-catching and impounding. In 2022, I attended a meeting of barangay officials in Oriental Mindoro, where they admitted to not having the resources to maintain a dog pound; they were also reluctant to catch dogs, as previous attempts had been recorded and spread on social media.

Barangay staff generally consist of elected representatives (councilors) who oversee volunteers (such as Barangay Health Workers also known as BHWs, or tanods) of their respective communities. Tanods maintain law and order, whereas BHWs deliver health care services and education. Each volunteer is paid less than $20 USD per month on average, yet the cooperation of barangay officials is crucial for rabies control efforts (especially dog vaccinations) to succeed in the Philippines. As seen in Chapter 4, their knowledge of dog-owning households is the key to successful house-to-house vaccination campaigns. During off-hand conversations with some BHWs, I was candidly informed that household survey results were more accurate when collected by those with strong relationships with the residents in their designated areas. In both Oriental Mindoro (Chapters 4 and 5) and Romblon (Chapter 3), BHWs served as intermediaries between the local community and the municipality. Suspicious dogs in Romblon were reported initially to barangay staff, who relayed the news to Municipal Agriculture Office (MAO). Additionally, in Oriental Mindoro, everyday duties of BHWs and tanods in tourist-heavy barangays include clearing White Beach of dog waste everyday. Good relationships between barangay staff and community members were evident in barangays with high vaccination coverages (as seen in Chapter 4).

During the dog vaccination and collaring in Puerto Galera, I was approached by an elderly person, who asked me how soon their dog could be consumed post-vaccination. It is not a question I ever had to answer while practicing small animal medicine in Manila, where the average resident would express dismay and disgust at the thought of consuming dog meat, much less dog meat made from their own beloved pet. Dog-eating has been commonly associated with northern Luzon provinces and Mindanao (Lassiter et al., 2002), and despite its illegality, is still practiced in some areas. While this may be in part due to ignorance of the law, a suspect rabies case in Romblon (mentioned in Chapter 3) demonstrated awareness of the crime. That case involved dog consumption following a biting incident, but none of the involved parties came forward to receive post-exposure prophylaxis (PEP) for fear of punishment. Moreover, no sample was collected for rabies testing because there was no carcass. Fortunately, human rabies cases did not result from that particular incident, as human rabies fatalities are rare. However, they have occurred elsewhere in Southeast Asia from the butchering and preparation of dog meat (Wertheim et al., 2009). Certain Southeast Asian incursions in Chapter 2 also resulted from dogs being transported for meat. Nevertheless, the illegal dog meat trade persists in some provinces in the Philippines (Senate of the Philippines, 2017), and may therefore continue to fuel increased dog movement and thus incursions, which are important for endemic persistence.

Chapter 4 details the lack of rabies awareness that is prevalent even among Filipino adults. There is a common misconception that all dogs are born with rabies, and the majority of questionnaire respondents exhibited misunderstanding of how dog vaccination can interrupt rabies circulation. This key issue may potentially prevent vaccination uptake, and if some politicians and health decision-makers share similar beliefs, it would explain why the rabies control situation in the Philippines remains dichotomous, wherein funding is allocated mainly to PEP (which is largely wasted on bites by healthy, often vaccinated dogs) while dog vaccination to reduce the source of exposures is limited or completely neglected in many municipalities. Lack of rabies knowledge has also resulted in human rabies deaths, as two human cases mentioned in Chapter 3 sought *tandok* instead of PEP, and some community members responded in Chapter 4 that they would do the same if bitten. Apart from increasing rabies awareness through community engagement, which was done alongside dog vaccination in Puerto Galera by incorporating rabies education in schools, social media could become a useful tool for debunking misconceptions about rabies, promoting reporting of suspicious dogs and discouraging dog meat consumption.

Meanwhile, dog population control is a much more complex issue: free-roaming dogs are ingrained in Philippine culture, but an alarming increase in their numbers was reported by provincial officials following the COVID-19 pandemic (Manglicmot, 2024), with limited resources available to vaccinate or control them. It should be noted that during the dog vaccination in Chapter 4, the majority of owners were very receptive: they showed appreciation for the effort and resources spent visiting them at home and vaccinating, then collaring their dogs for free. None protested upon being asked to restrain dogs that were familiar to them, whether owned or free-roaming, whereas in the previous year, central point vaccination was seen as inconvenient for owners, many of whom did not participate as they were not willing (or found it too difficult) to transport their dogs to the vaccination site. Owners should therefore be encouraged to pursue proactive healthcare measures, primarily focused on updating rabies vaccinations, to eliminate rabies risk among owned animals and free-roaming dogs in their community.

6.3 Looking forward: current and future challenges for rabies elimination

In October 2022, I started my PhD journey at a massive turning point for rabies control in the Philippines. Still reeling from the effects of the COVID-19 pandemic, rabies vaccination coverage had dropped nationwide (as discussed in Chapter 3) due to the suspension of dog vaccination campaigns in accordance with social distancing guidelines. Municipalities and cities were beginning to implement the Mandanas-Garcia Ruling, which allotted higher budgets to LGUs for investment into various services, including healthcare (Department of the Interior and Local Government, 2022). Government agencies such as the Bureau of Animal Industry would henceforth no longer manage rabies control programs (including dog rabies vaccine provision) on a municipal level. As a result, rabies was neglected in most municipalities, as the limited funding and resources available for MAOs were invested into livestock care (Swedberg et al., 2023). Puerto Galera municipality in Oriental Mindoro was an example of this, leading Boehringer-Ingelheim and other organizations to support their annual dog vaccination campaign (as seen in Chapter 4).

When it comes to the human health sector, rabies is seemingly better-funded. The number of Animal Bite Treatment Centres (ABTCs) nationwide increased by more than 200 within four years (2017 - 2021) (Quiambao et al., 2023). Nevertheless, the number of human rabies deaths in the Philippines exceeded 400 in 2024, the highest in at least 16 years (Smith et al., 2024). These statistics—coupled with findings from the Romblon outbreak (Chapter 3)—show that despite the ubiquity of ABTCs, PEP is not accessed by many of the bite victims that truly need it. Residents of GIDAs are often out-of-reach of public health facilities (Collado, 2019), with ABTCs being no exception. In addition, unaware Filipinos treat ABTCs as a last resort, with the two human rabies patients in Romblon serving as an unfortunate example, as they were bite victims were only brought to the hospital by loved ones after signs and symptoms had already manifested.

Apart from Tablas Island, rabies outbreaks have since then been reported in other previously rabies-free provinces in the Philippines, namely Marinduque and Ilocos Norte. Within the MIMAROPA region (where Oriental Mindoro and Romblon are located), rabies emerged in Sibuyan Island, Romblon and Marinduque province, which were both previously rabies-free Fig. 6.3. Globally, the rabies situation has been equally alarming. A human rabies death occurred in the country Timor-Leste, which was believed to be rabies-free (Mali et al., 2024), and more recently, following the incursions detailed in Chapter 2, outbreaks have been reported from formerly-rabies free areas like El Pedregal in Peru (Salazar et al., 2024), Sudurpaschim in Nepal (Thakur et al., 2024) and Nelson Mandela Bay in South Africa (Ravensberg et al., 2022), among others. As established in Chapters 2 and 3, rabies incursions are less likely to be detected in resource-limited countries with insufficient rabies surveillance, where public health response is often neglected until a human rabies death occurs.

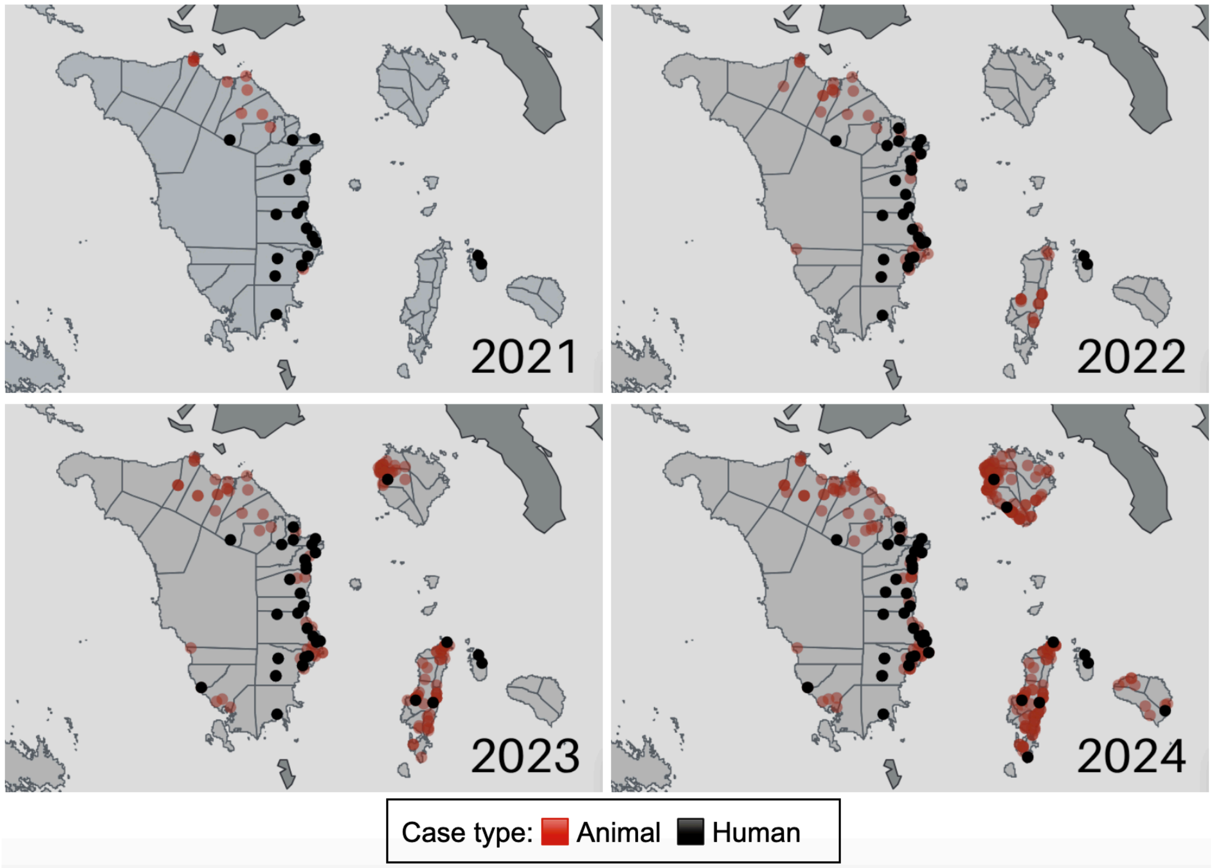


Figure 6.3: Time-series maps of inter-island rabies spread in MIMAROPA region, beginning with cases mainly in Oriental Mindoro province in 2021. Outbreaks were detected in Tablas Island, Romblon province in 2022, Marinduque province in 2023 and Sibuyan Island, Romblon province in 2024.

Despite the seemingly grim outlook, many LMICs have continued to strive toward the 'Zero by 30' goal. As of 2022, mass dog vaccination has been restarted in many Philippine provinces, despite several key challenges: insufficient vaccine and resource supply, few vaccinators, and prioritization of other diseases, such as African Swine Fever (a highly pathogenic virus causing mortality in pigs). But as seen in Chapters 4 and 5, collaborations with government and non-governmental organizations have been crucial in managing the aforementioned setbacks. The vaccination campaign in Puerto Galera would not have been possible without the involvement of Bohringer-Ingelheim, as well as the assistance of the Provincial Veterinary Office of Oriental Mindoro, which provided manpower and augmented vaccine supply. Veterinarians in the Philippines have always been few in number, with less than 20,000 overall officially licensed and registered out of a national population of over 110 million (World Health Organization 2024). Staff in various government agencies (i.e. not restricted to animal health) were therefore trained to become vaccinators, and veterinarians working in private practice volunteered to join the campaign. A similar initiative, called “One Time, Big Time”, was implemented in Romblon following the outbreak (Chapter 3), with a coalition of vaccinators from the municipal and provincial governments of Region IV-B collaborating to eliminate rabies in the provinces of Romblon, Marinduque, Oriental Mindoro, Occidental Mindoro and Palawan. This strategy was previously executed in 2019, and led to the declaration of rabies freedom in Romblon shortly afterward. Unfortunately, plans to conduct the practice yearly did not come to fruition when the COVID-19 pandemic was declared in 2020. At present, sustaining yearly dog vaccination to maintain a steady vaccination coverage remains a key challenge, especially considering how quickly neglect of rabies control measures can lead to reincursions (Chapter 2). Partnerships with non-governmental-organizations must be maintained to compensate for the lack of political will and central government funding committed toward rabies, and until municipalities prioritize rabies control, fund-sourcing is destined to become a yearly struggle for MAOs.

Limited or lack of rabies surveillance remains a common cause for delayed detection in rabies-endemic countries, and failure to detect the initial incursion has led to secondary transmission or outbreaks (Chapter 2). Mounting evidence continues to show that rabies must be managed through a One Health approach. Coordination of human and animal health sectors through IBCM has proven instrumental for case finding, sample collection and rabies confirmation. Biting incidents serve as a catalyst for animal investigations, which can be conducted inexpensively and with minimal manpower. IBCM was performed effectively in resource-limited Romblon (Chapter 3), despite a number of setbacks including delays in investigating and laboratory confirmation that accrued due to limited personnel, extended travel time for shipping samples, and adverse weather conditions. Although local One Health partnerships can operate informally between health workers and MAOs, IBCM did not expedite the public health response, as an outbreak was only declared after a human victim was diagnosed. As there is a lack of formal and more structural understanding of rabies risk and its One Health nature that is needed to ensure emergency public health responses to animal case detection, pressure must be placed on LGUs to improve healthcare capacity, with an emergency response plan prepared in the event of incursions.

Genomic surveillance is another useful tool that can trace incursion or outbreak origins (Chapters 2 and 3). However, while countries in Europe are able to co-coordinate oral rabies vaccination campaigns in response to wild animal incursions across shared borders (Chapter 2), LMICs seldom act on the information gained from phylogenetic analysis. During the Tablas Island outbreak (Chapter 3), a region-wide dog vaccination campaign (achieving >20,000 vaccinated dogs) was conducted, albeit several months after the first positive human rabies case was detected. Thus, Oriental Mindoro, which was one of the sources of introductions, was included as it is located in the same region as Romblon, but incursions that originated from provinces like Batangas and Bulacan provinces remain unaddressed. Rabies control measures, particularly dog vaccination, should also be concentrated toward rabies-endemic origin locations or else reintroductions are likely to occur.

This thesis is the first to review all recent rabies incursions in a global context, and our findings show that targeting rabies control toward rabies-endemic countries should be prioritized above border control measures, which are commonly permeated due to lack of or inefficiency in implementation. We further demonstrated facilitators and challenges to detecting and responding to an outbreak arising from incursions in an LMIC. We conceptualized strategies for improving outbreak response capacity despite limited resources and competing interests within government departments, guided by the use of IBCM and genomic surveillance. Our collar study was a broad evaluation of collar use in dog vaccination, transect surveys and implications for community behaviour toward free-roaming dogs. Our findings showed that even though estimates of free-roaming dog populations vary across local settings, the overall number of free-roaming dogs in MIMAROPA (and perhaps in many parts of the Philippines) is much higher than what is reported. Dog population estimates based on the recommended human-dog ratio likely far underestimate the dog population, and consequently, the necessary vaccine needs to control rabies. Future experimentation is still needed on how to align household survey data and transect survey data without potential double-counting of owned dogs, to provide more accurate population estimates that include free-roaming dogs. Collars made with different materials may be more effective in tropical settings such as the Philippines, as plastic collar durability was found to be lacking in our feasibility study. Notably, community sensitization to improve rabies awareness should be prioritized in order for the local community to understand the implications of collars. Overall, we presented an evaluation of current and potential measures that will inform rabies surveillance and control in LMICs. Taking into account socioeconomic, political and cultural challenges when adapting proven implementations in rabies-endemic settings can then accelerate global progress toward the 'Zero By 30' goal.

Appendices

A Chapter 2 supplementary files

Table S1: Animal incursions worldwide (2001-2022).

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Africa	South Africa	Jul-03	Horse	Africa	Zimbabwe	5 months	Human-mediated	International (shared border)	By land	Imported from Harare to Pietermaritzburg	No		No local transmission	No	Sabeta & Randles, 2005
Africa	Ethiopia	Sep-03	Dog	Africa	Ethiopia		Natural	In-country	By land	Incursion from nearby towns that caused rabies outbreak in Ethiopian wolves of Bale Mountains National Park	No	Trap-vaccination-release of Ethiopian wolves; controlled by 2004	Outbreak	Yes	Laurenson et al., 2005
Africa	South Africa	Aug-05	Dog	Africa	Zimbabwe		Natural	International (shared border)	By land	Caused sharp increase in dog rabies cases in Limpopo province	Yes	Mass dog vaccination	No local transmission	No	Zulu et al., 2008; Sabeta et al., 2011; Townsend et al., 2013
Africa	South Africa	2008	Dog	Africa	South Africa		Natural	In-country	By land	Suspected incursion from Nkomazi that led to outbreak in other parts of Mpumalanga	Yes		Outbreak	No	Phahladira et al., 2012
Africa	South Africa	2010	Dog	Africa	South Africa			In-country	By land (presumed)	Imported from KwaZulu-Natal and bit local pet dog in Witpoortjie, resulting in outbreak in Gauteng Province	No		Outbreak	No	Sabeta et al., 2013; Weyer et al., 2020; Ngoepe et al., 2022
Africa	South Africa	2011	Dog	Africa	Lesotho			International (shared border)	By land (presumed)	Suspected incursion into Sisonke district, KwaZulu-Natal	Yes		No local transmission	No	Mollentze et al., 2013
Africa	South Africa	2012	Dog	Africa	South Africa		Natural	In-country	By land (presumed)	Suspected incursion from North West Province that led to jackal rabies outbreak	Yes		No local transmission	No	Ngoepe et al., 2022

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										in uThukela, KwaZulu-Natal					
Africa	South Africa	2012	Dog	Africa	Lesotho			International (shared border)	By land (presumed)	Rescued stray; secondary transmission to 1 human (owner)	Yes		Secondary transmission	No	Mollentze et al., 2013
Africa	Chad	2014	Dog	Africa	Chad		Human-mediated	In-country	By land (presumed)	Suspected human-mediated incursion into N'Djamena from surrounding area	Yes		No local transmission	No	Zinsstag et al., 2017
Africa	Tanzania	Sep-16	Dog	Africa	Tanzania			In-country	By water (presumed)	Suspected incursion from Zanzibar that led to outbreak in Pemba facilitated by lapse in dog mass vaccination	Yes	Mass dog vaccination, PEP (subsidized); outbreak ended in 2018	Outbreak	No	Lushasi et al., 2022
Africa	South Africa	2016	Jackal	Africa	South Africa		Natural	In-country	By land	Suspected incursion from North West Province that led to outbreak in Gauteng Province	Yes	PEP	Outbreak	No	Ngoepe et al., 2022
Asia	Iran	Jan-01	Dog	Asia	Nepal	5 days	Human-mediated	International	By air	Vaccinated against rabies after importation	No	PEP (owners)	No local transmission	No	Johnson et al., 2011
Asia	Israel	Mar-03	Dog	Asia	Israel		Human-mediated	In-country	By land	Newly adopted by owner during trip to Beer Sheva and brought back to residence	No	Contact tracing, PEP, increased public awareness (tourists)	No local transmission	No	David et al., 2004; David and Yakobson, 2011
Asia	Indonesia	Aug-03	Dog	Asia	Indonesia		Human-mediated	In-country	By water	Imported from Sulawesi to Maluku islands for meat trade	No		No local transmission	No	Townsend et al., 2013

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Asia	Bhutan	May-05	Dog	Asia	India		Natural	International (shared border)	By land	Free-roaming dog that bit cow in Gongza village, resulting in outbreak that spread to other villages accessible to free-roaming dogs through road network	No	Mass dog vaccination, PEP, dog-catching, vaccination of exposed animals, increased public awareness	Outbreak	Yes	Tenzin et al., 2011; Townsend et al., 2013; Rinchen et al., 2020; Rinchen et al., 2020
Asia	China	Feb-06	Dog	Asia	China			In-country	By land	Suspected incursion from Hengshan city into Yongzhou city; led to secondary transmission to local free-roaming owned dog, which visited neighbouring farm and attacked pigs, causing outbreak with 20 pig deaths out of >50 exposed as no control measures were initiated	No		Outbreak	Yes	Jiang et al., 2008
Asia	Bhutan	2007	Dog	Asia	India		Natural	International (shared border)	By land	Incursion into Dala subdistrict, Chhukha, Bhutan	No	Culling; controlled by 2008	No local transmission	No	Townsend et al., 2013
Asia	Indonesia	2008	Dog	Asia	Indonesia		Human-mediated	In-country	By water	Imported from Flores to Bali by fishermen with no border controls; bit owners and caused outbreak that spread to other regions with >200 human deaths including owner; delayed detection and response due to poor bite surveillance, non-existent PEP policies, insufficient vaccine	No	Culling, mass dog vaccination	Outbreak	No	Scott-Orr and Putra, 2009; Clifton, 2010; Batan et al., 2014; Putra et al., 2013; Mahardika et al., 2014; Dibia et al., 2015; Cliquet and Wasniewski, 2018; De Jong et al., 2018; Drake, 2020; Rupprecht et al., 2020; Ward and Brookes, 2021

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										stocks and prioritisation of culling					
Asia	Bhutan	2008	Dog	Asia	Bhutan		Natural	In-country	By land	Incursion from south into southwest region	No		No local transmission	No	Rinchen et al., 2020; Rinchen et al., 2020
Asia	China	Mar-09	Dog	Asia	China		Human-mediated	In-country	By land	Suspected incursion from Sichuan Province; transport of dogs for meat trade enabled outbreak that resulted in >7,000 biting incidents and 20 human deaths	Yes	Culling, mass dog vaccination (limited), PEP (limited)	Outbreak	No	Zhao et al., 2011; Zhang et al., 2014;
Asia	Indonesia	Feb-10	Dog	Asia	Indonesia		Human-mediated	In-country	By water	Incursion from Sumatra into Nias; led to outbreak that caused >20 human deaths	No	Culling, mass dog vaccination	Outbreak	No	Senior, 2012; Townsend et al., 2013; Rupprecht et al., 2018
Asia	China	2010	Dog	Asia	China			In-country	By land	Suspected incursion from Hebei Province into Shanxi Province; led to secondary transmission to local owned dog which attacked neighbour's sheep, causing outbreak; spread attributed to high numbers of unvaccinated free-roaming dogs	Yes	Quarantine of exposed animals; sacrifice of associated animals (dog, sheep), mandatory vaccination of pets (owned dogs in the vicinity)	Outbreak	Yes	Zhu et al., 2011
Asia	China	Dec-10	Dog	Asia	China		Natural	In-country	By land	Free-roaming; suspected incursion from Hebei Province into Shaanxi Province indicated by	Yes	Vaccination of exposed animals (dogs), sacrifice of	Secondary transmission	No	Zhang et al., 2014

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										phylogenetic analysis; detected after secondary transmission to dog, which attacked neighbour's sheep and dog; spread due to unvaccinated free-roaming dogs, lack of border control and meat trade facilitating movement of dogs		associated animals (sheep)			
Asia	Russia	Feb-11	Fox	Asia	Mongolia		Natural	International (shared border)	By land, water (frozen)	Suspected incursion through crossing of frozen river; led to outbreak	Yes		Outbreak	No	Adelshin et al., 2012; Adelshin et al., 2015
Asia	Israel	Oct-11	Dog	Asia	Israel	2 months	Human-mediated	In-country	By land (presumed)	Unvaccinated; brought by owners on camping trip to coast of Sea of Galilee and Northern Israel and stayed outside, was bitten by local rabid stray dog and manifested symptoms after return to Israel	No	Contact tracing, PEP	No local transmission	No	David et al., 2012
Asia	Philippines	2011	Dog	Asia	Philippines		Human-mediated	In-country	By water (presumed)	Suspected long-distance migration from Central Luzon region to Tablas Island, Romblon; led to outbreak	Yes	Outbreak ended in 2012	Outbreak	No	Tohma et al., 2016
Asia	Russia	Feb-12	Fox	Asia	Mongolia		Natural	International (shared border)	By land, water (frozen)	Suspected incursion into through crossing of frozen river	Yes		No local transmission	No	Adelshin et al., 2015

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Asia	South Korea	Apr-13	Dog	Asia	South Korea		Natural	In-country	By land	Suspected incursion from Gangwon Province into Geyonggi Province	Yes		No local transmission	No	Oem et al., 2014
Asia	Israel	Sep-13	Cow	Asia	Israel	2 weeks	Human-mediated	In-country	By land	Suspected infection by jackal that had been shot in the vicinity and tested positive for rabies; 3 among group of >50 dairy calves transported from dairy farm in Kibbutz Ortal to Jezreel Valley; 2 out of 3 later transported to Kfar Yehoshua	No		No local transmission	No	David et al., 2015
Asia	China	2014	Red fox	Asia	Russia or Mongolia		Natural	International (shared border)	By land	Suspected incursion that led to secondary transmission to cow	Yes		Secondary transmission	Yes	Liu et al., 2014
Asia	China	2014	Raccoon dog	Asia	Russia or Mongolia		Natural	International (shared border)	By land	Suspected incursion that led to secondary transmission to goat	Yes		Secondary transmission	Yes	Liu et al., 2014
Asia	Malaysia	2015	Dog	Asia	Thailand			International (shared border)	By land		Yes		No local transmission	No	Leow et al., 2021
Asia	Malaysia	2015	Dog	Asia	Thailand			International (shared border)	By land		Yes		No local transmission	No	Leow et al., 2021
Asia	Bhutan	Oct-16	Dog	Asia	Bhutan		Natural	In-country	By land	Stray, free-roaming; incursion from Meral and Sakteng subdistricts into Rangjung town; bit 3 humans and caused	No	PEP	Outbreak	Yes	Tenzin et al., 2017

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										outbreak with >20 infected animals (dogs, cattle, cat); spread facilitated by large stray dog population and lack of public health response, as cases were previously detected in neighboring villages 2-3 months prior					
Asia	India	Feb-16	Jackal	Asia	India		Natural	In-country	By land	Incursion from West Bengal into Sikkim; bit 2 cows, causing secondary transmission; suspected infection by free-roaming dog while searching for food during winter, as dog vaccination coverage is low due to cultural beliefs that dogs should not be touched	No		Secondary transmission	Yes	Byrnes et al., 2017
Asia	Malaysia	Jul-17	Dog	Asia	Indonesia		Human-mediated	International (shared border)	By land	Suspected incursion attributed to workers bringing dogs during construction of Pan Borneo Highway; bit 2 children; spread facilitated by minimal rabies control at border and interaction of owned and stray dogs, resulting in outbreak	Yes	Culling, mass dog vaccination, PEP	Outbreak	No	Rupprecht et al., 2018; Taib et al., 2019; Leow et al., 2021; Ward and Brookes, 2021; Senior, 2012
Asia	Indonesia	2019	Dog	Asia	Indonesia		Human-mediated	In-country	By water	Imported from Bali or Sulawesi to Sumbawa Island to guard corn	No		No local transmission	No	Ward and Brookes, 2021

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										crops from wild monkeys					
Europe	France	Mar-01	Dog	Africa	Morocco (via Spain)	7 weeks	Human-mediated	Intercontinental, International (shared border)	By land, air/water (presumed)	Adopted by owners during camping trip in Morocco; no land border controls observed for rabies (FMD only); delayed reporting of contact with another dog by owners, resulting in fine for withholding information	No	Contact tracing, PEP, quarantine, controlled movement of dogs, sacrifice of associated animals (dog)	No local transmission	No	Bruyere-Masson et al., 2001; Ribadeau-Dumas, 2016; Alvarez et al., 2022
Europe	Albania	Mar-01	Dog	Europe	Kosovo		Natural	International (shared border)	By land	Migrated and bit 3 humans; suspected infection by wild animal (wolf/fox) as no ORV along border	No	PEP	No local transmission	No	WHO Collaborating Centre for Rabies Surveillance and Research, 2001; Blanton et al., 2007; Korro et al., 2009; Lika, 2010
Europe	Austria	Oct-01	Dog	Europe	Serbia		Human-mediated	International	By land (presumed)	Illegally imported and sold to new owners	No	PEP, contact tracing, quarantine of exposed animals (dogs), sacrifice of associated animals (second dog of owners)	No local transmission	No	Office International des Epizooties, 2001; McElhinney et al., 2011
Europe	Germany	Nov-01	Dog	Asia	Azerbaijan	2 days	Human-mediated	Intercontinental	By air	Adopted by worker; vaccinated and given health certificate without time for rabies antibodies to develop before importation	No	PEP, contact tracing	No local transmission	No	WHO Collaborating Centre for Rabies Surveillance and Research, 2001; Johnson et al., 2011; Ribadeau-Dumas, 2016; Alvarez et al., 2022

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Europe	Germany	2001	Dog	Asia	Nepal		Human-mediated	Intercontinental	By air	Imported	No		No local transmission	No	Cliquet and Wasniewski, 2018
Europe	Austria	Jan-02	Fox	Europe	Slovenia		Natural	International (shared border)	By land	Caused outbreak resulting in >20 rabid animals	No	ORV	Outbreak	No	Potzsch, 2014; Singh et al., 2018
Europe	France	2002	Dog	Africa	Morocco (via Spain)	7 weeks	Human-mediated	Intercontinental	By land, air/water (presumed)	Illegally imported without vaccination certificate	No	PEP	No local transmission	No	WHO Collaborating Centre for Rabies Surveillance and Research, 2001; Lardon, 2010; Johnson et al., 2011; Mailles et al., 2011; Ribadeau-Dumas, 2016; Alvarez et al., 2022
Europe	Switzerland	May-03	Dog	Africa	Algeria or Morocco	1 month	Human-mediated	Intercontinental		Suspected to have been illegally imported; found abandoned in Switzerland; and brought to animal shelter, later adopted	No	PEP, vaccination of exposed animals	No local transmission	No	Zanoni and Breitenmoser, 2003; Johnson et al., 2011; Ribadeau-Dumas, 2016
Europe	Finland	Jun-03	Horse	Europe	Estonia	1 month	Human-mediated	International	By land/water	Imported without vaccination, in accordance with local guidelines (rabies vaccination recommended but not required, contrary to OIE standards); was released to pasture with other horses; bit veterinarian during examination	No	PEP (veterinarian), vaccination of exposed animals (horses), quarantine of exposed animals (horses)	No local transmission	No	Englund and Pringle, 2003; Rimhanen-Finne et al., 2009; Metlin et al., 2016; Zoonoosikeskus (Zoonoses Centre), 2012; Dominguez et al., 2016

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Europe	France	2004	Dog	Africa	Morocco (via Spain)		Human-mediated	Intercontinental, International (shared border)	By land, air/water (presumed)	Vaccinated; illegally imported	No	PEP	No local transmission	No	Servas et al., 2005; Lardon, 2010; Ribadeau-Dumas, 2016
Europe	France	May-04	Dog	Africa	Morocco (via Spain)		Human-mediated	Intercontinental, International (shared border)	By land, air/water (presumed)	Unvaccinated; illegally imported	No	Contact tracing, PEP	No local transmission	No	Servas et al., 2005; Lardon, 2010; Ribadeau-Dumas, 2016
Europe	France	Jul-04	Dog	Africa	Morocco (via Spain)	1 month	Human-mediated	Intercontinental, International (shared border)	By land, air/water (presumed)	Unvaccinated; Illegally imported via car but allowed to roam unleashed at 3 summer music festivals, exposing >150 humans	No	Culling (free-roaming dogs only) Contact tracing (hotline established), PEP, monitoring of animals	No local transmission	No	Health Protection Agency, 2005; Servas et al., 2005; Lardon, 2010; Ribadeau-Dumas, 2016; Alvarez et al., 2022
Europe	France	2004	Dog	Africa	Morocco (via Spain)		Human-mediated	Intercontinental, International (shared border)	By land (presumed), air/water (presumed)	Illegally imported	No		No local transmission	No	Johnson et al., 2011; Alvarez et al., 2022
Europe	France	2004	Dog	Africa	Morocco (via Spain)		Human-mediated	Intercontinental, International (shared border)	By land (presumed), air/water (presumed)	Illegally imported; no pet passport	No	PEP	No local transmission	No	Johnson et al., 2011; Mailles et al., 2011; Alvarez et al., 2022
Europe	Germany	2004	Dog	Africa	Morocco	27 days	Human-mediated	Intercontinental	By air	Imported without complete travel requirements; died in quarantine	No	PEP, contact tracing, sacrifice of associated animals with confirmed direct exposure (cat), vaccination of associated animals (dogs)	No local transmission	No	Johnson et al., 2011; Ribadeau-Dumas, 2016; Alvarez et al., 2022

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Europe	Germany	Jan-05	Fox	Europe	Germany		Natural	In-country	By land	Incursion after ORV preventive vaccination cordon	No	ORV (changed from baits to aerial, at 6-week intervals instead of every autumn)	No local transmission	No	Selhorst et al., 2012; Cliquet and Wasniewski, 2018
Europe	Spain	2005	Dog	Africa	Morocco		Human-mediated	Intercontinental (shared border)	By land		No		No local transmission	No	European Food Safety Authority, 2007
Europe	France	Oct-07	Dog	Africa	Morocco (via Portugal and Spain)	15 days	Human-mediated	Intercontinental, International (shared border)	By water, land	Recently vaccinated before importation with visible injuries; had direct contact with 1 dog, leading to secondary transmission to 1 dog, with France losing rabies-free status for 2 years	No	Contact tracing, PEP	Secondary transmission	No	Eurosurveillance, 2008; Gautret et al., 2011; Johnson et al., 2011; Ribadeau-Dumas, 2016 ; Yamada et al., 2019; Alvarez et al., 2022
Europe	Belgium	Oct-07	Dog	Africa	Morocco	1 month	Human-mediated	Intercontinental	By air/water (presumed)	Adopted by owner while on vacation in Morocco; cleared for importation despite not fulfilling rabies vaccination and serology requirements; brought to dog park; resulted in Belgium losing rabies-free status for 6 months	No	Contact tracing, PEP, 6-month quarantine (visitor dogs at dog park), sacrifice of associated pets, recommended pet vaccination, enhanced surveillance, restrictions, active fox surveillance, mandatory dog leashing	No local transmission	No	European Food Safety Authority, 2007; Van Gucht and Le Roux , 2008; Ehnert & Galland, 2009; Johnson et al., 2011; Ribadeau-Dumas, 2016; Alvarez et al., 2022
Europe	Kosovo	Oct-07	Fox	Europe	Republic of North Macedonia		Natural	International (shared border)	By land		No		No local transmission	No	Muji et al., 2012

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Europe	Germany	2007	Dog	Africa	Morocco		Human-mediated	Intercontinental	By air/water (presumed)	Illegally imported	No		No local transmission	No	Ehnert & Galland, 2009
Europe	Finland	2007	Dog	Asia	India	<1 month	Human-mediated	Intercontinental	By air	Adopted from streets while attacked by stray dog and vaccinated shortly before importation	No	PEP	No local transmission	No	European Food Safety Authority, 2009; Johnson et al., 2011; Zoonoosikeskus (Zoonoses Centre), 2012; Väyrynen, 2020
Europe	France	Apr-08	Dog	Africa	Gambia (via Senegal and Belgium)	2 weeks	Human-mediated	Intercontinental, International (shared border)	By air, land	Fulfilled all travel requirements except serology; newly adopted and visibly wounded but given health certificate; brought into passenger cabin of plane	No	Contact tracing, PEP, 6-month quarantine of exposed animals (cats)	No local transmission	No	Eurosurveillance, 2008; Roux and Gucht, 2008; European Food Safety Authority, 2010; Ribadeau-Dumas, 2016; Cliquet and Wasniewski, 2018; Alvarez et al., 2022
Europe	United Kingdom	Apr-08	Dog	Asia	Sri Lanka	6 days	Human-mediated	Intercontinental	By air	Vaccinated; imported by rescue group along with >10 animals despite not meeting minimum age requirement for travel; symptoms manifested while in quarantine	No	Contact tracing, PEP, sacrifice of associated animals (nearby dogs at quarantine center)	No local transmission	No	Catchpole et al., 2008; Fooks et al., 2008; Goddard et al., 2008; Health Protection Agency, 2008; WHO Collaborating Centre for Rabies Surveillance & Research, 2009; European Food Safety Authority, 2010; Johnson et al., 2011; Johnson et al., 2011; Fooks and Johnson, 2015; Ribadeau-Dumas, 2016; Alvarez et al., 2022
Europe	Germany	Jun-08	Dog	Europe	Croatia	6 months	Human-mediated	International	By land	Illegally imported to animal shelter without vaccination certificate;	No	Contact tracing, PEP, quarantine of exposed animals	No local transmission	No	Johnson et al., 2011; Weiss et al., 2009; European Food Safety

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										no border control measures reported at EU border					Authority, 2010; Ribadeau-Dumas, 2016; Alvarez et al., 2022
Europe	France	Oct-08	Dog	Europe	Spain	1 month	Human-mediated	International	By land	Found in car park and adopted	No	Contact tracing	No local transmission	No	Johnson et al., 2011;
Europe	Italy	Oct-08	Red fox	Europe	Slovenia		Natural	International (shared border)	By land	1 fox bit 1 human, and caused rabies spread to other regions; ORV not maintained during that period	No	PEP, ORV (Emergency)	Outbreak	No	De Benedictis et al., 2008; Fusaro et al., 2013; Berg et al, 2015; Rupprecht et al., 2020; Kumar et al., 2021; Lojkić et al., 2021
Europe	Italy	Nov-08	Fox	Europe	Italy		Natural	In-country	By land	Continued incursion into Belluno, Venzone Province following incursion from Slovenia; caused rabies spread to other regions	No	PEP, ORV (Emergency)	Outbreak	No	Fusaro et al., 2013; Berg et al, 2015; Rupprecht et al., 2020; Kumar et al., 2021; Lojkić et al., 2021
Europe	France	2008	Dog	Europe	Spain	18 days	Human-mediated	International (shared border)	By land, air/water (presumed)	Found on highway and recently adopted; ilegally imported without vaccination	Yes	PEP	No local transmission	No	Mailles et al., 2011; Alvarez et al., 2022
Europe	Germany	2009	Dog	Europe	Croatia		Human-mediated	International	By land	Imported; no border control measures reported	No		No local transmission	No	Tietjen et al., 2011
Europe	France	2009	Dog	Asia	Afghanistan		Human-mediated	Intercontinental	By air	Imported	No		No local transmission	No	WHO Collaborating Centre for Rabies Surveillance & Research, 2009; Johnson et al., 2011

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Europe	Germany	Feb-10	Dog	Europe	Bosnia and Herzegovina (via Slovenia)	22 days	Human-mediated	International (shared border)	By land	Newly bought before importation with incomplete travel documents (no record of rabies vaccination) but allowed through border control; history of biting by aggressive dog	No	Contact tracing, PEP, destroyed associated animals (unvaccinated cats)	No local transmission	No	Eismann et al., 2011; Johnson et al., 2011; European Food Safety Authority and European Centre for Disease Prevention and Control, 2012; Ribadeau-Dumas, 2016; Alvarez et al., 2022
Europe	Poland	2010	Fox	Europe	Belarus or Ukraine		Natural	International (shared border)	By land	Incursion into Rzeszow	No	ORV	No local transmission	No	Smreczak et al., 2012
Europe	Poland	2010	Fox	Europe	Belarus or Ukraine		Natural	International (shared border)	By land	Incursion into Lublin	No	ORV	No local transmission	No	Smreczak et al., 2012
Europe	Poland	2010	Fox	Europe	Russia or Ukraine		Natural	International (shared border)	By land	Incursion into Malopolskie region; caused outbreak, resulting from weak surveillance (minimal sample collection)	No	ORV (maintained)	Outbreak	No	Berg et al, 2015; Ortiz et al., 2018
Europe	France	Jul-11	Dog	Africa	Morocco (via Spain)	4 days	Human-mediated	Intercontinental, International (shared border)	By water, land	Newly adopted; illegally imported without fulfilling all travel requirements (underage, unvaccinated, not microchipped, no travel certificate)	No	Contact tracing, PEP, (booster) vaccination of exposed animals (dogs), sacrifice of associated animals (cats)	No local transmission	No	Mailles et al., 2011; Roberts and Lopez, 2011; European Food Safety Authority and European Centre for Disease Prevention and Control, 2013; Alvarez et al., 2022
Europe	Norway	2011	Arctic fox	Europe	Norway		Natural	In-country	By water (frozen)	Incursion from Svalbard mainland into Hopen Island by crossing frozen sea ice	No	(Booster) vaccination of exposed animals (dogs)	No local transmission	No	Roberts et al., 2011

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										during winter; fought 4 dogs and was killed					
Europe	Croatia	2011	Cow	Europe	Romania	8 months	Human-mediated	International	By land	One of 1,000 unvaccinated cows imported with valid documents (health certificates) but no rabies vaccination required; 6 bulls exhibited symptoms	No	Sacrifice of associated animals (bulls in same box)	No local transmission	No	Lojkić et al., 2013
Europe	Norway	2011	Arctic fox	Europe	Russia		Natural	International	By water (frozen)	Incursion into Svalbard by crossing frozen sea ice	No		No local transmission	No	Simon et al., 2021; Hueffer, 2022
Europe	Poland	2011	Fox	Europe	Russia		Natural	International	By land		No	ORV (intensified)	No local transmission	No	Berg et al, 2015
Europe	Netherlands	Feb-12	Dog	Africa	Morocco (via Spain)	1 day	Human-mediated	Intercontinental, international	By air, land/water (presumed)	Purchased in parking lot and illegally imported without vaccination; examined at customs but pet passport and vaccination status not checked; stayed in passenger cabin of plane	No	Contact tracing, PEP, (booster) vaccination of exposed animals (dogs), sacrifice of associated animals (cats) due to lack of available venue for quarantine	No local transmission	No	Roberts and Lopez, 2012; Van Rijckevorse et al., 2012; Ribadeau-Dumas, 2016; Veda et al., 2021; Alvarez et al., 2022
Europe	Greece	Oct-12	Red fox	Europe	Republic of North Macedonia		Natural	International (shared border)	By land	Seen exhibiting symptoms by villagers; led to secondary transmission to 6 foxes and 2 dogs; spread attributed to neglect of ORV and lack of mountains	No	ORV, improved passive surveillance, mandatory pet vaccination, increased public awareness	Secondary transmission	Yes	Tsiodras et al., 2013; Tsiodras et al., 2014; Giannakopoulos et al., 2016; Rupprecht et al., 2020; Lojkić et al., 2021

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Europe	Spain	Jun-13	Dog	Africa	Morocco	2 months	Human-mediated	Intercontinental	By land, air/water (presumed)	Attempted importation to Morocco 4 months prior but denied due to lack of serology test; illegally imported through Ceuta immediately after vaccination; later escaped, attacked 5 humans and died, resulting in loss of rabies-free status in Spain for 6 months; owners fined for not disclosing all information	No	Contact tracing, PEP, mandatory pet vaccination (animals in Castilla-La Mancha restriction area), serology of all exposed dogs, sacrifice of associated animals (dog with insufficient antibodies according to serology), restricted movement of pets	No local transmission	No	Suarez-Rodriguez at al., 2013; Pérez de Diego et al., 2015; Ribadeau-Dumas, 2016; Veda et al., 2021; Alvarez et al., 2022
Europe	France	Oct-13	Cat	Africa	Morocco	11 days	Human-mediated	Intercontinental	By air	Imported with certificate of good health despite not meeting qualifications for importation (no vaccination); escaped home and was adopted twice by different owners	No	Contact tracing, PEP, monitoring of vaccinated animals, sacrifice of associated animals (non-vaccinated), restricted movement of pets, increased surveillance	No local transmission	No	Veterinary Record, 2013; Ribadeau-Dumas, 2016
Europe	Slovakia	2013	Dog, fox, marten	Europe	Poland		Natural	International (shared border)	By land	Incursion despite ORV	No	ORV (continued)	No local transmission	No	Ondrejková et al., 2020
Europe	France	May-15	Dog	Europe	Algeria	9 days	Human-mediated	International	By air/land (presumed)	Illegally imported without fulfilling travel requirements (no vaccination, no identification, underage); brought to Algeria 4 months later by owners despite surveillance orders, escaped for a period; manifested symptoms	No	Contact tracing, PEP, sacrifice of associated animals (unvaccinated), monitoring of vaccinated animals (dogs) for 6 months, catching of stray animals, restricted movement of pets,	No local transmission	No	European Food Safety Authority and European Centre for Disease Prevention and Control, 2015; Veterinary Record, (2015); Veda et al., 2021; Alvarez et al., 2022

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										upon return and had direct contact with 9 humans and 1 dog		increased surveillance			
Europe	Slovakia	2015	Fox	Europe	Poland		Natural	International (shared border)	By land		No	ORV	No local transmission	No	Ondrejková et al., 2020
Europe	United Kingdom	Jan-20	Sable	Europe	Russia (via Italy)		Human-mediated	International	By air (presumed)	Imported	No		No local transmission	No	European Food Safety Authority and European Centre for Disease Prevention and Control, 2021
Europe	France	Feb-20	Dog	Africa	Morocco		Human-mediated	Intercontinental	By air/water (presumed)	Illegally imported (no vaccination)	No	PEP	No local transmission	No	Bacigalupo et al., 2022; European Food Safety Authority and European Centre for Disease Prevention and Control, 2021; Veda et al., 2021 ; Alvarez et al., 2022
Europe	Poland	Jan-21	Fox	Europe	Belarus or Ukraine		Natural	International (shared border)	By land	Observed to be 'sick', killed by dog; spread facilitated by limitation of ORV to borders only	No	Increased public awareness, increased rabies surveillance, hunting ban, cancellation of pet-centric events, mandatory leashing of dogs, emergency ORV	No local transmission	No	Smreczak et al., 2023
Europe	Germany	Jul-21	Dog	Asia	Republic of Türkiye (via Bulgaria)	11 days	Human-mediated	Intercontinental, international	By air (presumed)	Illegally imported (no vaccination)	No	Contact tracing, PEP	No local transmission	No	Alvarez et al., 2022; European Food Safety Authority and European Centre for Disease Prevention and Control, 2022

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
Europe	France	Oct-22	Dog	Europe	Morocco		Human-mediated	Intercontinental	By air/water (presumed)	Suspected to be illegally imported to shelter; bit several humans	No	Contact tracing, PEP, monitoring of shelter	No local transmission	No	Bacigalupo et al., 2022
North America	United States of America	2001	Raccoon	North America	United States of America		Natural	In-country	By land	Incursion from Pennsylvania into Ohio despite immune corridor from ORV; attributed to weakened surveillance	No	ORV (expanded)	No local transmission	No	Krebs et al., 2002
North America	Canada	Dec-02	Arctic fox	Europe	Greenland		Natural	Intercontinental	By water (frozen)	Incursion by crossing through packed ice during winter	Yes		No local transmission	No	Nadin-Davis et al., 2008
North America	Canada	2002	Fox	North America	Canada		Natural	In-country	By water (frozen)	Incursion from mainland to Cartwright, Labrador by crossing through packed ice; overlap with red fox populations facilitated spread in arctic foxes	No		No local transmission	No	Nadin-Davis et al., 2008
North America	United States of America	2003	Dog	North America	United States of America		Human-mediated	In-country	By air	Imported	No	PEP	No local transmission	No	Lankau et al., 2014
North America	United States of America	Mar-04	Dog	North America	Mexico		Natural	International (shared border)	By land		No	Mass dog vaccination, ORV, monitoring	No local transmission	No	Blanton et al., 2007
North America	United States of America	Jun-04	Dog	Asia	Thailand	2 days	Human-mediated	Intercontinental	By air	newly adopted and imported without vaccination; given health certificate despite history of respiratory illness;	No	Contact tracing, PEP	No local transmission	No	Castrodale et al., 2008; McQuiston, 2008; Ehnert & Galland, 2009; Lankau et al., 2014

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										stayed in passenger cabin					
North America	United States of America	Jul-04	Raccoon	North America	United States of America		Natural	In-country	By land	Suspected incursion from mid-Atlantic state to Ohio; detected despite weakened surveillance, limited testing	Yes	ORV, enhanced surveillance	No local transmission	No	Russell et al., 2005; Henderson et al., 2008; Slate et al., 2008
North America	United States of America	2004	Raccoon	North America	United States of America		Natural	In-country	By land	Incursion into Cape Cod from nearby areas; crossed vaccine barrier and led to outbreak in raccoons with transmission to other species (skunks, domestic animals, etc.)	No	ORV, trap-vaccination-release of raccoons and skunks	Outbreak	Yes	Wang et al., 2009
North America	United States of America	Feb-06	Red fox	North America	United States of America		Natural	In-country	By land	Incursion from mid-Atlantic state to Tennessee; found during enhanced surveillance in non-ORV area; suspected infection by raccoon; ORV not recommended, considered 'waste of resources'	Yes	Enhanced surveillance (increased sampling)	No local transmission	No	Slate et al., 2008
North America	Canada	Jun-06	Raccoon	North America	United States of America		Natural	International (shared border)	By land			ORV	No local transmission	No	Shwiff et al., 2013; Stevenson et al., 2016; Trewby et al., 2017; Nadin-Davis, 2018; Nadin-Davis et al., 2020

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
North America	United States of America	Mar-07	Dog	Asia	India	2 days	Human-mediated	Intercontinental, in-country	By air	Newly adopted before importation by volunteer veterinarian; no vaccination; given to 2nd veterinarian; despite symptoms and biting history (veterinarian owner, dog), health certificate obtained from 3rd veterinarian for travel	No	PEP, contact tracing, sacrifice of associated pets (dog)	No local transmission	No	Blanton et al., 2008; Castrodale et al., 2008; Ehnert & Galland, 2009; Lankau et al., 2014
North America	United States of America	2008	Dog	Asia	Iraq	3 days	Human-mediated	Intercontinental	By air	Adopted by soldier and kept on military base for 7 months before importation; transported with >20 dogs with no vaccination certificates, leading to 30-day quarantine for all animals; diagnosed in quarantine centre	No	Contact tracing, PEP, vaccination of associated animals (dogs, cat); 6-month quarantine of exposed animals (dogs, cat)	No local transmission	No	Mangieri et al., 2008; Lankau et al., 2014; Hercules et al., 2018
North America	United States of America	Jan-10	Cow	North America	Mexico	5 months	Human-mediated	International (shared border)	By land	Imported without documentation; presumed unvaccinated suspected infection by vampire bat	Yes		No local transmission	No	Blanton et al., 2011; Pieracci et al., 2020
North America	United States of America	Jan-13	Raccoon	North America	United States of America		Natural	In-country	By land	Incursion from mainland Georgia to Jekyll Island by crossing bridge; led to outbreak	No	Outbreak ended in 2017	Outbreak	No	Ortiz et al., 2018
North America	Canada	Jul-13	Dog	North America	Canada	1 month	Human-mediated	In-country	By air	Found in area with ongoing outbreak, scavenging for food with other dogs	Yes	PEP, quarantine of exposed animals (mother and litter dogs), sacrifice of	Outbreak	Yes	Curry et al., 2016

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										(mother and newborn litter); not vaccinated before importation due to no vaccination requirement for in-country travel; suspected infection by arctic fox		associated animals (dog negative for rabies but euthanized at request of owner)			
North America	Canada	Dec-14	Dog	North America	Canada	0 days	Human-mediated	In-country	By air, land	Found in construction work camp; not vaccinated before importation due to no vaccination requirement for in-country travel; manifested symptoms during travel and bit owner; suspected infection by arctic fox	Yes	PEP, vaccination of exposed animal (dog), 45-day quarantine of exposed animal (dog)	No local transmission	No	Curry et al., 2016
North America	United States of America	May-15	Dog	Africa	Egypt	4 days	Human-mediated	Intercontinental	By air	Found on street and imported by animal rescue organization along with >30 pets (dogs, cats) despite fracture injury; transported in same crate with own puppy; falsified vaccination certificate	No	Contact tracing, PEP, vaccination of exposed animals (puppy, booster for vaccinated dogs), quarantine of exposed dogs (puppy)	No local transmission	No	Sinclair et al., 2015; Pieracci et al., 2020; Latzer et al., 2022
North America	Canada	Dec-15	Raccoon	North America	United States of America		Human-mediated	International (shared border)	By land/water (presumed)	Suspected long-distance incursion by stowing away on truck or ship; picked up by animal control along with 2 dogs; escaped cage and fought with dog; led to outbreak (>400 animals)	No	PEP, mass vaccination, ORV, enhanced surveillance (increased testing of sick animals), increased public awareness	Outbreak	Yes	Stevenson et al., 2016; Trewby et al., 2017; Lobo et al., 2018; Gilbert & Chipman, 2020; Nadin-Davis et al., 2020

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
North America	Canada	2015	Raccoon	North America	United States of America		Natural	International (shared border)	By land		Yes		No local transmission	No	Birhane et al., 2017; Trewby et al., 2017; Nadin-Davis et al., 2020
North America	Canada	2015	Raccoon	North America	United States of America		Natural	International (shared border)	By land		Yes		No local transmission	No	Trewby et al., 2017
North America	United States of America	Mar-16	Raccoon	North America	United States of America		Human-mediated	In-country	By land	Suspected human-mediated incursion from Connecticut into New York	Yes	Enhanced surveillance, increased public awareness	No local transmission	No	Brunt et al., 2020
North America	United States of America	Dec-16	Cat	North America	United States of America		Human-mediated	In-country	By air/land (presumed)	Imported from Iowa to New York for vacation without vaccination; attacked 1 dog, 3 humans; suspected infection by skunk	Yes		No local transmission	No	Brunt et al., 2021
North America	United States of America	Dec-16	Otter	North America	United States of America		Natural	In-country	By water	Suspected incursion from Connecticut into New York	Yes		No local transmission	No	Brunt et al., 2020
North America	United States of America	Feb-17	Cat	North America	United States of America	5 months	Human-mediated	In-country	By air/land (presumed)	Newly adopted before importation from North Carolina to Arkansas along with >10 other pets (cats, dogs) then later surrendered to Humane Society of Summit County in Ohio; vaccinated but not for rabies (according to facility guidelines, rabies vaccination only administered at time of spay/neuter);	Yes	PEP, vaccination of exposed animals (recommended), 6-month quarantine of exposed animals (cats)	No local transmission	No	Singh et al., 2018

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										suspected infection by raccoon					
North America	United States of America	Nov-17	Cat	North America	United States of America			In-country	By land (presumed)	Imported from Westchester County to Long Island without vaccination; bit veterinary staff; suspected infection by raccoon	Yes		No local transmission	No	Brunt et al., 2020
North America	United States of America	Dec-17	Dog	Africa	Egypt	1 day	Human-mediated	Intercontinental	By air	Iimported from with 3 other dogs by animal rescue organization despite visible injuries; suspected falsified rabies vaccination document; bit 1 human (flight parent) before boarding plane	No	Contact tracing, PEP, booster vaccination of exposed animals (dogs), quarantine of exposed animals (dogs), monitoring	No local transmission	No	Blanton et al., 2009; Hercules et al., 2018; Chevalier & Havas, 2019; Latzer et al., 2022
North America	United States of America	Jan-19	Dog	Africa	Egypt (via Canada)	1 month	Human-mediated	Intercontinental, international (shared border)	By air, land	Recently fostered before importation with >20 other dogs; bit 1 human (veterinary technician) during examination; had rabies vaccination certificate but serologic testing showed lack of vaccination in some dogs, indicating vaccination failure or falsification of vaccination certificate	No	PEP, suspension of dogs entering USA from Egypt, vaccination of exposed animals (booster) and 45-day monitoring, 6-month quarantine of exposed animals (unvaccinated dogs), quarantine of imported animals (dogs) and serologic monitoring	No local transmission	No	Raybern et al, 2019; Latzer et al., 2022
North America	United States of America	May-21	Anteater	North America	United States of America	2 months	Human-mediated	In-country	By air/land (presumed)	Imported from Virginia zoo to Tennessee Zoo;	Yes	Contact tracing, PEP, vaccination of exposed animal (tamandua) that was	No local transmission	No	Grome et al, 2022

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										suspected infection by raccoon		presumed unvaccinated due to missing vaccination records), quarantine of exposed animal (tamandua)			
North America	United States of America	Jun-21	Dog	Asia	Azerbaijan	3 days	Human-mediated	Intercontinental	By air, other	Imported with >30 other animals (dogs, cat) by animal rescue organization; serologic testing showed insufficient levels despite confirmed vaccination, indicating vaccination failure due to underdosing	No	Contact tracing, PEP, (booster) vaccination of exposed animals (dogs, cat), serologic monitoring and 45-day quarantine of imported animals (dogs), suspension of dog importations from DMRVV high-risk countries	No local transmission	No	Williams & Pieracci, 2021; Whitehill et al., 2022
North America	Canada	Jul-21	Dog	Asia	Iran (via Germany)	11 days	Human-mediated	Intercontinental	By air	Newly adopted and imported by animal rescue organization; presumed vaccinated but was not revaccinated upon arrival despite vaccination policy for young dogs	No	Contact tracing, PEP, (booster) vaccination of exposed animals (dog), 3-month quarantine of exposed animal (dog) due to delayed identification	No local transmission	No	Rebellato et al., 2022
South America	Brazil	2006	Dog	South America	Bolivia		Natural	International (shared border)	By land	Attributed to high numbers of free-roaming dogs	No	Mass dog vaccination	No local transmission	No	Galhardo et al., 2019
South America	Peru	2015	Dog	South America	Peru		Natural	In-country	By land	Incursion from Puno into Arequipa; attributed to low vaccination rate among free-roaming dogs, commonly found foraging in water	No	Mass dog vaccination, culling (stray dogs)	Outbreak	No	Castillo-Neyra et al., 2017; Castillo-Neyra et al., 2017; Raynor et al., 2020

Continent	Incursion location	Incursion date	Species	Origin continent	Location origin	Time between incursion & symptoms	Type of incursion	Borders crossed	Mode of travel	Incursion details	Phylogenetic analysis	Public health response	Local transmission	Unusual cross-species transmission	Reference(s)
										channels throughout city that collect garbage for foraging during dry season; led to outbreak					
South America	Brazil	2015	Dog	South America	Bolivia		Natural	International (shared border)	By land	Further spread led to outbreak in Mato Grosso do Sul	No	Outbreak ended in 2015	Outbreak	No	Benavides et al., 2019

B Chapter 3 supplementary files

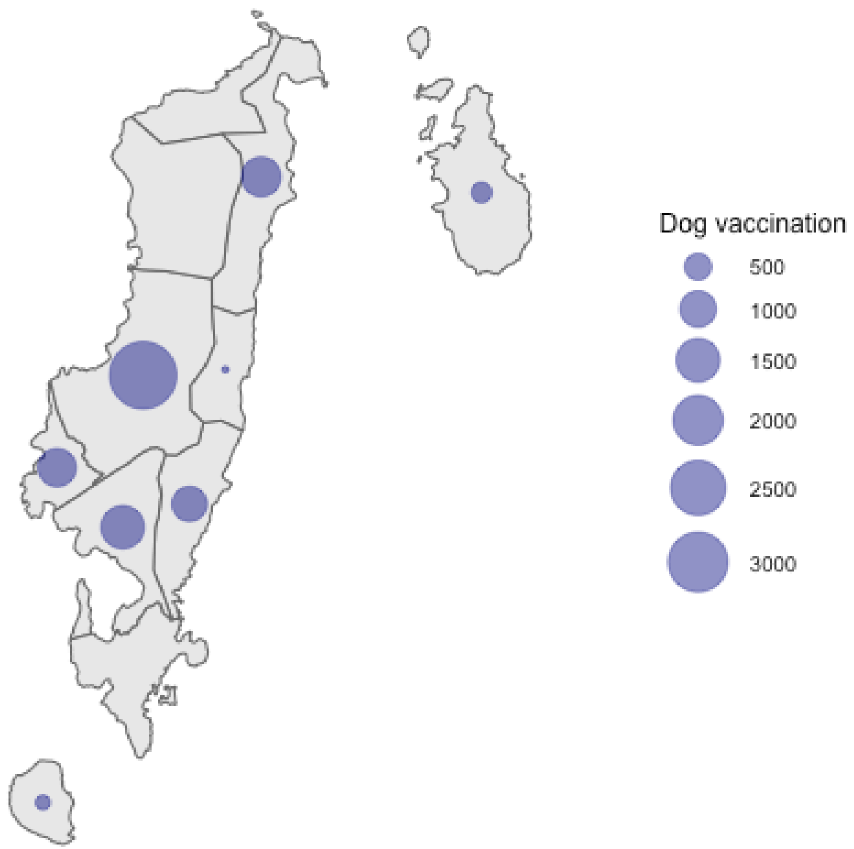


Figure S1: Number of dogs vaccinated per municipality in Romblon Province (Sept 2022-Sept 2023).

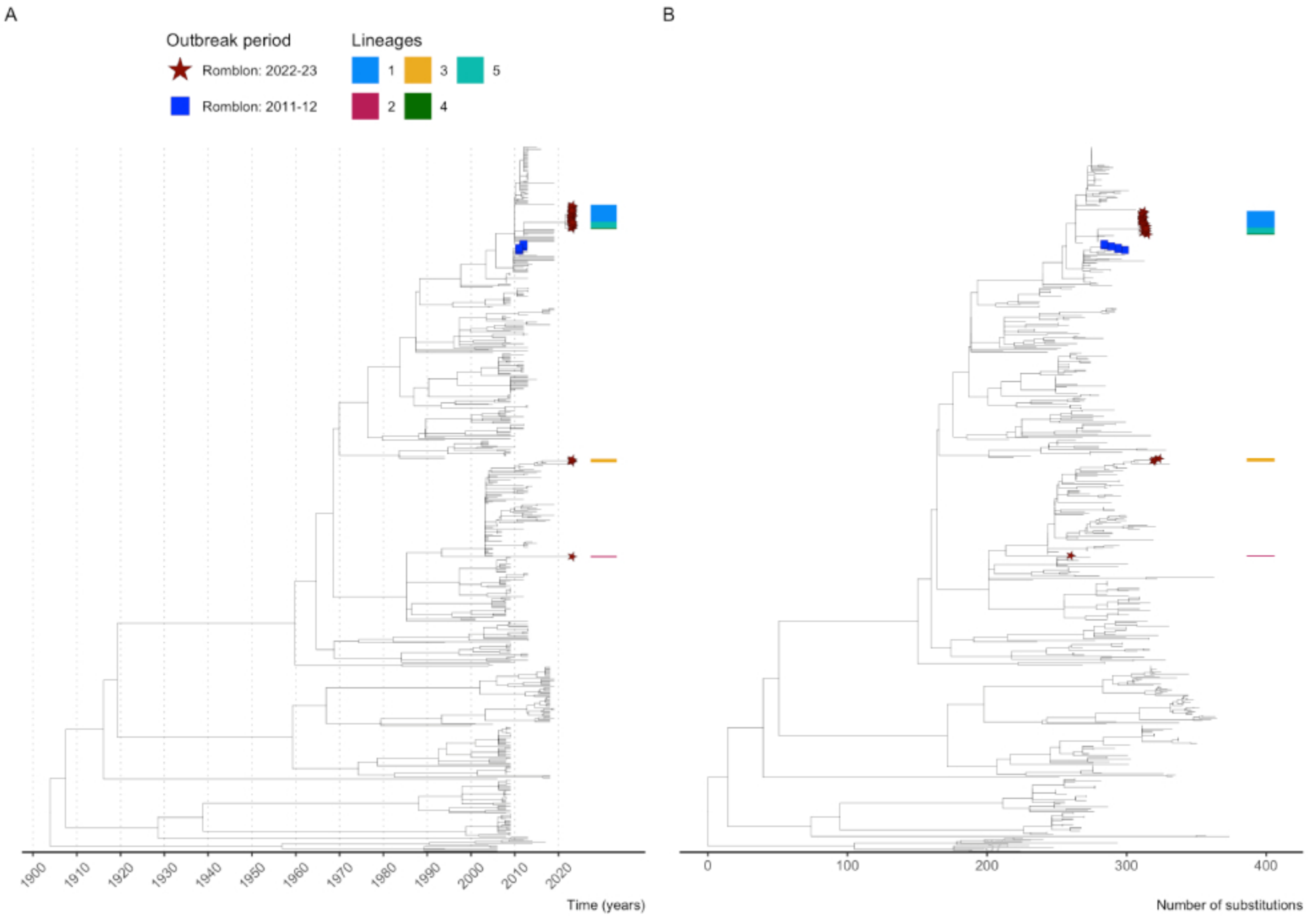


Figure S2: Time-scaled and substitution-scaled phylogenies from publicly available Philippines RABV sequences. A) Time-scaled and B) substitution-scaled maximum likelihood trees of 518 sequences (211-11797bp) from the Philippines spanning 1998 to 2023. The phylogenetic placement of Romblon cases from historical (2011-12) and current (2022-23) outbreaks are highlighted, as are the genetic lineages described in the main text. The top cluster from the 2022-23 Romblon outbreak represents the cluster A1 as shown in Figure 3, while the middle cluster is C1 and the lower cluster is the human case B1.

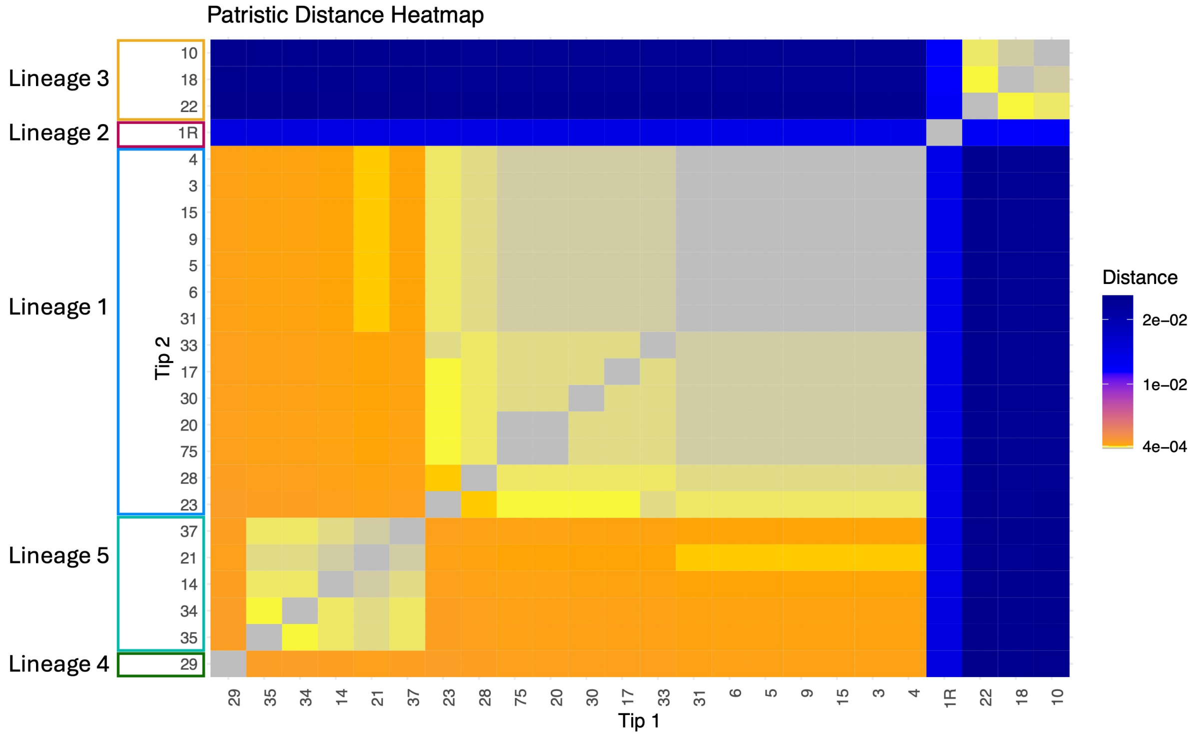


Figure S3: Patristic distance heatmap of Romblon sequences. The heatmap illustrates the genetic distances between sequences from Romblon, with distances calculated using the patristic method. The colour gradient runs from grey to yellow to dark blue with shades of blue representing higher genetic distances, indicating less similarity, while yellow/orange shades indicate smaller distances. The transition from yellow to orange marks the 0.0004 threshold used to delineate lineages, which are annotated on the y axis.

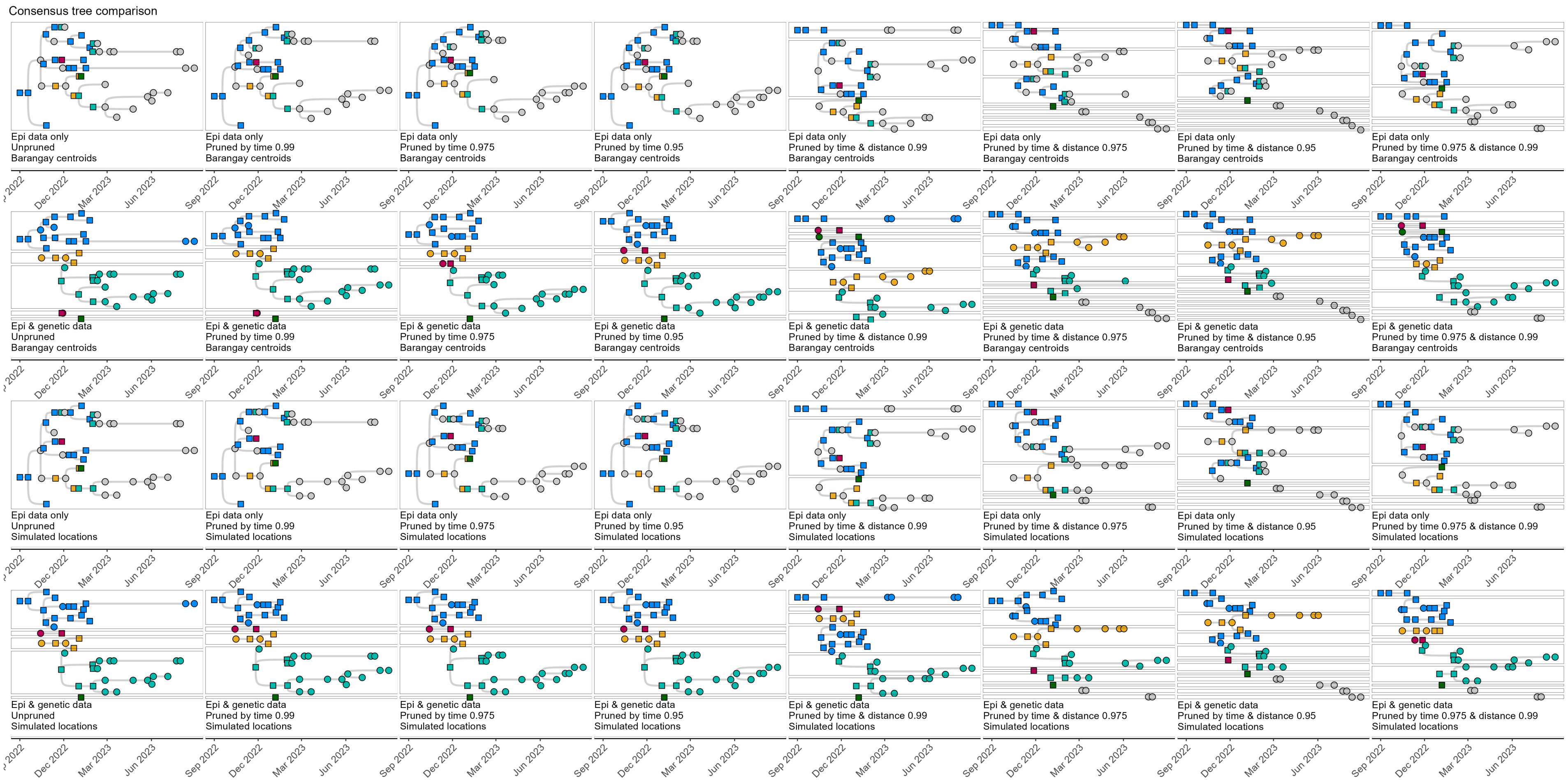


Figure S4: Consensus transmission tree reconstructions under different pruning thresholds and assumptions about case locations. Row 1) trees constructed using epidemiological data only and barangay centroids to represent case locations; Row 2) trees constructed from epidemiological data consistent with phylogenetic assignments (according to the three introductions and subsequent divergence of cluster 1 into three genetic lineages, with barangay centroid locations); Rows 3) and 4) trees constructed as per Rows 1 and 2 but using case locations simulated in proportion to human population density. Columns 1-8 represent pruning thresholds, specifically 1) unpruned, 2-5) pruned by the 99th, 97.5th and 95th percentile of the serial interval; and 5-7) by the 99th, 97.5th and 95th percentiles of the serial interval and dispersal kernel, and 8) by the 97.5th and 99th percentiles of the serial interval and the dispersal kernel respectively. Squares represent sequences coloured according to lineage, and circles represent detected cases without sequences, coloured by lineage when assigned.

Table S2: Whole genome sequences used in the phylogeography.

Case ID	Lineage	Cluster	Municipality	Species	Collection Date
9	1	1	Alcantara	*Canis familiaris*	01/10/2022
4	1	1	Alcantara	*Canis familiaris*	21/10/2022
3	1	1	Santa Maria	*Canis familiaris*	21/11/2022
5	1	1	Odiongan	*Canis familiaris*	24/11/2022
6	1	1	Alcantara	*Canis familiaris*	26/11/2022
15	1	1	Odiongan	*Canis familiaris*	11/12/2022
75	1	1	Santa Maria	*Canis familiaris*	12/12/2022
14	5	1	Odiongan	*Canis familiaris*	28/12/2022
20	1	1	Santa Maria	*Canis familiaris*	20/01/2023
17	1	1	Odiongan	*Canis familiaris*	13/01/2023
21	5	1	San Agustin	*Canis familiaris*	20/01/2023
23	1	1	Santa Maria	*Canis familiaris*	02/02/2023
29	4	1	San Andres	*Canis familiaris*	07/02/2023
28	1	1	Santa Maria	*Canis familiaris*	07/02/2023
33	1	1	Santa Maria	*Canis familiaris*	14/02/2023
31	1	1	Odiongan	*Canis familiaris*	09/02/2023
30	1	1	Odiongan	*Canis familiaris*	16/02/2023
34	5	1	Odiongan	*Canis familiaris*	28/02/2023
35	5	1	Odiongan	*Canis familiaris*	01/03/2023
37	5	1	San Agustin	*Canis familiaris*	01/03/2023
1-R	2	2	Santa Maria	*Homo sapiens*	02/02/2023
10	3	3	San Augustin	*Canis familiaris*	19/12/2022
18	3	3	San Agustin	*Canis familiaris*	22/01/2023
22	3	3	San Agustin	*Canis familiaris*	31/01/2023

Table S3: GenBank accession numbers for sequences from rabies samples collected in Tablas Island, Romblon from 2022-2023.

Sequin file name	**Local reference ID**	**Accession number**
4B-23-06.sqn	4B-23-06	PP858749
4B-23-05.sqn	4B-23-05	PP858750
Z-22-119.sqn	Z-22-119	PP858751
4B-23-02.sqn	4B-23-02	PP858752
4B-23-01.sqn	4B-23-01	PP858753
4B-22-44.sqn	4B-22-44	PP858754
4B-23-07.sqn	4B-23-07	PP858755
4B-23-19.sqn	4B-23-19	PP858756
4B-23-12.sqn	4B-23-12	PP858757
4B-23-13.sqn	4B-23-13	PP858758
Z-22-103.sqn	Z-22-103	PP858759
4B-23-15.sqn	4B-23-15	PP858760
Z-17-046.sqn	Z-17-046	PP858761
H-23-011Sk_12.sqn	H-23-011Sk_12	PP858762
4B-23-11.sqn	4B-23-11	PP858763
4B-22-41.sqn	4B-22-41	PP858764
4B-23-04.sqn	4B-23-04	PP858765
Z-22-121.sqn	Z-22-121	PP858766
4A-22-203.sqn	4A-22-203	PP858767
4B-23-16.sqn	4B-23-16	PP858768
Z-14-098.sqn	Z-14-098	PP858769
4B-22-39.sqn	4B-22-39	PP858770
4B-23-03.sqn	4B-23-03	PP858771
4B-22-37.sqn	4B-22-37	PP858772
4B-22-45.sqn	4B-22-45	PP858773
4B-23-17.sqn	4B-23-17	PP858774
4B-22-42.sqn	4B-22-42	PP858775
Z-18-224.sqn	Z-18-224	PP858776

C Chapter 4 supplementary files

Table S4: Completed TIDieR-PHP checklist for collar use in MDVs.

Item	Item description	Page in manuscript where item is reported	Other*
1 Brief name	Provide the name or a phrase that describes the intervention	81	
2 Why	Describe the logic, mechanisms, or rationale of the intervention, clearly linking intervention elements to the expected effects on immediate or longer term outcomes (or both)	81 – 83	
3 What materials	Describe any materials used in the intervention (including online appendices or URLs for further details). For example:—informational materials (may include those provided to recipients of the intervention or in training of intervention providers)—nature and value of any benefit provided (eg, cash, voucher, meal)—any physical resources or infrastructure provided as part of the intervention	81 – 83	

Continued on the next page

4 What and how	Describe how the intervention was planned, established, and intended to be delivered. Depending on the type of intervention, it may be useful to consider:—how sources of funding for the intervention and the service providers were obtained, how users were enrolled and the service delivered—how any payments were made or benefits delivered, how qualifying conditions were implemented—the entity being regulated, the scope of the regulation, permitted level of use; procedures for monitoring or enforcing compliance, and any sanctions for non-compliance—how people were exposed to the intervention, whether it was provided to individuals or larger populations—any underpinning legislation including name, date passed, and legislative body	81 – 83	
5 Who provided	Describe the provider of the intervention, including legal status and powers, field organisations and staff responsible for planning, implementation, monitoring and enforcement. Where relevant, describe intervention provider expertise and training (general or specific to the intervention)	81 – 83	
6 Where	Describe the type of location (eg, school, community centre) and the geographical scope of the intervention (eg, national, regional, city-wide). Where relevant, describe the historical, cultural, socioeconomic, or political background to the intervention	81 – 82	
7 When and how often	Describe when the intervention was implemented, how long it remained in place, and, if applicable, the number, duration, and scheduling of occasions	82	

Continued on the next page

8.1 Planned variation	Describe and provide the reason for any variation or tailoring that was planned or allowed for in the design of the intervention. Examples include differences between locations, geographical areas, population subgroups, or over time	83	
8.2 Unplanned variation	Describe and provide the reason for any unplanned variation or modifications in the intervention (eg, between different locations, geographical areas, population subgroups, or over time) that were made after the intervention commenced	93 – 101	
9.1 How well	Describe any strategies used or actions taken to maintain fidelity of the intervention (ie, to ensure that the intervention was delivered as intended)	84 – 85	
9.2 How well—delivery	Describe the fidelity of the intervention (ie, the extent to which the intervention was delivered as intended)	88 – 102	

* If the information is not provided in the primary paper, give details of where this information is available (eg, protocol, other published papers (provide citation details), or a website (provide the URL))

Table S5: Semi-structured interview topic guide for practitioners.

Purpose: To gather data on participant's views on how feasible it is to administer collars, by summarizing their recent experiences during the mass vaccination program, including perceived benefits of collars and barriers to implementation

NOTE: Before starting, ensure that the interviewee has been given an information sheet, which they have ample time to read, before obtaining their signed consent to transcribe the interview.

General Information	
What is your name?	
What is your designated job title?	
Please give a brief description of your position's responsibilities.	

Questions on Coherence	
From your perspective, what do you think collars are used for and why are they important?	
What were your experiences applying collars during the last mass vaccination? *(i.e. How long did it take, similar methods used in the past, how much effort was put into planning the event, learning experiences, points for improvement, etc.)*	
Do you think everyone, including community members, understands collars and what they are used for? *(i.e. Perception and acceptance of colleagues and community members, dog owners, etc.)*	

Questions on Collective Action	
Do you think collars can be integrated into future mass vaccinations, even those in other settings?	
How easy did you find it to administer collars?	
Do you have confidence in your own and in others' ability to apply collars?	
Do you think that you had the appropriate skill set and were given sufficient training for administering collars?	
Do you think sufficient training, resources and support are provided to staff? Does management support collar implementation?	
Do you think there is a supportive environment in implementing collars? Are community members and dog owners accepting of using collars?	

Questions on Reflexive Monitoring	
Are you aware of the impact of using collars?	
Do you think collar application has a big effect on dogs? Do they benefit or cause harm to dogs, directly or indirectly?	
How was knowledge shared among those implementing collars? Did colleagues and pet owners agree that collars are worthwhile? How do you find out, with others, how collars were received?	
Do you value the effects that collars have had on your work?	
Do you think that feedback about collars can be used to improve it in the future?	
Can you modify how you work with collars? Would you change your implementation of collars given your experience and/or feedback in this role?	

Barriers and Facilitators (if not already addressed earlier)	
What has helped/constrained collar application in terms of organizational aspects? *(i.e. Management and logistics during mass vaccination event)*	
What has helped/constrained collar application in terms of geographical aspects? *(i.e. Distance and scale)*	
What has helped/constrained collar application in terms of resources? *(i.e. Aside from money, time, labour)*	
What has helped/constrained collar application in terms of political aspects? *(i.e. Distribution of power amongst stakeholders and others with an interest in promoting or obstructing implementation of the intervention)*	
What has helped/constrained collar application in terms of policy & programme (national, regional, provincial, municipal)? *(i.e. Laws, regulations, ordinances, and mandates)*	
What has helped/constrained collar application in terms of socioeconomic aspects? *(i.e. Distribution of social and economic resources among communities or populations affected by the intervention)*	
What has helped/constrained collar application in terms of cultural aspects? *(i.e. Human-dog relations, traditions and practices, attitudes and behaviours)*	
What else has helped/constrained collar application in terms of other local, community or societal context?	

Unintended consequences	
What surprised you during the event?	

Table S6: Questionnaire guide with responses from San Isidro community members.

	Community member perceptions of dogs, rabies and collars		Frq.	%
A1	How old are you?	18-25 years old	2	3.3
		26-40 years old	19	31.7
		41-60 years old	30	50.0
		Over 60 years old	9	15.0
		Total	60	
A2	Are you male or female?	Male	22	36.7
		Female	38	63.3
		Total	60	
A3	What is your job/profession? (Select all that apply)	Tourism-related	28	46.7
		Transportation-related	8	13.3
		None	17	28.3
		Different industry	7	11.7
		Shop	4	6.7
		Barangay official	1	1.7
		Laundry-related	1	1.7
		Fisherman	1	1.7
		Total	60	
A4	Which barangay do you live in?	Aninuan	3	5.0
		Balatero	1	1.7
		San Isidro	54	90.0
		Santo Nino	1	1.7
		Tabinay	1	1.7
		Other barangays	0	0.0
		Total	60	
B1	How many dogs do you have?	None	17	28.3
		1	26	43.3
		2	8	13.3
		3	5	8.3
		More than 3	4	6.7
		Total	60	
B1.1	Where does your dog stay? (Select all that apply)	Inside the house	22	51.2
		Outside the house	20	46.5
		Tied	20	46.5
		Cage	3	7.0
		Free-roaming	9	20.9
		Total	43	
B2	When was your dog last vaccinated against rabies?	Less than 1 year ago	30	69.8
		More than 1 year ago	1	2.3
		Never vaccinated	12	27.9
		Total	43	
B2.1	Where was your dog vaccinated?	Mass vaccination event	25	80.6
		Private clinic	5	16.1
		Total	31	
B2.2	Why isn't your dog vaccinated? (Select all that apply)	Too young	3	25.0
		Too expensive	0	0.0
		Wanted to but too busy	0	0.0
		I didn't want to	0	0.0
		Other reasons	10	83.3
		Total	12	
B2.2.1	Other reasons for not vaccinating	Dog too big to transport	1	10.0
		Vaccination site too far	1	10.0
		I was not at home during event	3	30.0
		Vaccinator didn't visit	1	10.0
		Couldn't restrain/catch dog	3	30.0
		I didn't have a dog at the time	1	10.0
		Total	10	

C1	Are you fond of dogs?	Yes	24	40.0
		No	21	35.0
		Ambivalent	0	0.0
		Depends on the dog	15	25.0
		Total	60	
C1.1	Type of dogs you are fond of (Select all that apply)	Own dog only	6	60.0
		No answer	2	20.0
		Few only/sometimes	2	20.0
		Non-biting dogs	1	10.0
		Small and nice-looking dogs	1	10.0
		The ones my child likes	1	10.0
		Aspins/mixed breeds only	2	20.0
		Total	15	
C2	Are you afraid of dogs? (Select all that apply)	I'm not scared of any dog.	10	16.7
		I'm afraid of dogs I don't know.	15	25.0
		I'm afraid of rabid dogs.	6	10.0
		I'm afraid of certain dogs.	36	60.0
		I'm afraid of all dogs.	2	3.3
		Total	60	
C2.1	Type of dogs you are afraid of	Aggressive/biting dogs	14	38.9
		Big dogs	6	16.7
		Stray/free-roaming dogs	8	22.2
		Aspins/mixed breeds	3	8.3
		Unowned dogs	1	2.8
		Aggressive and large	1	2.8
		Aggressive and free-roaming	1	2.8
		Scary-looking	1	2.8
		Large and free-roaming	1	2.8
		Total	36	
C3	Have you ever been bitten by a dog? (Select all that apply)	No	39	65.0
		Yes, by an owned dog	13	21.7
		Yes, by a stray/free-roaming dog	7	11.7
		Yes, by my own dog	3	5.0
		Total	60	
C3.1	If yes, how many times have you been involved in a dog biting incident?	1	16	76.2
		2	2	9.5
		More than 2	3	14.3
		Total	21	
C.3.2	Where did this/these incident(s) take place?	Public place	13	61.9
		Inside someone else's house	5	23.8
		Inside my house	2	9.5
		In another private place	1	4.8
		Total	21	
C4	Are you comfortable interacting with a dog that isn't yours?	Yes	6	10.0
		No	39	65.0
		Depends on the dog	15	25.0
		Total	60	
C4.1	Type of dogs you would interact with	Known	4	26.7
		Kind/looks kind	6	40.0
		Aspin/mixed breeds only	2	13.3
		Good-looking dogs	1	6.7
		Specific dogs only	1	6.7
		Total	15	
C5	Do you think the number of dogs has increased in the past year?	Yes, more owned and free-roaming dogs	30	50.0

		Yes, more free-roaming dogs	23	38.3
		Yes, more owned dogs	3	5.0
		No	4	6.7
		Total	60	
C6	How often do you see free-roaming dogs?	Everyday	56	93.3
		Sometimes (depends on the place)	4	6.7
		Several times a week	0	0.0
		Not often (less than once a week)	0	0.0
		Rarely (once ever few weeks)	0	0.0
		Total	60	
C7	What do you think of free-roaming dogs? (Select all that apply)	Dogs should stay at home.	51	85.0
		I don't like them.	26	43.3
		Their presence doesn't bother me.	14	23.3
		People should own fewer dogs.	8	13.3
		People should own more dogs.	4	6.7
		Dogs should stay outside the house.	4	6.7
		Total	60	
C7.1	What bothers you about free-roaming dogs? (Select all that apply)	Biting people	38	63.3
		Dog waste	29	48.3
		Motor accidents	22	36.7
		Rabies	19	31.7
		Biting other dogs	3	5.0
		Other reasons	21	35.0
		Total	60	
C7.1.1	Other reasons	Going through garbage	8	38.1
		Destroying sandcastles	1	4.8
		Destroying property	1	4.8
		Bothering tourists	1	4.8
		Stealing food	4	19.0
		Chasing people	2	9.5
		Noise	4	19.0
		Fighting each other	1	4.8
		Total	21	
D1	Have you seen dogs wearing collars?	Yes, everyday	31	51.7
		Yes, on some days	10	16.7
		Yes, once or twice	2	3.3
		No	17	28.3
		Total	60	
D2	Do you know what the collars are for?	Yes, I participated in the mass vaccination	20	46.5
		Yes, someone who participated in the vaccination told me	7	16.3
		Yes, someone I know told me	6	14.0
		Yes, someone who volunteered during the mass vaccination told me	1	2.3
		Yes, I realized it on my own	5	11.6
		No	4	9.3
		Total	43	
D3	Do you think other community members know what the collars mean?	Yes, most know	23	53.5
		Only some know	7	16.3
		Only a few know	2	4.7
		Only dog owners know	9	20.9
		No one knows	1	2.3
		Total	43	

D4	Are you afraid of dogs wearing collars?	I'm not afraid because the dog has a collar	25	58.1
		I'm not afraid of dogs with or without collars	7	16.3
		I'm afraid of dogs with or without collars	11	25.6
		Total	43	
D5	If you were bitten by a dog wearing a collar, would you go to the hospital/ABTC?	I would go because the dog might have rabies	32	74.4
		I would go because ________	10	23.3
		I wouldn't go because _______	0	0.0
		I wouldn't go because the dog doesn't have rabies	1	2.3
		Total	43	
D5.1	Reasons for going	To be safe/sure	3	30.0
		Can't say if dog has rabies or not	1	10.0
		Doctor said even vaccinated dogs can transmit rabies even if they don't get rabies	1	10.0
		It depends	1	10.0
		If within budget	1	10.0
		I would go because I don't trust the owner	3	30.0
		Total	10	
D6	What do you think collars are used for? (Select all that apply)	Informs me that the dog is vaccinated against rabies.	39	90.7
		Informs me that the dog is owned.	4	9.3
		It informs me that the dog can be touched	0	0.0
		It informs me that ________	2	4.7
		None of the above	2	4.7
		Total	43	
D6.1	Informs me that _____	The dog has no owner	1	50.0
		For survey purposes	1	50.0
		Total	2	
D7	Are your dogs currently wearing collars?	Yes, my dog participated in the MDV	19	44.2
		No, I wasn't aware of the MDV	8	18.6
		No, I didn't allow my dog to be vaccinated because ______	7	16.3
		No, I wanted my dog to join but _______	5	11.6
		No, my dog wasn't collared even though it was part of the MDV	3	7.0
		Total	43	
D7.1	Dog wasn't vaccinated because _______	Too young	1	9.1
		It's already vaccinated	2	18.2
		I wasn't at home	1	9.1
		Too far	1	9.1
		Dog couldn't be restrained	2	18.2
		I didn't have a dog at the time	1	9.1
		Dog has mange	1	9.1
		Dog bit the collar off	1	9.1
		I was given the collar but I couldn't put it on	1	9.1
		Total	11	
D7.2	If your dog has a collar, is it comfortable wearing one?	Yes, my dog(s) is/are comfortable	11	57.9
		No, my dog(s) is/are not comfortable	7	36.8
		Some are comfortable, some are not	0	0.0

		I don't know	1	5.3
		Total	19	
D7.2.1	Did you remove or will you remove the collar(s)?	Yes, because _______	12	60.0
		Yes, while bathing the dog	0	0.0
		Yes, if it bothers the dog	0	0.0
		Yes, if my dog is vaccinated again next year	0	0.0
		Yes, if a health worker advises me	0	0.0
		No	8	40.0
		Total	20	
D7.2.1.1	Reasons for removal (Select all that apply)	Bitten off	4	33.3
		Some said to remove it when the dog is vaccinated	1	8.3
		Dog got bigger	1	8.3
		It was loose	1	8.3
		It split down the middle (broke)	1	8.3
		It fell off	2	16.7
		Too tight	1	8.3
		Used it only to keep the dog indoors for New Year	1	8.3
		Wasn't given collar	1	8.3
		Bitten off by another dog	1	8.3
		Total	12	
E1	Are you concerned about rabies? (Select all that apply)	I am concerned whenever I see any dog	36	60.0
		I am concerned whenever I am bitten by a dog	17	28.3
		I am concerned whenever I see certain dogs	14	23.3
		I am concerned whenever I am bitten by an unvaccinated dog	7	11.7
		I am concerned if someone tells me about a dog with rabies.	4	6.7
		I am not concerned about rabies.	4	6.7
		Total	60	
E2	Do you think your dog(s) is/are protected against rabies?	Yes, because my dog was vaccinated less than a year ago.	19	44.2
		Yes, because my dog doesn't play with other dogs.	6	14.0
		Yes, because my dog was vaccinated more than a year ago.	1	2.3
		No, my dog can always get rabies.	17	39.5
		Total	43	
E3	Can a dog not wearing a collar get rabies?	Yes	37	86.0
		No	3	7.0
		I don't know	3	7.0
		Total	43	
E4	Do you think a dog wearing a collar can get rabies?	Yes	34	79.1
		No	3	7.0
		I don't know	6	14.0
		Total	43	
E5	If you are bitten by a dog not wearing a collar, what actions would you take to avoid getting rabies? (Select all that apply)	Go to the hospital/ABTC for PEP	41	95.3
		Wash the wound	19	44.2
		Consult doctor/nurse	9	20.9
		Quarantine the biting dog	8	18.6
		Tandok	7	16.3
		Consult friends/family	5	11.6

		Kill the biting dog	1	2.3
		Send/give away the biting dog	1	2.3
		Nothing	0	0.0
		Punish the biting dog	0	0.0
		Total	43	
E6	If you are bitten by a dog wearing a collar, what actions would you take to avoid getting rabies? (Select all that apply)	Go to the hospital/ABTC for PEP	39	90.7
		Wash the wound	20	46.5
		Consult doctor/nurse	10	23.3
		Quarantine the biting dog	7	16.3
		Tandok	7	16.3
		Consult friends/family	4	9.3
		Kill the biting dog	1	2.3
		Send/give away the biting dog	0	0.0
		Nothing	1	2.3
		Punish the biting dog	0	0.0
		Total	43	

Table S7: Examples of interview quotes categorized under 16 secondary constructs.

Coherence (sense making work)	**Cognitive participation** (relational work)	**Collective action** (operational work)	**Reflexive monitoring** (appraisal work)
Differentiation "*It depends. If the dog was very friendly, it would be very easy for me, like, less than 1 minute. But if the dog was not used to being touched then it would take more than—between 1 and 10 minutes.*" –Volunteer Veterinarian-1	Initiation *"Before we scheduled the mass vaccination, they told us on that day that there would be people from Agriculture coming. So that afternoon, before they announced the mass vaccination, I already told those in my area that there'll be a vaccination tomorrow, vaccines for cats and dogs. They said "okay, Ma'am, got it." That's why they prepared."* –Barangay Health Worker-1	Interactional workability "*The dogs, when putting on the collar, it was really easy, around 5 minutes or less. Not more than that if the dog wasn't going wild and could be held. When it came to vaccinating, it was also easy, mere seconds. But there were times that the animal couldn't be injected or the owner couldn't secure the pet, which would take long.*" –Government Staff Member-4	Systematization "*Definitely, as someone in the private sector, and then, if you're gonna do something like this in one locality then definitely, the SOP there would be to coordinate with the LGU within the area.*" –Volunteer Recorder-2
Communal specification *"They were aware of the purpose and why we were conducting the mass vaccination and the inclusion of collars, so that there'd be a sense of safety among the community, why the collars were used, to be aware of the pets in the vicinity."* –Government Staff Member-5	Enrolment *"We had to figure out the logistics. Everything that was needed for the vaccination, we had to ready. Such as the freezer, the ice, just like—the supplies that were needed, such as the extensions, and pentel pens. Those were prepared, too."* –Government Staff Member-6	Relational integration *"No one complained. They were really happy. Whenever we'd give the collars, there'd be people saying "Wow, there are free collars"."* –Government Staff Member-2	Communal appraisal "*When it comes to the domestic animals, particularly the strays, if you see a collar, you can conclude—for example, if tourists see them and ask why there are collars on strays, we can explain their purpose. We can explain why they're wearing collars, say that we conducted a mass vaccination, and the tourist will think that even the animals aren't being neglected by the LGU.*" –Government Staff Member-6
Individual specification "*We know whose house belongs to who, because each worker has an area that he/she is in charge of. We knew where to go for each area.*" –Barangay Health Worker-2	Legitimation "*When they announced the mass vaccination, I already told those in my area that there'll be an event tomorrow, vaccines for cats and dogs. They said "Okay, got it." That's why they prepared.*" –Barangay Health Worker-1	Skill set workability "*If the dog is aggressive, it's hard. It's really hard.*" –Volunteer Veterinarian-2	Individual appraisal *"We still visit them. Someone will walk in, and want to schedule with us, then depending on their availability, we plan a visit."* –Government Staff Member-5

Internalisation "*Another benefit, specifically for Puerto Galera, is because it's a tourist spot, Because there are so many free-roaming animals, so if they see a lot of dogs with yellow collars—of course, they'd feel more confident walking around, and then of course [it's better] for the LGU since they're handling the rabies vaccination.*" –Volunteer Recorder-1	Activation "*It was a very easy lesson. We witnessed the actual application so it was easy to learn how to put the collars on the dogs. The applying of collars was done on the spot. We were going to vaccinate, it was demonstrated to us once and we got it immediately.*" –Government Staff Member-4	Contextual integration "*I think what's nice about it is we partnered with the LGU in that area up to the barangay level. So the barangay officials are more familiar with the community that you're going to, so that's a good thing. It should be continued, the close coordination, close participation, on both sides. It leads to the successful implementation of vaccination.*" –Volunteer Recorder-2	Reconfiguration "*There should be an infographic, printed infographics for the vaccination team so that they would have prepared information readily available to explain to the pet owner as to why the collar is needed and so that they don't leave out necessary information to convince the owners of the pros and cons.*" –Volunteer Veterinarian-1

D Chapter 5 supplementary files

During a mass dog vaccination event in Puerto Galera, all adult dogs that were vaccinated were collared. The total number of vaccinated dogs per barangay was recorded. In six barangays (Palangan, Poblacion, Santo Niño, Sinandigan, San Isidro and Tabinay), mark-recapture surveys were conducted to collect data on sighted collared (vaccinated) and non-collared (non-vaccinated) dogs. The Bayesian statistical model used was adapted from Gsell et al. (Gsell et al., 2012), using code available in the the Supplementary Material. Below are parameters used in the model. Uniform prior distributions serving as probabilities of recapture and of confinement were based on questionnaire responses from Chapter 4.

Table S8: Parameter estimates of Bayesian model.

	Palangan	Poblacion	Santo Niño	Sinandigan	San Isidro	Tabinay
Vaccinated dogs ($M_v^{(i)}$)	145	314	396	446	583	335
Unmarked sighted dogs ($Z_t^{(i)}$)	220	324	243	166	306	365
Marked sighted dogs ($X_1 t^{(i)}$)	1	86	78	58	193	16
Petersen-Bailey estimate of owned dogs ($M^{(i)}$)	16,095	1,483	1,614	1,700	1,503	7,528
Recapture probability ($p_t^{(i)}$)	0.49	0.49	0.49	0.49	0.49	0.49
Confinement probability for owned, collared dogs ($c_1^{(i)}$)	0.20	0.63	0.69	0.41	0.43	0.19
Confinement probability for owned, non-collared dogs ($c_2^{(i)}$)	0.48	0.35	0.29	0.12	0.26	0.20

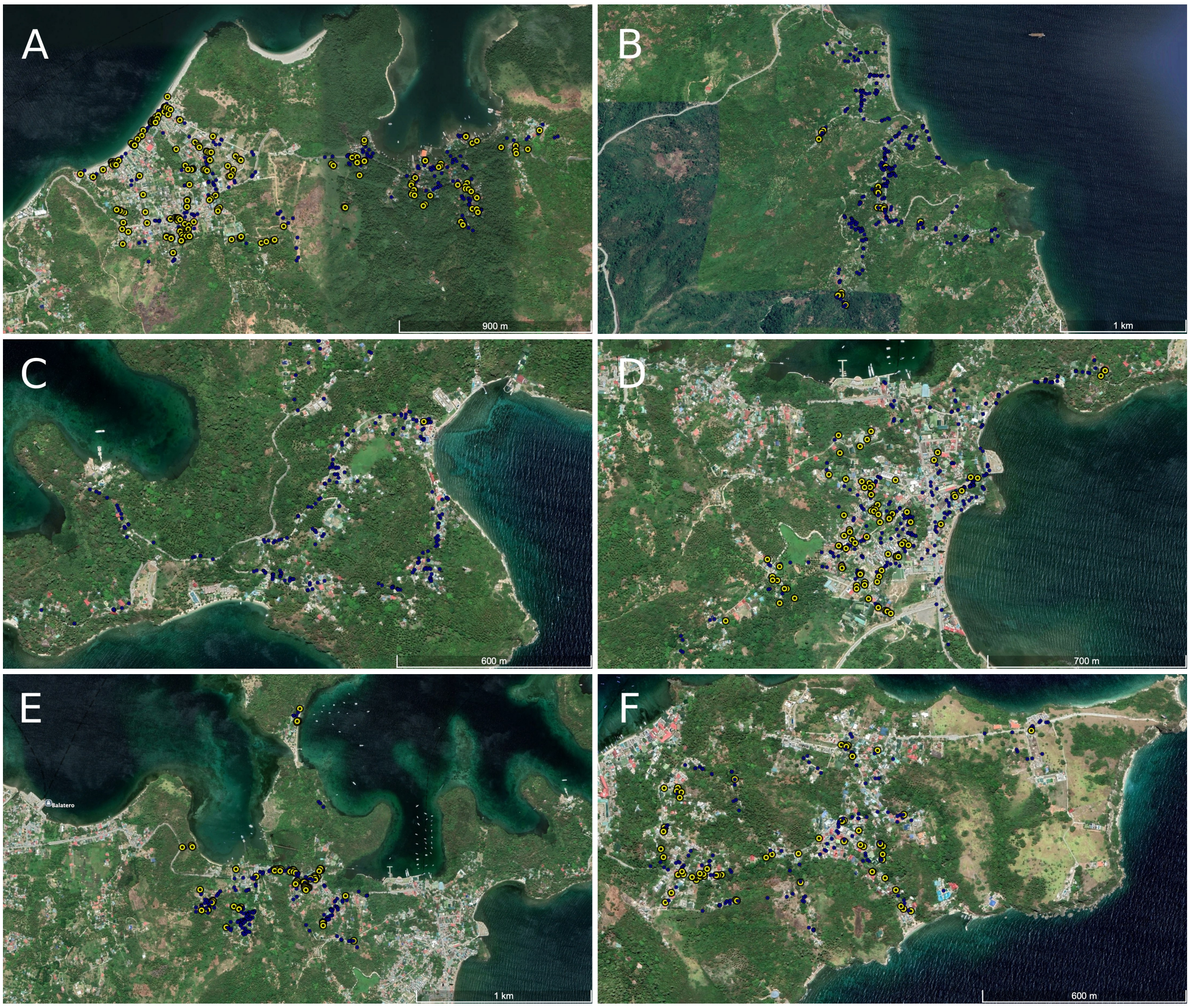


Figure S5: Maps showing collared (yellow) and non-collared (blue) dogs in Puerto Galera's barangays: A) San Isidro, B) Tabinay, C) Palangan, D) Poblacion, E) Santo Niño, and F) Sinandigan.

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