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Measuring, monitoring and improving mass dog vaccination programmes to control and eliminate rabies

by

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Abstract

Rabies is an acute viral infection which causes horrifying neurological symptoms that inevitably result in death. Every year at least 59,000 people are estimated to die from rabies and more than 10 million are treated with post-exposure prophylaxis (PEP). Over 90% of human rabies deaths occur in Asia and Africa following bites from domestic dogs. Although human rabies deaths are 100% preventable through the delivery of prompt PEP to bite victims following a bite, PEP is not accessible to many poor rural victims, most of whom subsist on less than US$1.25/day.

Empirical and theoretical evidence shows that mass dog vaccination that reaches 70% of susceptible dog population can interrupt the transmission cycle. Rabies has been eliminated from industrialized countries through mass dog vaccination, and the continent-wide elimination of canine rabies from the Americas is now within reach. In contrast, no effective large-scale control of dog rabies has been achieved in Africa and information is still needed to optimise and sustain dog vaccination programmes.

The aim of this thesis was to evaluate the rabies control programme in Tanzania. This thesis is presented as a series of three standalone chapters (Chapters 2-4) that are introduced and then summarised by a general introduction (Chapter 1) and a general discussion (Chapter 5) respectively.

Achieving high coverage is the most important aim of any vaccination programme; however, assessing the vaccination coverage achieved is often neglected in rabies endemic countries. In Chapter 2, I compare three methods of measuring vaccination coverage (post-vaccination transects, school-based surveys, and household surveys) across 28 districts in different settings in southeast Tanzania and Pemba island in order to determine which is most precise method. These approaches were explored in detail in a single district in northwest Tanzania (Serengeti), where their performance in producing precise estimates of coverage was compared with a complete dog population census that also recorded dog

vaccination status. Our analysis found that transect studies (counting vaccinated and unvaccinated dogs) immediately after the campaign is cheap, quick, and provides precise estimates. Therefore, transects were considered more appropriate for routine monitoring of mass vaccination campaigns than household or school-based surveys.

In Chapter 3, I used data from Chapter 2 together with human population census data from Tanzanian Bureau of Statistics to develop a model for estimation of the size of dog populations in Tanzania. Knowledge of the size of the dog population is necessary to adequately plan and achieve the target of vaccinating 70% of susceptible dogs. I demonstrate that estimating dog population size using transect data gave more precise results than either household or school-based surveys. Therefore, transect data were used to develop a predictive model for estimating dog populations in districts lacking transect data. Using this model, I predict a dog population of 2.32 (95% CI 1.57,3.12) million in Tanzania and an average human to dog ratio of 20.7:1.

In Chapter 4, I evaluate the implementation and performance of large-scale dog vaccination campaigns against rabies in Tanzania. For an effective rabies control and elimination, it is necessary to conduct vaccination campaigns in every village/street (completeness), achieve coverage of 70% (coverage) and return for dog vaccination within one year (timeliness). Therefore, in this Chapter 4, I assessed vaccination campaigns in terms of completeness, coverage and timeliness; I also investigated factors associated with and potentially causing success or failure of mass dog vaccinations, in terms of completeness and coverage.

Overall, this study shows that Tanzania experienced notable challenges in the delivery of mass dog vaccinations. For example, although vaccination completeness improved over time, until the last two rounds of vaccinations, only 25% of districts had 100% campaigns completeness. Additionally, very few districts (27-36% of the study districts) achieved the recommended vaccination coverage of 70% between third and fifth round of vaccinations. Vaccination interval was planned to be annually but vaccinations delayed to more than two years, as a result, vaccinations were conducted in pulsed approach (not annually).

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Dedication

Dedicated to my grandmother Brelia Burton Kahema, a woman with a heart of gold, who passed away in 2015 without seeing my graduation whom I miss every day.

and

To those who lost their life because of rabies. May these thesis findings generate evidence for investments in controlling and preventing of rabies.

“Science knows no country, because knowledge belongs to humanity, and is the torch which illuminates the world” - Louis Pasteur (1822 -1895).

Rabies is an ancient and universally feared disease. Human deaths associated with dog bites were already identified since 2300 BC (Bos, 2014, Taylor and Nel, 2015). Despite being ancient and 100% preventable; rabies is still important today. Globally, ~2000 people are bitten by suspected rabid dog everyday, of those ~ 160 people die of rabies, most of them children (Hampson et al., 2015).

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Author’s Declaration

I, Maganga Burton Sambo, confirm that the work presented in this thesis is the result of my original research work. Where information has been derived from others, every effort has been made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions. Most of the data chapters in this thesis have been produced as stand-alone manuscripts for publication (or already published) and has been produced in co-authorship with others, and my personal contribution to each chapter is indicated in each data chapter:

Chapter 1: I solely conducted the literature review and all background information searches under supervision of PJ and KH.

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Chapter 5: I solely developed and wrote the final discussion chapter while supervisors reviewed the discussion chapter.

I further, declare that no part of this work has been submitted as part of any other degree. Furthermore, this study was approved by Ifakara Health Institute, the Medical Research Coordinating Committee of the National Institute for Medical Research of Tanzania (NIMR/HQ/R.8a/Vol.IX/2109) and Tanzania Commission for Science and Technology (COSTECH). Before administering any questionnaires, participants or headteachers were informed about the background and purpose of the study, highlighting that their participation was voluntary and that their answers would be kept confidential in a safe secure. Only participants who verbally agreed were interviewed. The dissertation does not exceed the required word limit.

Maganga Sambo,

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Abbreviations

CI	Confidence Intervals
CNS	Central nervous system
CVR	Capture-vaccinate-release
DALY	Disability-Adjusted Life Year
FAO	Food and Agriculture Organisation of the United Nations
GARC	Global Alliance for Rabies Control
GIS	Geographic Information Systems
GPS	Global Position Systems
HDR	Human dog ratio
IHI	Ifakara Health Institute
IRB	Institutional Review Board
Kms	Kilometre
LMICs	Lower middle-income countries
MDV	Mass dog vaccination
NBS	National Bureau of Statistics
NIMR	National Institute for Medical Research
OIE	World Organisation for Animal Health
OR	Odds ratio
PAHO	Pan American Health Organization
PAR	Puppies to adult ratio
PEP	Post-exposure prophylaxis
RABV	Rabies virus
RIG	Rabies Immunoglobulin
Sq.km	Square Kilometres
TZS	Tanzania Shillings
USA	United States of America
US$	United States of America’s dollar
UTM	Universal Transverse Mercator
VIF	Variance Inflation Factors
WHO	World Health Organization

Chapter 1 General Introduction

1.1 Background

Rabies is an ancient and much-feared disease that continues to pose a substantial threat to human and animal health. Over the centuries, rabies has been well documented by different authors, from clinicians, veterinarians, surgeons, pharmacists, philosophers and poets (Tarantola, 2017). For example, the first written reference of rabies was documented as early as 2300 B.C. in the "Law code of Eshnunna and mad dogs" in ancient Mesopotamia, or modern-day Iraq (Bos, 2014). These laws dictated that the owner of a dog showing symptoms of rabies should take preventive measures against bites. If a person was bitten by a rabid dog and later died, the law code prescribed that the dog owner had to pay two thirds of mina (40 shekels) in silver as compensation (Bos, 2014). The law further prescribed that if the dog bit a slave and caused his death the dog owner shall pay fifteen shekels of silver. Despite being the oldest reported zoonotic disease (Tarantola, 2017), rabies still kills tens of thousands of people each year today (Hampson et al., 2015).

In 1885, Louis Pasteur obtained his first success against rabies by vaccinating Joseph Meister, a 9-year-old boy presenting with multiple deep bite wounds, using desiccated nerve tissue containing the virus (Bourhy et al., 2010). By November 1886, around 2500 people had been successfully treated by Pasteur's method; and by the time of Pasteur's death in 1895 around 20,000 persons had undergone the treatment, with a mortality of less than 0.5% (Théodoridès, 1989). For control of rabies in animals, dog vaccinations were introduced in 1915 and the first country to implement large-scale mass dog vaccinations was Japan in the 1920s (Umeno, 1921, Taylor and Nel, 2015). These campaigns resulted in successful control and elimination of rabies in Japan in 1956. Since then, mass dog vaccination has been used successfully to eliminate dog-mediated rabies in all countries of Western Europe and North America, plus Japan and Malaysia (King et al., 2005, Hampson et al., 2007). Moreover, through mass dog vaccination the continent-wide elimination of canine rabies from the Americas is now within reach (Vigilato et al., 2013).

Whereas dog rabies has been successfully controlled and eliminated in most developed countries through dog vaccinations, it remains prevalent in Africa and Asia, where rabies control programmes have been unsuccessful or have not even begun. Currently, rabies causes an estimated 59,000 human deaths in the world annually (Hampson et al., 2015). Over 99% of these human rabies deaths occur in Africa and Asia and the vast majority of these deaths are due to bites from domestic dogs. Human rabies is 100% vaccine-preventable through two complementary interventions: first, administration of post-exposure prophylaxis (PEP) to people exposed to bites from rabid animals to prevent disease onset. The second intervention is through sustained mass dog vaccination to eliminate transmission from the main source (reservoir) of rabies, i.e. domestic dog populations (Cleaveland et al., 2018). Currently, more than 10 million people are administered PEP annually (Hampson et al., 2015). While human rabies can be effectively prevented with PEP, the intervention is expensive, with direct expenditure on PEP estimated at 1.70 billion USD per year and indirect costs estimated at 1.31 billion USD (Hampson et al., 2015). The burden of rabies falls disproportionately upon people in remote, rural communities where most rabies cases occur. A case study in Tanzania estimated that a patient from a rural area, where most people live on less than US$1.25 per day, would need to spend over US$100 to access and complete World Health Organisation (WHO) recommended PEP regimens (Sambo et al., 2013). Many families struggle to obtain these vaccines, because they cannot raise the required funds and because vaccines are often not stocked or are out of stock in local clinics, leading to poor compliance with PEP regimens, delays in presentation to health facilities, and increased risk of death (Hampson et al., 2008).

The human rabies vaccine is the only way to prevent rabies following a bite by a rabid dog, but it cannot control and eliminate rabies alone. A complementary intervention targeting vaccination at the animal reservoir is needed to control infection at source (Cleaveland et al., 2018). For example, many countries, particularly Asian countries, spend substantial resources on provision of PEP, with only limited investment in dog vaccinations, and human deaths continue to occur at an unacceptably high rate (Hampson et al., 2015). Mass dog vaccination is the most cost-effective strategy for preventing rabies in people by inoculating the reservoir host responsible for more than 99% of human infections (Cleaveland et al., 2003, Hampson et al., 2009, Kaare et al., 2009, Durr et al., 2009, Lembo et al., 2010, Fitzpatrick et al., 2014, Fahrion et al., 2017). A detailed cost analysis study found that canine mass vaccination has a higher cost-effectiveness than PEP alone and is less costly over a period of 15–20 years (Mindekem et al., 2017). Therefore, combined strategies of PEP to bite patients alongside mass dog vaccinations under a "One Health" approach would be optimal (Lankester et al., 2014, Cleaveland et al., 2018). One Health is an idea that reflects the interconnectedness of the health of human and animal populations, and therefore, a "One Health" approach is needed to tackle rabies (Lankester et al., 2014).

Theoretical and empirical research demonstrates that rabies can be eliminated by vaccinating 70% of the susceptible dog population. Maintaining 70% coverage through annual vaccinations would be enough to stop virus circulation, and stop human deaths (Coleman and Dye, 1996, Hampson et al., 2009). Case studies demonstrated that this 70% coverage target is achievable even in low- and middle-income countries (LMICs) through parenteral vaccination of dogs (Kayali et al., 2003, Kayali et al., 2006, Kaare et al., 2009). Control and elimination of dog rabies through mass dog vaccinations have been successful in different settings previously endemic for dog rabies (Jibat et al., 2015, Cleaveland et al., 2018). Furthermore, controlling dog rabies through dog vaccinations reduces demand for PEP (Cleaveland et al., 2003, Lavan et al., 2017).

Rabies has several epidemiological features that make it amenable to elimination through mass dog vaccination: first, the existence of the means to fight rabies through safe and effective vaccines, which were developed more than 100 years ago. Second, domestic dogs, not wildlife, are the main cause of about 99% of human rabies cases (Knobel et al., 2005, Hampson et al., 2015). In the wildlife–rich Serengeti ecosystem in Tanzania results from epidemiological and genetic analyses suggest that domestic dogs are the only population essential for maintenance with occasional but short-lived chains of infection in wildlife resulting from spill over from domestic dogs (Lembo et al., 2008). Third, the basic reproductive ratio ($R0$ – the expected number of secondary infections produced from a primary case) of canine rabies is consistently low (~1.2) even across populations that differ widely in dog density (Hampson et al, 2009). The low R0 for rabies suggests that the disease should be feasible to control in most, if not all, populations across the world (Hampson et al., 2009, Taylor and Nel, 2015). Fourth, mass vaccination programmes demonstrated that most free-roaming dogs could be vaccinated, and that higher levels of coverage above the critical threshold is achievable. In Africa, studies show that despite the appearance of being stray, at least one household usually claims ownership of free-roaming dogs and most of these animals are accessible to parenteral vaccination through central-point campaigns (Kaare et al., 2009, Lembo et al., 2010, Gsell et al., 2012, Davlin and VonVille, 2012, Vigilato et al., 2013). In Asia, large numbers of free-roaming dogs have also been vaccinated using catch-vaccinate-release (CVR) methods in areas where dog ownership appears to be less clear cut (Gibson et al., 2019). Fifth, despite their apparently poor condition, village dogs respond effectively to rabies vaccine (McNabb, 2008).

These epidemiological features provided important evidence and further catalysed advocacy for investment in dog vaccinations. In December, 2015, the WHO, the World Organisation for Animal Health (OIE), the Food and Agriculture Organization of the United Nations (FAO), and the Global Alliance for Rabies Control (GARC), a coalition known as “United Against Rabies collaboration”, endorsed a global framework to eliminate human deaths from dog-mediated human rabies by 2030 (Abela-Ridder et al., 2016).

The road to zero human deaths from dog-mediated rabies is characterized by three distinct programmatic phases: control, elimination and maintenance phase. To understand the process of eliminating dog-mediated human rabies it is important to adhere to agreed concepts of control, elimination and maintenance. Control of an infectious disease has been defined as: “a reduction in disease incidence, prevalence, morbidity, or mortality to a locally acceptable level, as a result of deliberate efforts” (Dowdle, 1998). Whereas elimination of an infectious disease refers to the interruption of local transmission of the organism and the reduction-to-zero case incidence from a defined geographical area (Dowdle, 1998). Maintenance is the continued measures (efforts) to prevent the re-establishment of transmission. When the country is free from the infectious disease of interest it receives a WHO certification, which confirms to the international community that the country, at that time, has halted local transmission and has created an adequate system for preventing re-establishment of the disease. Dog rabies has been eliminated in large parts of the industrialized countries in Europe and North America (Hampson et al., 2007). The continent-wide elimination of dog rabies from the Latin American countries is now within reach (Vigilato et al., 2013). In contrast there has only been very limited dog vaccinations in most African countries (Hampson et al., 2015).

A stepwise approach (the Stepwise Approach towards Rabies Elimination, SARE), has been developed for rabies control, where a country can use this tool to evaluate it's efforts in controlling rabies (The Global Alliance for Rabies Control et al., 2020). The SARE tool serves as a self-assessment and practical guide in developing a national rabies program. The SARE score shows clear progress (or lack thereof) in each of the three distinct programmatic phases (control, elimination and maintenance).

To reach zero human deaths, more than 100 countries in which rabies is currently endemic would need to implement nationwide dog vaccination campaigns. However, lessons learned from previous rabies elimination programmes in developed countries, and experiences from successful programmes in Latin America and the Caribbean, as well as pilot projects in different parts of the world such as Bangladesh, the Philippines, Sri Lanka, Vietnam, Tanzania and South Africa, have generated important knowledge and clearly highlighted basic scales that can be used to measure performance of the campaigns for the control and elimination of rabies (Hampson et al., 2009, Vigilato et al., 2013, Townsend et al., 2013, Ferguson et al., 2015, Mpolya et al., 2017, Velasco-Villa et al., 2017, Minghui et al., 2018). These scales include: campaign completeness, dog vaccination coverage and campaign timeliness and are briefly described below.

Vaccination campaigns must vaccinate 70% of the susceptible dog population in every year to break transmission. Therefore, knowledge of the dog population size is required for assessing the effectiveness of mass dog vaccination campaigns. In most of LMICs, reliable data on the size of dog populations are rarely available.

Since reliable data does not exist, assessing the effectiveness of mass dog vaccination campaigns is a challenge in LMICs. Data from post-vaccination surveys such as household surveys, and mark-recapture methods, for example by photographic census and transects, have been used for assessing the performance of vaccination campaigns. These surveys are also used to generate estimates of the human-to-dog ratio (HDR), which can be extrapolated to larger regions. However, there has been no study that comprehensively compared these methods and assessed which approach provides the most accurate or precise estimates of coverage. This comparison is needed to provide operational guidance to improve the performance of current or future dog vaccination campaigns.

In most dog rabies-endemic areas, vaccination coverage levels decline rapidly as vaccinated dogs die and are replaced by new-borns susceptible dogs (Hampson et al., 2009, Gsell et al., 2012, Czupryna et al., 2016). To eliminate rabies, annual campaigns must vaccinate at least 70% of each community's susceptible dog population in order to maintain the minimum coverage above 20 – 45% (the critical threshold, P_{crit}) throughout the year (Hampson et al., 2009). In areas with high dog population turnover, a campaign target (P_{target}) of vaccinating 70% of the susceptible dog population is required for population immunity to remain at all times above P_{crit} (Hampson et al., 2009). Timeliness of campaigns further influences their effectiveness. Long intervals between vaccination campaigns results in coverage dropping below P_{crit} and therefore allows sustained transmission. Lessons learned from Tanzania showed that delivering timely campaigns is still a challenge, and it is particularly hindered by financial, organisational, operational and logistical challenges (Mpolya et al., 2017).

Elimination prospects depend on completeness of vaccination coverage and the rate of re-introductions (Townsend et al., 2013). Across most of Western Europe, campaign completeness of oral rabies vaccination campaigns speeded up the elimination of fox rabies, reducing cases from 17,202 in 1978 to 7,581 cases in 2010 (Freuling et al., 2013). Recent work from Asia has also highlighted that unvaccinated villages can jeopardize control and elimination efforts. Models indicated that even small gaps in coverage (unvaccinated communities) can significantly delay time to elimination (Townsend et al., 2013).

1.2 Dog ownership in relation to rabies control.

Previous studies in Africa have highlighted that vaccination efforts are influenced by local dog ownership practices (Wallace et al., 2017, Gsell et al., 2012, Sambo et al., 2014). Most publications have suggested that dog keeping is much more common in rural areas compared to urban areas (Davlin and VonVille, 2012). I used the criteria of the Tanzanian National Bureau of Statistics (NBS) in differentiating rural and urban areas (National Bureau of Statistics, 2012). The definition of urban areas according to NBS, applied in this study, is that urban areas are regional and district headquarters with boundaries as identified by the Tanzanian Village Act of 1975 and The Urban Ward (Administration) Act of 1976. According to the NBS, regions are sub-divided into districts, and districts into wards. Wards in urban districts are sub-divided into streets, while those in rural districts are sub-divided into villages. Thus, a village (in a rural area) or a street (in an urban area) is the lowest government administrative unit. Rural areas are characterised by fewer settlements, large household sizes, lower human population density and greater poverty. In most developing countries, rural incomes appear to be far lower than urban incomes (Young, 2013). Much of the developing world's population lives in rural areas and agriculture plays a key role in national and local economies. For example in Tanzania, approximately 3.6 million people from 158,690 households depend on agriculture, and agricultural sectors contribute 56% of the country's domestic income (National Bureau of Statistics, 2012). Other communities fully or partly depend on livestock-keeping. As in most of sub-Saharan Africa, throughout Tanzania, dogs are widely used for herding, and for protecting families, crops and livestock against wild animals and thieves (Bardosh et al., 2014).

Differences in livelihood patterns between a range of systems (e.g. town, farmland and pastoral) have been demonstrated to influence human-dog relationships and the spatial distribution of dogs (Bardosh et al., 2014). Understanding of practices associated with dog ownership, and, most importantly, of the responsibility for vaccinating dogs are important steps towards the effective design and implementation of mass dog vaccinations. A recent publication found that all dogs in higher-income villages were reportedly vaccinated against rabies (Wallace et al., 2017). Additionally, studies in Africa found that dog keeping is much less common in urban and Muslim communities (Davlin and VonVille, 2012, Knobel et al., 2008, Bardosh et al., 2014). There are generally broad similarities for the predictors of dog ownership across Africa (Davlin and VonVille, 2012).

Understanding the ownership patterns and roles of dogs in a community is important for deciding upon an appropriate vaccination method and strategy, thereby ensuring enough dogs are reached and vaccinated to break the cycle of rabies transmission. Dog populations can be categorized based on (1) ownership status (owned, community, feral), and (2) the confinement status (confined, semi-confined, free-roaming). A dog that depends on a household/family is called an owned dog, while a dog that depends on the community a called community-owned dog (Taylor et al.). Dog rabies is transmitted from a rabid dog to a susceptible dog through bites. Transmission therefore depends on frequency contacts between rabid and susceptible dogs. Therefore, confined owned dogs have less risk of contacting rabid animals and therefore are not in practice as susceptible to rabies as free-roaming dogs (owned and feral) (Taylor et al.). Not all of owned dogs should therefore be targeted for mass dog vaccinations. For example, in developed countries, such as Australia, the United Kingdom and the United States of America (USA), most of their dogs are confined, if not confined their dogs (known as pet dogs) are always under the direct control of their owners. In urban areas where people keep dogs in confined spaces, there is a lower rabies risk due to fewer effective contacts between animals and easier access to veterinary services. On the other hand, in much of Africa, Asia and Latin America most of the dogs are free-roaming dogs and when exposed to bites by rabid animals, their owner may not be aware. These free-roaming dogs (family or community-owned dogs) are susceptible for rabies transmission and should be targeted for mass dog vaccinations.

The current dog vaccination methods are either parenteral vaccination or oral vaccination (Kaare et al., 2009, Estrada et al., 2001). Understanding the different characteristics of dog ownership in different settings will be crucial to decide which delivery strategy to use. The delivery strategies include: central-point, house-to-house, oral bait and capture-vaccinate-release (CVR). Different campaign strategies will reach different segments of the dog population. For example, owned dogs can usually be vaccinated efficiently at central vaccination points. This method has been reported to be effective in agropastoral communities in Tanzania and in urban areas in Africa (Kayali et al., 2006, Kaare et al., 2009, Gsell et al., 2012). However, not all owned dogs can be vaccinated at central vaccination points. Experience from Tanzania has shown that central vaccination points in pastoral communities achieved only low coverage (Kaare et al., 2009). Pastoral communities that live in remote and dispersed rural areas, often have dogs that are less used to handling and restraint and families are often absent during seasonal transhumance movements and therefore require the adoption of a door-to-door vaccination strategy (Kaare et al., 2009). However, door-to-door vaccination is time-consuming and expensive, particularly for a national-wide elimination program (Kaare et al., 2009). Moreover, dog densities in pastoralist areas are too low for rabies to be maintained. The focus should therefore be to eliminate the infection in agropastoral communities that tend to have higher dog densities (Sambo et al., 2018). For ownerless dogs (with no responsible person to take dogs to vaccination points, particularly in urban areas of Asian countries), the CVR strategy could be used whereby mobile vaccination teams (dog catchers) catch vaccinate and release vaccinated dogs. Another method that can be applied to both owned and ownerless dogs is the use of oral baits, whereby oral baits can be distributed to dog owners or the dedicated teams can distribute baits to ownerless dogs (Gibson et al., 2019). However, to assess the effectiveness of baits methods reported to be difficult as it is not possible to physically mark all dogs that consume baits (Gibson et al., 2019). These methods are also time-consuming and expensive (Gibson et al., 2019). Therefore, vaccination strategies should be tailored to local contexts based on the human-dog relationship or characteristics of the dog. Door to door, oral baits, and CVR strategies are not easily scalable because of their costs and time-consuming nature, but they can supplement to central point methods to ensure sufficient dogs are vaccinated (Kaare et al., 2009, Gibson et al., 2019).

1.3 Methods for data generation

1.3.1 Mass dog vaccinations

In the study districts in Tanzania, dog vaccinations were conducted using a central point approach, which has proven effective for accessing a large proportion of the dog population in other parts of Tanzania (Kaare et al., 2009). In each district, annual mass dog vaccination campaigns were managed and supervised by the District Veterinary Officer or the Head of the Livestock Department. In urban districts, mass dog vaccinations were carried out (implemented) at the ward level while in rural districts mass dog vaccinations were carried out at the village level. In this thesis, we consider these areas (i.e. ward or village) where dog vaccination was carried out as a vaccination unit. Ideally, each vaccination unit had one or more central vaccination points depending on the geographical areas of the vaccination unit. To reach more dogs, some vaccinators decided to have more vaccination points per vaccination unit. Prior to vaccinations, communities were informed about the campaign (free dog vaccinations, place, time and the day of the campaign) using loud-speakers, posters, announcements at schools and using community messengers urging dog owners to bring their dogs for vaccinations. In most cases, dog vaccinations began at 7 A.M. in the morning and lasted 3.30 PM in the evening. However, in some areas vaccinators did not achieve these specified hours at central points and vaccination update was reduced (Bardosh et al., 2014). Despite this problem, the number of vaccinated dogs in these areas were included in my analysis. At each vaccination point, most of the time, dog owners restrained the dog, a livestock field officer (dog vaccinator) injected the vaccine and asked dog owners to put a temporary plastic collar around the neck of their vaccinated dog before going to the recorder (Figure 1-1). The recorder (registrar) who was normally a volunteer from the local community collected information (address of the dog owner, sex, age and colour of the dog) and then recorded this information into the register. They then issued a vaccination certificate to the dog owners to validate the vaccination status of their dogs. Vaccination campaigns were normally conducted over a one-day period per vaccination unit. Register data on dogs vaccinated were compiled and used in subsequent calculations for the different methods of estimating coverage and dog population sizes in all the following analyses.

Figure 1-1: Image of vaccinated (and marked with collar) Tanzanian dogs.

1.3.2 Post-vaccination evaluations

Three methods were used to evaluate the effectiveness of dog vaccination campaigns:

1.3.2.1 Household surveys (HHSs)

Household surveys (HHSs) were conducted in all districts in south-eastern Tanzania and Pemba. Six villages were randomly selected from a list of all villages in each of the study districts. Then, thirty households in each of the six 6 villages per district were visited to conduct the household survey. In every randomly selected village, a key village landmark (e.g. such as a dispensary, school, church or mosque) was identified and used as the starting point. At the starting point, an interviewer spun a pen to get the direction for interviews (Kongkaew et al., 2004). Then, the households along the roadside in the chosen direction were included and interviewed until 30 households were completed in each village. These household surveys were conducted in July and August 2011, around 4 months after dog vaccination campaigns conducted in March and April 2011. Interviewers were accompanied by members of the local authority to identify village households and to introduce the interviewer to the households. Prior to the administration of the questionnaire, permission was sought from the household head or other household members of at least 18 years of age in the absence of the household head. For households that owned dogs, the questionnaire captured details of dogs owned (adults and puppies <3 months) and their vaccination status on the basis of owner recall or presentation of a dog vaccination certificate.

1.3.2.2 Post-Vaccination Transects (PVTs)

After completion of each vaccination campaign, post-vaccination transects (PVTs) were conducted in each vaccination unit on the same day from 4 p.m. to 6 p.m. when dogs are most active and visible. Transects involved recording all dogs observed while walking (or occasionally cycling) a route through villages counting (tallying) marked (vaccinated) and unmarked (unvaccinated) dogs. To facilitate counting dogs during transect surveys, tallies were broken down into two sections for marked and unmarked dogs (see example record sheet in Appendix A). The record sheet also included information on: the start and end time for each route, the mode of transport (walking or bicycle) and a section for comments e.g. bad weather conditions. The record sheet did not include dog information such as age and gender of the observed dog. The length of the route was dictated by the mode of transport as the aim was to create a route that took no longer than 2 hours to complete, usually 5-8 km and 8-10 km maximum in the length of the route for walking and biking respectively. Transects (observation of dogs) were each conducted by one livestock officer who had also delivered vaccination in the village. The Livestock Officer was selected based on their familiarity with the sub-village or street boundaries. In each vaccination unit, single-day transects were conducted and lasted for two hours only.

Two protocols were used for rural and urban areas respectively. In rural villages which tend to have dispersed communities and a large geographical area compared to urban areas, it is difficult to survey all sub-villages within two hours. A practical solution to this problem relied upon randomly sampling two sub-villages from each village for transects. In the first sub-village, enumerators (observers) were instructed to count dogs starting transects from the centre of the sub-village heading to the outskirts, while in the other sub-village, transects started from the edge (periphery) of the sub-village and headed towards the centre. Each transect was conducted for one hour per sub-village, therefore taking a total of two hours to complete each village.

In urban areas, enumerators were required to pass across streets covering key landmarks (e.g. the dispensary, shopping centres, primary school, church or mosque) for two hours. Observers randomly selected the direction to be walked at the beginning of each transect, at the border of sub-villages/streets and at road junctions. One day of training was held for enumerators prior to data collection. Printed protocols and data collection forms were provided to enumerators during training. Transects have been conducted annually since 2013, with the aim of completing at least one transect in each vaccinated village on the day of or immediately following the vaccination campaign.

1.3.2.3 School-based surveys

School-based surveys (SBSs) were conducted within two months of vaccination campaigns in south-east Tanzania, Pemba and in Serengeti district. In each district, six primary schools (one school per village) were randomly selected. Logistic and financial limitations meant that school surveys were not conducted in some districts or were conducted in less than six schools per district as initially planned. Between 50 to 100 pupils (one per household per school) from standard IV-VII (aged 11-15 years), were asked to complete a questionnaire to collect data from their household. Written consent from the District Executive Officer and verbal consent of teachers and pupils were obtained at each primary school prior to the study. We used total population purposive sampling with a target to interview 100 pupils per school. This resulted in all Standard VII pupils being selected to fill the questionnaire. If there was more than one pupil from one household recruited, the oldest was selected. If the school had fewer than 100 standard VII pupils, additional pupils were recruited from lower classes (Standard IV–VI). No time limit was set for questionnaire completion. The questionnaire included questions on the number of adults and children (<18 years of age) living in the household. the number of dogs and puppies (<3 months of age) kept at the household, and the number of dogs and puppies that had been vaccinated during the most recent campaigns. We decide to conduct questionnaires to children to reduce recall bias, as observed from HHSs surveys, as the children are the largest segment of the population that usually bring dogs to vaccination centres.

1.4 Thesis overview

My thesis focused on measuring, monitoring and improving mass dog vaccination programmes to control and eliminate rabies. There were three key questions in this thesis: 1) What is the best way to implement, monitor and assess the success of campaigns? 2) What are key determinants for reaching the appropriate vaccination coverage and completeness in each community? and 3) How can vaccination strategies be maintained to eliminate infection? To answer these questions, I analysed vaccination and post-vaccination data from mass dog vaccination campaigns conducted between 2010 and 2017, in 28 districts across Tanzania: 24 from southeast Tanzania and four from Pemba Island.

1.5 Thesis organisation

This thesis has been compiled as a collection of three data chapters in research article format. As each chapter has its own introduction and discussion, I include only a brief introduction (Chapter 1) and a general discussion (Chapter 5), as well as an appendix on guidance for conducting post-vaccination evaluations.

Chapter 2 compared the effectiveness of the methods that were used for post-vaccination evaluations in term of vaccination coverage in rural and urban communities in Tanzania. I compared household surveys, school-based surveys and transect surveys to assess which of these methods provides the most precise estimates of coverage. For comparison of how sampling impacted coverage estimates, only data from Serengeti were considered as it was the only district with a full census completed. However data on costs of implementation data from Pemba and Southeast Tanzania were used, and data from these areas were also used to inform our simulation study to assess the effects of sampling in communities with fewer dogs. A method that provides acceptable coverage estimates is needed to guide policies and provide operational guidance for improving the performance of current or future campaigns. Poorly enumerated dog populations is a critical issue facing many rabies-endemic countries (Downes et al., 2013). In Chapter 3, I tried to address this problem by comparing three methods of household, school-based and transect surveys in estimating the size of dog populations. This comparison is required to help other countries to initiate vaccination programmes, refine their dog population estimates, choose better methods for evaluating vaccination programs and guide ongoing and future vaccinations on a large scale in Africa and beyond. My analyses found that transect surveys, which involve counting vaccinated and unvaccinated dogs immediately after vaccination campaigns, are cheap, quick, and provide more precise dog population estimates than either household or school-based surveys. I subsequently used transect data together with human census data from the Tanzanian Bureau of Statistics to develop a predictive model for estimating dog populations in districts lacking transect data, where no vaccination campaigns have been undertaken.

Chapter 4 evaluated the implementation and the performance of large-scale dog vaccination campaigns against rabies. My evaluations were based on three basic scales that can be used to measure performance of the campaigns. I evaluated whether the campaigns: (a) reached the coverage target (P_{target}); (b) campaign intervals (timeliness); and (c) reached all dog-owning communities (completeness). I also discuss the lessons learned (about delivery, costs, obstacles, etc) from one campaign to another and how coverage, timeliness and completeness of the campaigns can be improved. In Chapter 5, I briefly summarize the results of the research and draw general conclusions to guide policy on the best way to establish and monitor the effectiveness of rabies control programmes in different settings in Tanzania and in Sub-Saharan Africa as a whole.

Overall, this thesis contains timely information whereby findings can be directly incorporated into ongoing practices across the country and the region, potentially enabling the impacts of mass dog vaccination campaigns to be effectively monitored and future implementation is improved.

Chapter 2 Comparing Methods of Assessing Dog Rabies Vaccination Coverage in Rural and Urban Communities in Tanzania

2.1 Abstract

Rabies can be eliminated by achieving comprehensive coverage of 70% of domestic dogs during annual mass vaccination campaigns. Estimates of vaccination coverage are, therefore, required to evaluate and manage mass dog vaccination campaigns; however, there is no specific guidance for the most accurate and efficient methods for estimating coverage in different settings. Here, we compare post-vaccination transects, school-based surveys, and household surveys across 28 districts in southeast Tanzania and Pemba island covering rural, urban, coastal and inland settings, and a range of different livelihoods and religious backgrounds. These approaches were explored in detail in a single district in northwest Tanzania (Serengeti), where their performance was compared with a complete dog population census that also recorded dog vaccination status. Post-vaccination transects involved counting marked (vaccinated) and unmarked (unvaccinated) dogs immediately after campaigns in 2,155 villages (24,721 dogs counted). School-based surveys were administered to 8,587 primary school pupils each representing a unique household, in 119 randomly selected schools approximately 2 months after campaigns. Household surveys were conducted in 160 randomly selected villages (4,488 households) in July/August 2011. A complete dog census was conducted in Serengeti district continuously over a 7-year period (ranged from 0-11 months after dog vaccination) and was used to inform simulation experiments on the accuracy of coverage estimation methods. Costs to implement these coverage assessments were $12.01, $66.12, and $155.70 per village for post-vaccination transects, school-based, and household surveys, respectively. Simulations were performed to assess the effect of sampling on the precision of coverage estimation. The sampling effort required to obtain reasonably precise estimates of coverage from household surveys is generally very high and probably prohibitively expensive for routine monitoring across large areas, particularly in communities

with high human to dog ratios. School-based surveys partially overcame sampling constraints, however, were also costly to obtain reasonably precise estimates of coverage. Post-vaccination transects provided precise and timely estimates of community-level coverage that could be used to troubleshoot the performance of campaigns across large areas. However, transects typically overestimated coverage by around 10%, which therefore needs consideration when evaluating the impacts of campaigns. We discuss the advantages and disadvantages of these different methods and make recommendations for how vaccination campaigns can be better monitored and managed at different stages of rabies control and elimination programmes.

2.2 Introduction

Rabies is a fatal viral disease transmitted to humans by animal bites, usually from domestic dogs. Although under control in most industrialized countries, rabies continues to kill an estimated 59,000 people each year in low- and middle-income countries (LMICs (Hampson et al., 2015)). Reliable estimates of the proportion of dogs vaccinated against rabies are crucial to determine the performance of vaccination campaigns and their impact on disease transmission. Empirical and theoretical evidence shows that mass dog vaccination campaigns that reach at least 70% of the dog population can control rabies (Coleman and Dye, 1996, Hampson et al., 2009). While achieving this coverage in all communities can lead to elimination, even small gaps in coverage can delay the time to elimination (Townsend et al., 2013). As progress is made toward reaching global targets of zero human rabies deaths from dog-mediated rabies through the implementation of mass dog vaccinations (Abela-Ridder et al., 2016), there is a clear need to identify reliable, cost-effective, and feasible approaches that can be used, at scale, to assess community-level vaccination coverage.

Limited population data on owned and free-roaming dogs in most LMICs make estimation of vaccination coverage challenging. Several methods have been used to estimate coverage including (i) the use of pre-campaign estimates of dog population size through human to dog ratios (HDRs) as the denominator, and the number of dogs vaccinated during the campaign as the numerator (6); (ii) post-vaccination household surveys to estimate the proportion of vaccinated dogs (Kayali et al., 2003, Cleaveland et al., 2003, Kongkaew et al., 2004, Kayali et al., 2006, Suzuki et al., 2007, Gsell et al., 2012); and (iii) post-vaccination transects to estimate the proportion of marked (vaccinated) dogs (Townsend et al., 2013, Muthiani et al., 2015, Tenzin et al., 2015b, Léchenne et al., 2016). However, these methods all have limitations (Davlin and VonVille, 2012). If dog populations are estimated from data on HDRs, inaccuracies in estimates of the human population will invariably affect the accuracy of dog population estimates. This may occur, for example, through errors in extrapolating current human population sizes from census data (for example, using average population growth rates) or from administrative/boundary changes that affect village demarcations across different time periods. Furthermore, published data on HDRs usually reflect a sample from surveys across several communities (Knobel et al., 2008), and even a small degree of variation in HDRs can have a major effect on dog population estimates at the community level.

Household surveys are restricted to capturing estimates of vaccination coverage in owned dog populations and are relatively intensive to complete. Moreover, there is known to be wide variability in patterns of dog ownership within communities—for example, in Tanzania, a much smaller proportion of Muslim and urban households own dogs in comparison with rural, livestock-keeping communities (Knobel et al., 2008). This variability and the highly skewed pattern of dog ownership in some communities make household surveys prone to selection and measurement biases (Jibat et al., 2015). Additional uncertainty from household surveys arises in relation to validation of dog vaccination status. In Tunisia, for example, about 14% of dog owners who claimed their dogs were vaccinated but were unable to validate their claims by providing dog vaccination certificates (Touihri et al., 2011).

Post-vaccination transects are limited to observations of free-roaming dogs and will, therefore, be biased toward dogs that are more likely to be observed from transects. For example, young puppies are likely to be less visible and are known to represent an age group that typically has a low vaccination coverage (Kongkaew et al., 2004, Kaare et al., 2009, Minyoo et al., 2015), thus resulting in the potential for overestimating coverage. In a recent study from Tanzania, post-vaccination transects were shown to overestimate coverage by approximately 7% in comparison with household surveys, although it was unclear in this study which of the approaches was most accurate (Minyoo et al., 2015).

Here, we present a detailed assessment of three methods to estimate dog vaccination coverage across settings in Tanzania. We use a complete household census as reference data for a simulation experiment to determine the impacts of sampling on the precision of coverage estimates. Specifically, we aim to answer the following questions: (i) What are the resources (personnel, time, and money) required to implement these methods? (ii) Which methods provide the most precise estimates of coverage? and finally (iii) Which approaches, therefore, generate acceptable coverage estimates to provide operational guidance to improve the performance of current or future campaigns?

2.3 Materials and Methods

2.3.1 Study Sites

The study was conducted in 29 districts across Tanzania: 24 districts from southeast Tanzania, 4 districts from Pemba island, and 1 district (Serengeti district) from northwest Tanzania (Figure 2-1). These areas are inhabited by an estimated 9.1 million people (20% of the Tanzanian population) according to the 2012 national census (National Bureau of Statistics, 2012) and represent districts that span a wide range of settings, comprising rural, urban, coastal and inland areas, and a range of livelihoods and religious backgrounds. Mass dog vaccination campaigns were conducted in all these districts by local government teams, with support of WHO and collaborating institutions (Mpolya et al., 2017). Various methods of estimating vaccination coverages achieved during campaigns were compared.

summarizes the methods used in different locations and the rationale for data collection.

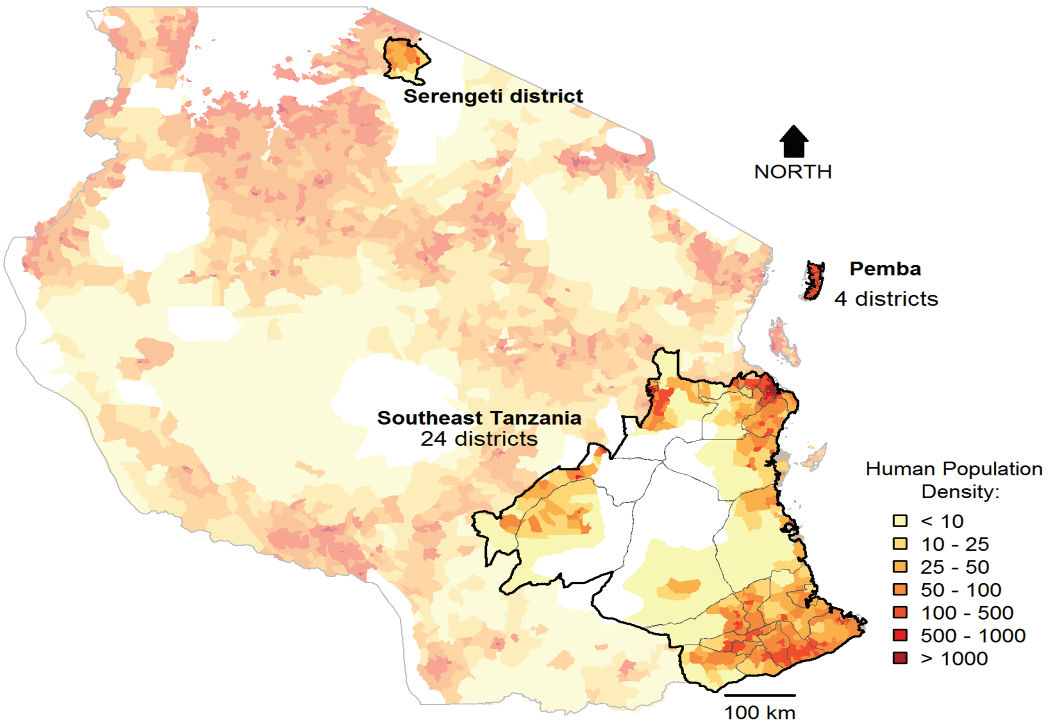


Figure 2-1: Study sites in Tanzania. Post-vaccination transects (2 sub-villages/village in 2,070 villages), school-based surveys (6 schools/district), and household surveys (30 households/village in 6 villages/district) were conducted in southeast Tanzania and Pemba. In Serengeti district, transects were conducted in all sub-villages in almost all villages (85/88), and four school-based surveys and a complete census of dogs (surveys of 35,867 households) were undertaken. Km sq, Square Kilometres.

2.3.2 Post-Vaccination Transects

To generate rapid estimates of village-level vaccination coverage, post-vaccination transects were conducted on the same day as vaccination campaigns in each village from 4 p.m. to 6 p.m. when dogs were active and visible. Transects involved recording all dogs observed while walking (or occasionally cycling) a route through villages counting marked (vaccinated) and unmarked (unvaccinated) dogs. In rural communities, transects were conducted in two randomly selected sub-villages from each village (villages ranged in size from 2 to 10 sub-villages, with a median of 4 sub-villages/village), aiming to representatively sample coverage within each village. In the first sub-village, enumerators were instructed to start transects at the centre of the sub-village heading to the outskirts, while in the other sub-village, transects started from the edge of the sub-village and headed toward the centre. Some of transects were performed in the same sub-village where vaccination were undertaken. Each transect was conducted by one enumerator for 1 h, therefore, taking a total of 2 h to complete each village. In urban areas, enumerators were required to cover the jurisdiction of a street (a geographical area defined from the National Census, which covers a neighbourhood with several roads). One day of training was held for enumerators prior to data collection and printed protocols, and data collection. Printed protocols and data collection forms were provided to enumerators during this training. Enumerators selected the direction at the start of transects, at the border of sub-villages/streets and at road junctions by spinning a pen. In Serengeti district, transects were conducted in every sub-village of vaccinated villages.

Table 2-1: Study design and data collection including purpose of each dataset

Method	Areas (number of villages)	Sampling design	Data collection period	Interval between village-level campaign and coverage survey	Purpose
Post-vaccination transects	Serengeti (85)	1 transect in every sub-village (357 total) in all villages	May-Oct 2015	2-3 hours	Coverage estimates at village- and district-level. Data used for simulations to explore how the number of transects/village affect precision of district-level estimates
	Southeast Tanzania & Pemba (2070)	1 transect in 2 sub-villages (4140 total) in every village/ district	Nov 2014 to Jan 2015	2-3 hours	Set-up & implementation costs
School-based surveys	Serengeti (4)	100 pupils/school in 4 schools/ district (333 pupils)	July 2015	1 month	Coverage estimates at district-level. Precision of estimates compared with census data and simulation experiments.
	Southeast Tanzania & Pemba (115)	100 pupils/school in 6 schools/ district (8254 pupils)	Nov 2014 & Feb 2015	1-2 months	Set-up & implementation costs
Household survey	Southeast Tanzania & Pemba (160)	30 households/village in 6 villages/ district (4488 households)	Jul-Aug 2011	2-6 months	Set-up & implementation costs. Data used to parameterize simulations for settings with high: human dog ratios to explore precision of household surveys
Complete human and dog census	Serengeti (88)	All households in district (35,867)	From 2008 to 2015	Vaccination campaigns ~May-Jul each year. Census at different times of year for each village ranged from 0-11 months after vaccinations.	Census does not provide a point estimate of coverage relative to a specific campaign. Data used for simulation experiment to determine how sampling (e.g. household and school-based surveys) affects precision of coverage estimates

2.3.3 School-Based Surveys

School-based surveys were planned to be conducted immediately after completion of the 1-day vaccination campaign but were conducted within 2 months of vaccination campaigns as a result of delays in the delivery of funds for their completion. Logistically, it was not possible to conduct two post-vaccination surveys in all study districts in short time period. We decided to start with transect surveys then school based-surveys. These surveys required help from 6 other researchers to train and administer these surveys. School-based surveys were conducted in southeast Tanzania, Pemba, and Serengeti district (Table 2-1). In each district in southeast Tanzania and Pemba, six primary schools (one school per village, as most villages in Tanzania have a primary school) were randomly selected, and in Serengeti district, four primary schools were selected. Logistic and financial limitations meant that school surveys were not conducted in some districts or were conducted in less than six schools per district as initially planned. Between 50 and 100 pupils (one per household) from Standard IV–VII (aged 11–15 years) were asked to complete a questionnaire to collect data from their household. We used total population purposive sampling with a target to interview 100 pupils per school. This resulted in all Standard VII pupils being selected to fill the questionnaire. If there was more than one pupil from one household recruited, the oldest was selected. If the school had fewer than 100 standard VII pupils, additional pupils were recruited from lower classes (Standard IV–VI). Written consent from the district executive officer and verbal consent of teachers and pupils were obtained at each primary school prior to the study. To introduce the project to schools, researchers were accompanied by the district veterinary officer, district health officer, and district education officer. Questionnaires were administered to pupils by the lead author and his research team. The questionnaire included questions on the number of adults and children (<18 years of age) living in the household, the number of dogs and puppies (<3 months of age) kept at the household, and the age of dogs and their vaccination status.

2.3.4 Household Surveys

Household surveys were conducted in all districts in southeast Tanzania and Pemba with the aim of obtaining an initial assessment of coverage from the first phase of vaccination campaigns. Six villages were randomly selected from all villages in each district, and the survey was conducted by surveying 30 households in each of the selected villages. In every randomly selected village, a landmark was identified (preferably a school, otherwise a dispensary, church, or mosque). From this starting point, interviewers randomly chose a direction for selecting households for interview by spinning a pen. Every third household was sampled, and interviews conducted until 30 households were completed in each village. Surveys were conducted in July and August 2011, around 4 months after dog vaccination campaigns conducted in March and April 2011. Interviewers were accompanied by local village officers to identify household heads and provide introductions. Prior to the administration of the questionnaire, permission was sought from the household head or other household members of at least 18 years of age in the absence of the household head. Interviewers explained the study background to each respondent and obtained verbal consent to carry out the questionnaire. For households that owned dogs, the questionnaire captured details of dogs owned (adults and puppies <3 months) and their vaccination status on the basis of owner recall.

2.3.5 Serengeti district dog population census

In Serengeti district, a complete dog census was conducted to collect the same household questionnaire data as described above, for every household in the district. The census began in 2008 and was administered continuously by local enumerators working in each village. The census was completed in 2015 (Table 2-1), as enumerators were only able to conduct the census in between other activities. some villages census was conducted the same month of dog vaccination while in other villages the time between census data collection and vaccinations was 11 months. The census recorded the number of people (adults and children) in each household, and the number of adult dogs and puppies (<3 months) and cats and kittens in each household, as well as the numbers of each that were vaccinated and the GPS location of the household. Because the census was conducted over an extended period, it was not used to generate point estimates of vaccination coverage in relation to specific vaccination campaigns, which in Serengeti have been conducted annually over the last decade. Instead, these data were used for a simulation experiment, whereby the data were sampled to simulate a household survey, thereby enabling a comparison of methods and how they affect the precision of coverage estimates (see Data Analysis).

2.3.6 Resources for estimating vaccination coverage

The number of people involved in each survey method, the time required to complete data collection and associated costs to set up and implement each assessment across southeast Tanzania were recorded. Costs per surveyed village were calculated as total costs incurred in all of the study districts divided by the number of villages surveyed. Costs per district were calculated as the overall costs for conducting the surveys across surveyed districts, divided by the number of surveyed districts. The costs incurred included per diems to government officials such as District Veterinary Officers, District Health Officers, District Education Officers, and researchers and allowances to enumerators who conducted transects. Communication costs covered phone calls to coordinate with enumerators and data collectors. Fares covered travel to districts to facilitate training, supervision, and to collect records. For school-based and household surveys, travel covered fuel for vehicle use. All costs were calculated for evaluation of a single mass dog vaccination campaign in Tanzanian shillings (TZS) and converted to US dollars (US$) using the average exchange rate in 2011 [1 TZS to US$ 0.000632 (Bank of Tanzania, 2012)].

2.3.7 Data analysis

The census data from Serengeti district together with the transects and school-based surveys conducted in Serengeti in 2015 were used to determine the impacts of sampling on the precision of vaccination coverage estimation. We define accuracy as lack of bias. Repeated estimates using an accurate method will converge on the true coverage value as sample size increases. Precision is the absence of random sampling error from the measured value. Repeated estimates using a precise method will be close to their mean, although not necessarily close to the true coverage. Clearly, for an estimation method to be informative about the true coverage, it must be both accurate and precise. Across Tanzania there is considerable variation in dog ownership, from largely. Muslim communities with very few dogs per household to pastoralists with many dogs in most households. This variation in dog ownership patterns among communities means that sampling designs should aim to deal with these variations and give accurate and precise estimates.

To examine the precision and accuracy of different methods in estimating vaccination coverage, we estimated the district-wide mean coverage and 95% confidence intervals in Serengeti from the complete census (all households in all 88 villages) and from subsamples of households and villages from the census equivalent to a household survey. We also compared these to the precision of district-wide coverage estimates from the school-based surveys (in 4 villages) and post-vaccination transects (in 85 villages) in Serengeti district. To facilitate comparison, the four villages selected for the household survey during the simulation in Figure 2-2 were the same ones sampled by the school-based survey. We fitted binomial generalized linear mixed models (GLMMs), with a random intercept to account for variation in mean coverage between villages. The dependent variable was dog vaccination status followed a binary distribution (vaccinated, unvaccinated) and the independent variable was intercept whereas the random effect was village.

Table 2-2: Descriptive characteristics of the study districts.

			Post-vaccination transects			Household survey				School-based survey			
District	Setting	Total villages (or wards)	Villages /streets surveyed	Dogs (Village mean)	Villages with no dogs	Villages surveyed	HH surveyed	Dogs recorded (mean dogs/ HH)	Households without dogs	Schools surveyed	respondents	Dogs recorded (mean dogs /pupil)	Pupils without dogs
Chake Chake	Coastal Island	29	29	182 (6.28)	0	6	178	7 (0.04)	176	3	152	3 (0.02)	151
Ilala	Urban Coastal	26	NA	NA	NA	6	133	34 (0.26.)	119	NA	NA	NA	NA
Kibaha Rural	Rural	55	55	759 (13.80)	0	2	93	30 (0.32)	82	6	412	199 (0.50)	355
Kibaha Urban	Urban	50	50	526 (7.21)	0	6	151	66 (0.44)	117	6	407	237 (0.51)	341
Kilombero	Rural	80	77	1989 (25.83)	0	6	147	32 (0.22)	132	6	548	218 (0.40)	470
Kilwa	Rural Coastal	102	78	606 (7.77)	4	6	158	26 (0.16)	144	NA	NA	NA	NA
Kinondoni	Urban Coastal	34	83	349 (4.20)	19	6	183	59 (0.32)	154	6	471	163 (0.35)	430
Kisarawe	Rural	77	77	578 (7.41)	1	6	170	9 (0.05)	163	6	283	109 (0.39)	230
Lindi Rural	Rural Coastal	134	134	1754 (10.83)	8	6	177	15 (0.08)	168	5	254	60 (0.24)	242
Lindi Urban	Urban Coastal	30	60	588 (9.80)	2	6	177	17 (0.10)	168	4	343	70 (0.20)	316
Liwale	Rural	76	73	531 (7.27)	6	6	175	19 (0.11)	169	NA	NA	NA	NA
Masasi	Rural	159	97	554 (6.16)	5	6	180	27 (0.15)	162	3	161	32 (0.20)	147
Micheweni	Coastal Island	27	27	178 (6.59)	0	6	173	25 (0.14)	164	3	156	4 (0.03)	155
Mkoani	Coastal Island	33	33	303 (9.18)	4	6	154	9 (0.06)	151	3	177	8 (0.05)	175
Mkuranga	Rural Coastal	116	90	262 (2.91)	30	6	174	4 (0.02)	171	6	328	58 (0.18)	306
Morogoro Rural	Rural	144	93	1056 (12.00)	15	6	168	41 (0.24)	145	5	393	103 (0.25)	356
Morogoro Urban	Urban	19	163	572 (3.51)	1	6	169	49 (0.29)	146	6	557	225 (0.40)	489

District	Setting	Total villages (or wards)	Villages surveyed	Dogs (Village mean)	Villages with no dogs	Villages surveyed	House holds (HH) survey ed	Dogs recorded (mean dogs/ HH)	Household s without dogs	Schools surveyed	Pupil respon dents	Dogs recorded (mean dogs /pupil)	Pupils without dogs
Mtwara Rural	Rural	156	85	427 (5.02)	16	5	140	16 (0.11)	138	5	334	31 (0.09)	328
Mtwara Urban	Urban Coastal	86	15	148 (9.87)	1	6	150	14 (0.09)	130	3	288	69 (0.24)	266
Nachingwea	Rural	118	115	1576 (13.70)	4	6	170	37 (0.22)	160	6	342	84 (0.25)	307
Nanyumbu	Rural	89	58	415 (7.16)	10	6	176	1 (0.01)	175	6	475	28 (0.06)	466
Newala	Rural	153	83	626 (7.54)	1	6	180	4 (0.02)	178	6	645	55 (0.09)	623
Ruangwa	Rural	89	79	758 (9.59)	1	6	179	37 (0.21)	164	4	168	24 (0.14)	156
Rufiji	Rural Coastal	115	78	470 (6.03)	16	6	172	2 (0.01)	171	5	459	61 (0.14)	427
Tandahimba	Rural	156	130	360 (2.77)	42	3	79	2 (0.03)	78	3	175	24 (0.14)	170
Temeke	Urban Coastal	30	106	276 (2.60)	19	6	159	8 (0.05)	155	NA	NA	NA	NA
Ulanga	Rural	70	70	2381 (28.35)	0	6	177	85 (0.48)	146	6	560	326 (0.58)	464
Wete	Coastal Island	32	32	213 (6.63)	2	6	146	56 (0.38)	124	3	166	7 (0.04)	162
Serengeti	Rural	88	85	6285 (35.21)	0	4*	120*	179 (0.37)*	0*	4	333	892 (2.68)	51

To assess the impact of sampling on district-wide coverage estimates, we conducted simulations where we sub-sampled from the complete census (88 villages) different numbers of households per village (10, 20, 30, 40, and 50) and villages (5, 10, 20, 30, 40, 50, 60, 70, 80, and 88). In my simulation experiment, I also incorporated transect data from Serengeti district which were conducted in every sub-village. to assess the effects of sampling in communities with less dogs.

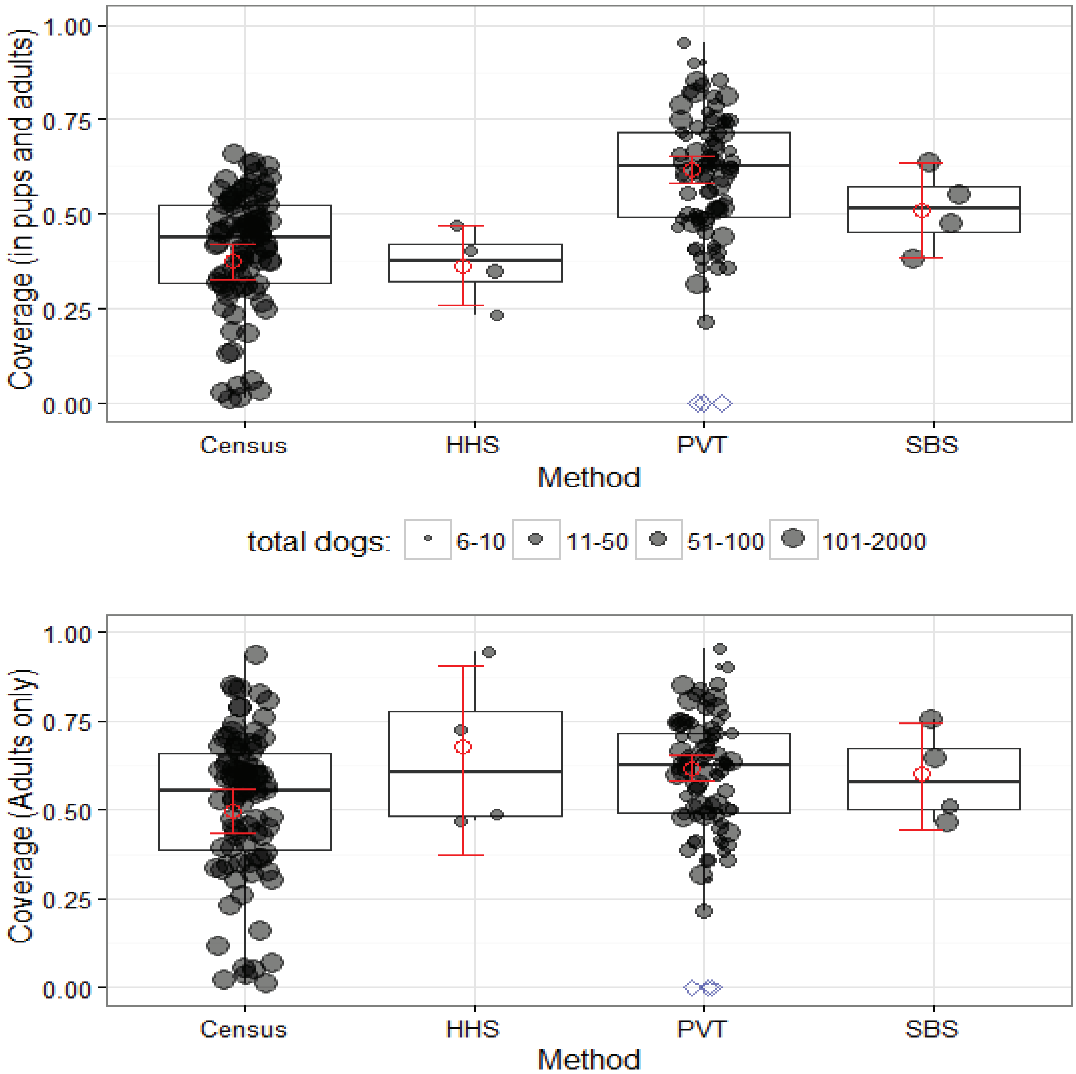


Figure 2-2: District and village-level vaccination coverage estimates and precision in Serengeti District. Coverage estimates are shown for all dogs (including puppies, top) and adult dogs only (bottom) in surveyed villages (dots); the dots also represent the village-level coverage. Red squares and error bars show mean district-level coverage ±95% CI, estimated using generalized linear mixed models (see main text for details). The coverage distribution is plotted for individual villages (shaded circles) and summarized by box-and-whisker plots, where the thick line shows the median, the box covers the interquartile range and the whiskers extend to the range. Blue diamonds represent villages with no vaccination campaign where vaccination coverage was assumed to be zero (not included in calculation of mean ± 95% CI or boxplots). PVT, post-vaccination transects; SBS, school-based surveys; HHS, household surveys.

Each of the 50 combinations of these two sampling choices was simulated 500 times, and mean coverage for the district was estimated from each simulated data set as the total number of vaccinated dogs divided by the total number of dogs. Although generally this simple method is inferior to fitting a GLMM as above (Bolker et al., 2009), this was not feasible for sampling designs with low total dog numbers. The precision achieved using each sampling design was assessed by plotting coverage estimates against the numbers of villages and households sampled.

To assess the impact of variability in dog ownership or HDR on the precision of coverage estimates, we repeated the simulation described above. However, instead of subsampling from the Serengeti census dataset, we used a simulated dataset with the same structure but with fewer dogs per household. The number of dogs in each household was simulated from a negative binomial distribution with mean $\mu = 0.2$ and dispersion parameter $k = 0.06$ [calculated from the mean and variance of the household survey data in southeast Tanzania using the parameterization of the negative binomial with variance $\mu + (\mu2/k)$]. The number of vaccinated dogs was simulated with mean coverage and random effect variances between villages, sub-villages, and households estimated from a binomial GLMM fitted to the Serengeti census dataset.

As a result, the "low dog ownership" dataset was as similar as possible to (and therefore comparable to) the Serengeti dataset, but with dog numbers similar to the mean dogs/household in southeast Tanzania (Table 2-2). As the results presented here come from a single simulated "low dog ownership" dataset, we checked for sensitivity to random variation by comparing across several (>5) simulated data sets. We also assessed the impact of sampling using transect surveys. We examined the scenario of sampling 1, 2, 4 and 8 (or all if <8) sub-villages in a village and determined which sampling effort (sampling design) provided reasonable estimates of village-level coverage.

All statistical analyses were conducted using R version 3.3.1 (R Core Team, 2017). GLMMs were fitted using the lme4 package (Bates et al., 2014), and the "low dog *ownership*" data set was simulated using the *sim.glmm* function (Johnson et al., 2015).

2.4 Results

Across southeast Tanzania, Pemba Island and Serengeti district, we conducted (i) post-vaccination transects following vaccination campaigns in 2,155 villages and counted 24,721 dogs, (ii) questionnaires with 8,587 primary school pupil respondents, each representing a unique household, in 119 randomly selected schools (3,090 dogs recorded), and (iii) 4,488 household surveys in 160 randomly selected villages (731 dogs recorded—excluding Serengeti district). In addition, a complete census was conducted in Serengeti district covering 35,867 households, which collectively owned 62,771 dogs (Table 2-1). Table 2-2 summarizes the attributes of each study district and dogs recorded by each method. Many more dogs were observed on transects than were recorded in either household or school-based surveys, even in districts with low dog ownership i.e., high HDR (Table 2-2).

2.4.1 Logistics and costs for coverage assessments

Post-vaccination transects usually took around 2 hours to complete. Collars were fitted to dogs during vaccination campaigns with very few cases where this was not possible. As transects were conducted the same day as campaigns, collar loss was assumed to be negligible. School-based surveys involved two research scientists with the help of teachers. The questionnaire was administered in one classroom, and all pupils normally took approximately 40 min to complete questionnaires. Household surveys involved a research team comprised of two drivers, eight interviewers, and one supervisor split between two vehicles. Each vehicle covered four villages per day (an average of one village per interviewer/day), and the village leader accompanied each interviewer in every village. The census in Serengeti district was the most time-consuming method, with locally trained interviewers spending an average of 14 (8 h/day) days to complete a census of one village.

Costs of estimating coverage varied depending upon the method. The costs per village were $12.01, $66.12, and $155.70 for transects, school-based, and household surveys, respectively, and these costs scaled up with the sampling for each method (Table 2-3). Specifically, the average cost for assessing district-level coverage was around $1,300 with transects completed in every village, approximately $300 based on 6 school-based surveys per district and $900 based on sampling 30 households per village in six villages per district.

2.4.2 Comparison of Coverage Estimates and Their Precision between Methods

Vaccination coverage in Serengeti district was estimated using each method and from the complete census to assess precision in coverage estimates. Figure 2-2 illustrates village-level coverage estimates and the district-wide mean estimates. Transects in Serengeti were conducted in 85 out of 88 villages, with 6,285 dogs counted and school-based surveys were conducted in four schools, with interviewed pupils representing 333 households and collective ownership of 892 dogs. We observed that excluding puppies resulted in higher estimates of coverage (from 37.5% as estimated from the census including puppies and adults to 49.7% including only dogs >3 months of age), with similar increases for both the household and school-based surveys. However, we were unable to analyse the post-vaccination transect data according to age class of observed dogs as this information was not recorded during transects.

Table 2-3: Cost comparison between methods of evaluating dog vaccination campaigns in Southeast Tanzania and Pemba island (excluding Serengeti district).

	Cost item	Transects (n=2070)		School-based surveys (n=115)		Household surveys (n=160)	
Set-up		Total cost ($)	Cost/village ($)	Total cost ($)	Cost/village ($)	Total cost ($)	Cost/village ($)
	Communication costs	606.08	0.29	20.01	0.17		
	Fare	613.02	0.3				
	Training/ supervision	2,256.28	1.09	4,203.06	36.55		
Subtotal (set-up costs)			***$1.68***		***$36.72***		
Implementation	Per-diems/allowances	6541.2	3.16	624.45	5.43	21,345.30	133.41
	Data collection	176.80	0.09			659.5	4.12
	Collars	13,858.09	6.69				
	Questionnaire	806.16	0.39	1,200.88	10.44		
	Fuel			1,555.64	13.53	2,992.92	18.17
Subtotal (implementation costs)			***$10.33***		***$29.40***		***$155.70***
Cost per village			***$12.01***		***$66.12****		***$155.70****
Cost per district		***$1,307.37***		***$310.60***		***$889.05***	
Cost household		***NA***		***$0.90***		***$5.55***	
Cost per dog counted		***$1.43***		***$2.51***		***$34.05***	

The numbers of villages and districts which these calculations were based on data shown in Table 2-1. All costs are in USD. Per diem for household surveys covered supervisors, drivers, village leaders, and researcher. Allowances for enumerators conducting transects were $3.16/village. Households survey costs were based on interviewing 30 households per village. Data collection for household surveys are also included the cost of mobile phones used by researchers for submitting data (six phones at $94.8/phone). *cost per villages was based on 6 village per district.

Our GLMM estimate of district-level coverage of all dogs (puppies and adults) from the census was 37.5% with relatively narrow 95% confidence intervals (32.8–42.3%). The coverage estimate from the census data subsampled to represent a household survey fell outside of these confidence intervals at 44.5% and had wider 95% CI (37.1–52.0%). Although the district-wide coverage for the school-based survey (51.2%) was not directly comparable to the census data, the span of the 95%CI can be compared and was found to be much wider (38.7–63.4%). The transect coverage estimate (61.7%) was higher than the school-based survey but had narrow 95% CI (58.2–65.2%) similar in span to the census.

In comparison to the census, only the post-vaccination transects method provided similar precision in coverage estimates (Figure 2-2) but these appeared to overestimate district-level vaccination coverage in comparison to the school-based survey. This is likely due to few puppies being observed during the transects. Transects generated coverage estimates for every village in a district, although village-level estimates were not very precise. Nonetheless, these village-level estimates were sufficient for identifying villages with low coverage, for example, less than 70% coverage.

2.4.3 Impact of sampling on district-level coverage estimates

Estimates of coverage from the school-based and household surveys were sensitive to the sampling design (Figure 2-3). As the sample size increases, in terms of the numbers of households sampled per village, coverage estimates became increasingly precise (Figure 2-3A). In Serengeti district, where there is high dog ownership, once at least 30 households within each of 20 villages were sampled, estimates were very close (±10% with high probability) to the true mean from the census data. In scenarios with low dog ownership (i.e., higher HDR), approximately three times the sampling effort (30 households × 60 villages) is required to achieve an equivalent degree of precision (Figure 2-3B). It was possible to sample more households more rapidly through school-based surveys than household surveys because it is easier to recruit pupils at school than visiting individual households.

For the transects, sampling two or more sub-villages per village gave coverage estimates that were within 10% of the true village-level coverage, although coverage estimates were more precise if transects were completed in all villages in all wards rather than just a sample of villages per ward (Figure 2-3C).

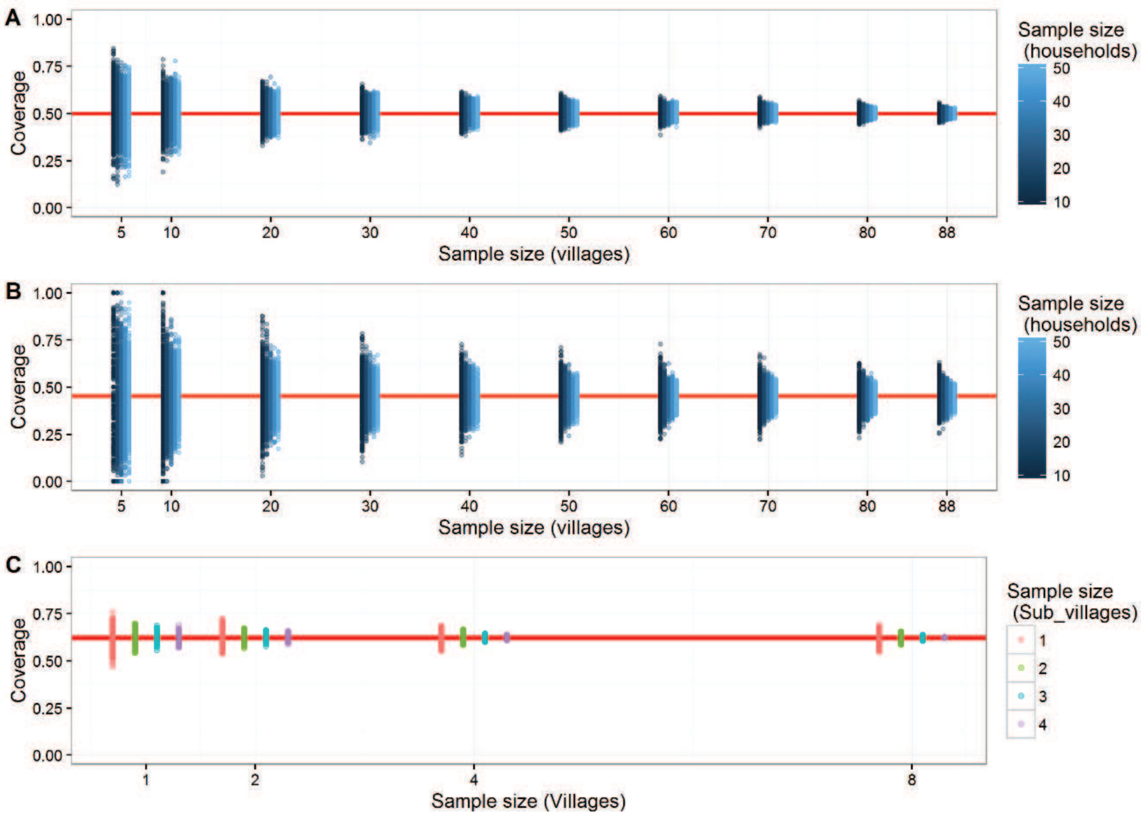


Figure 2-3: The impact of sampling on precision of coverage estimates derived from household surveys in communities with (A) low human:dog ratios and, (B) high human:dog ratios, and from (C) post-vaccination transects. Estimated mean district-level vaccination coverage (red line) for different numbers of villages and households sampled from (A) actual Serengeti district dataset and (B) a dataset from Serengeti District but simulated with lower dog ownership (0.2 dogs per household). For each sampling design [i.e., the number of villages and households sampled in panels (A,B)], coverage estimates from 500 subsampled data sets are plotted (blue dots), with shading indicating the number of sampled households, and the mean of these estimates is shown by red line. Similar to panels (A,B), each column of points shows sampling variation among 500 subsampled data sets for each sampling design using transects (C). Coloured dots represent the number of subvillages sampled per village for estimating coverage from transects.

2.5 Discussion

The feasibility of global canine rabies elimination has been recognized by major international health agencies, including the WHO, the World Animal Health Organization (OIE), and the Food and Agriculture Organization of the United

Nations (FAO (Abela-Ridder et al., 2016)). Implementation of mass dog vaccination campaigns to meet the 2030 target of zero human deaths are now underway in several countries in Asia and Africa. To guide the progress of these vaccination campaigns, it is important to evaluate the performance of mass dog vaccination campaigns. Specifically, monitoring is useful to determine whether campaigns have reached the required vaccination coverage, to identify problematic areas with low coverage, and target communities with coverage gaps. Dog rabies control programmes typically operate under financial constraints that affect both implementation and evaluation. While several studies have evaluated vaccination coverage as part of small-scale research/pilot vaccination campaigns (Davlin and VonVille, 2012), here we evaluate different approaches in the context of comparison of setup and implementation costs for generating precise and accurate coverage estimates at scale.

A weakness of the study was that the dog census data did not provide a point estimate of coverage relative to a specific campaign. Serengeti district has been subject for long term dog vaccination interventions since 1990s (Dye and Cleaveland, 1995). In this district, baseline data on number of dogs have been established through accurate records of dogs vaccinated in each village. Therefore, changes in dog demographic structure did not affect much of our results and we were confident to use the dog census data as a valuable comparison to get the picture on how sampling affect coverage estimates.

Mark-resight technique requires sufficient time should be given after marking to allow mixing of marked animals within the population. In our experience of implementing and monitoring dog vaccinations, we did not observe any concern of temporarily change of the behaviour of the vaccinated dogs in the community as a result of dog vaccination activities (including putting collars around their necks) that could lead to inaccurate counts. For example, we didn’t observe or receive information on dogs left vaccination points or left the village due to vaccination activities.

It is important to recognize this trade-off between precision and degree of spatial resolution, which are offset by time and cost. However, in many situations, a combination of both spatial resolution (level of spatial details) and level of precision of data (consistent and reliable data) is very important in rabies control and elimination efforts. For example, high spatial resolution may be needed to detect coverage gaps, yet the corresponding data samples may be usable at less than full precision to adequately approximate measured coverage. In this study, we demonstrated that transects were the simplest method that generated precise estimates of vaccination coverage and was cheap. Transects generated sufficient precise data even in villages where detection rates were extremely low such as in island or coastal areas, and we can recommend for monitoring the dog vaccinations in country-wide campaigns in Tanzania.

Our study revealed that transect surveys can detect coverage gaps in areas where vaccinations were conducted. We found that rapid assessment of dogs vaccinated in each unit can be used to inform remedial vaccinations. The analysis of these fine-scale resolution data collected through transect surveys (or from vaccination records of areas with no campaign) will help to map spatial heterogeneities in vaccination coverage at the local level i.e. village or street level. Mean coverage at district-level can appear to sufficient because averaging good and poor performing villages. However, fine scale data are needed to help project managers to troubleshoot why some areas campaigns were not successful. However, in our study in Tanzania, transect surveys were paper-based. The process of compiling, entering into the database, analysing and presenting these paper-based data were tedious. These paper-based approaches do not allow a rapid high-resolution analyses to be carried out to identify vaccination coverage gaps. It is now urgent that rapid, practical and effective approaches of measuring coverage are used by program managers to support national and global policymakers to track progress towards implementation of stated goals and check whether milestones are being met. The developments in mobile phone technology and spatial modelling that facilitate rapid assessment of vaccination programs, and reporting to the project managers to take actions will greatly advance transect surveys (Gibson et al., 2015). Spatial analysis will inform/visualize the performance of campaign and suggest response. Additionally, using paper-based surveillance it was impossible to track the path route of enumerators, with mobile phone monitoring will help indicate if the transect routes was performed in the same sub-villages where vaccination were undertaken. This will help to assess detection rate in areas close/far from vaccination points.

A limitation of transects is that they tend to overestimate coverage because of excluding puppies and a solution for this is to incorporated puppies to adult ratio (PAR) when calculating the coverage. It was previously reported that post-vaccination coverage estimates in Tanzania from transects overestimate coverage by 10–15% (Minyoo et al., 2015). We saw a similar difference in our coverage estimates from the complete census when puppies were excluded. This suggests that puppies are rarely observed on transects and that puppies are less likely to be vaccinated, which could explain why coverage is overestimated from transects (Minyoo et al., 2015). Estimates of vaccination coverage from transects should therefore be reduced by around 10% when assessing whether coverage is sufficient or if remedial vaccination is required, and for determining the impacts of vaccination programs.

Household surveys generate useful data on vaccination coverage of owned dogs and provide opportunities for collection of additional demographic data (Knobel et al., 2008, Kaare et al., 2009, Minyoo et al., 2015). Evaluation costs are often the major factors affecting the choice of design. For example, we found that household surveys were time consuming and costly at ~$34 dog recorded or ~150 per village. Because of these costs, we restricted out household (and school-based) surveys to a set number (6) per district, which meant that larger districts were sampled less. This was the underlying statistical reason why household (and school-based) surveys performed worse than transect surveys. However, this problem can be solved by increasing sample size, but would be very expensive to achieve levels comparable to transects. We found that village sampling is more important that household sampling. Our simulation experiment showed that approximately 30 villages would need to be surveyed to generate district-level estimates of coverage precise to within 10% of the true coverage. We therefore conclude from our simulation experiment that the sampling required to reach an adequate level of precision (say within 5% of confidence interval) would likely be expensive in most settings, particularly where HDRs are high and even larger sample sizes would be needed. The effort required to conduct these surveys would be difficult to justify, given the more urgent priority of vaccinating dogs.

School-based surveys can generate data from more households at lower cost, as pupils are easily recruited. Moreover, school pupils typically take their dogs to vaccination stations (Kaare et al., 2009). Therefore, school pupils are more likely to recall vaccination status of their dogs than parents. The main costs of school-based surveys are at the setup stage, which requires considerable government support, although this cost is not incurred on successive campaigns. School-based surveys are, therefore, simple to implement and can capture a range of socioeconomic and religious backgrounds. However, estimates may be less accurate because of a biased subsample of children attend school and less precise in areas with low numbers of pupils attending schools, such as pastoralist communities. Critically, this method may, therefore, fail to capture coverage in the most vulnerable populations with the highest dog ownership (lowest HDR) but lowest school attendance (Bardosh et al., 2014). In communities with few dogs, school-based surveys are also sensitive to sampling, as very few pupils (<10 pupils per 100 households) reported to own dogs at their households (see also simulation experiments in Figure 2-3B). In these areas, large numbers of households would need to be surveyed to obtain representative sample sizes for adequately precise coverage estimates.

Among the limitations of our household and school-based surveys was their timeliness. For example, our study was conducted 2 months after vaccination, and since then some dogs may have died and therefore were not counted. However, our questionnaire asked about dogs <3 months including those born after vaccination, which would affect the coverage estimate (we assume both vaccinated and unvaccinated dogs are likely to die with equal probability and therefore this will not affect our coverage estimates). We also considered the vaccination status of dogs reported by owners, which could be biased. More logistic effort was involved in setting up these surveys than for transects, therefore rapid assessments of vaccination performance (and remedial action if required) are more difficult with these methods, which also do not provide estimates of coverage for every village unless completed in every village which would be very costly. By contrast, transects were very efficient and generated immediate operational guidance at the village-level (Figure 2-4).

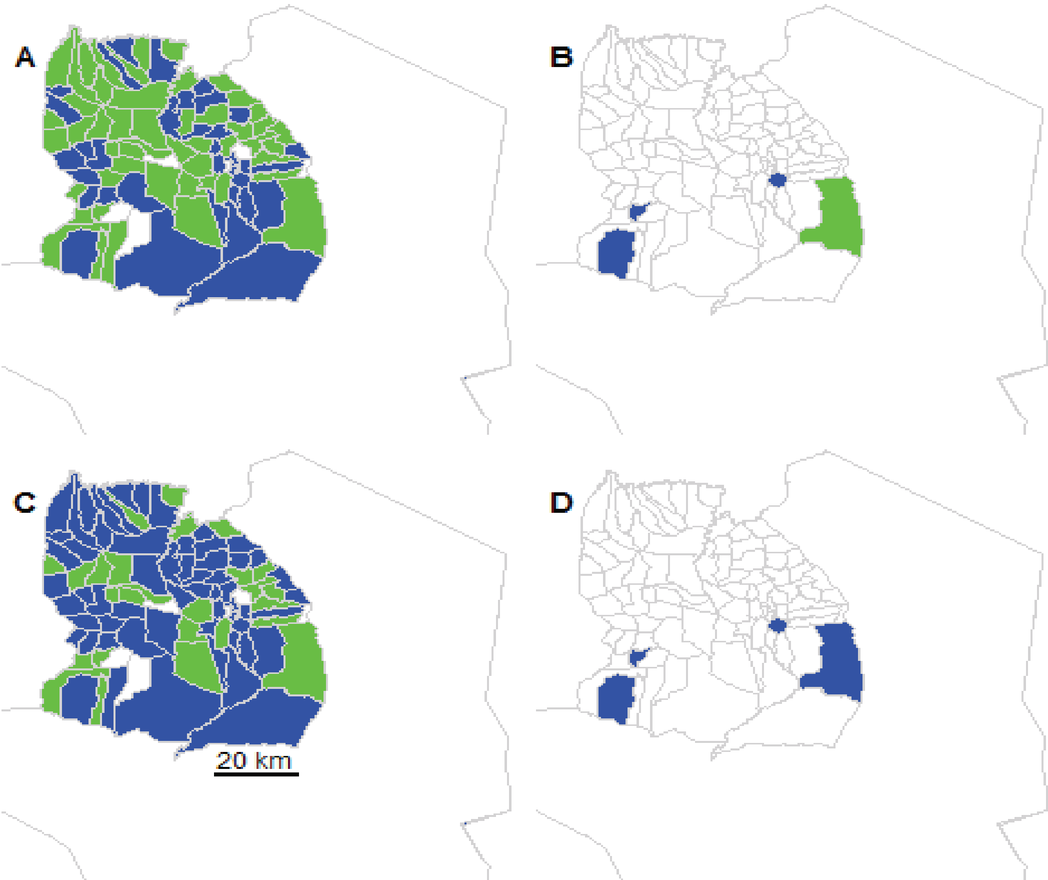


Figure 2-4: Vaccination performance in villages in Serengeti District. Villages where surveys were conducted are coloured based on whether village-level coverage exceeded 60% (green) or were less than 60% (blue) based on (A) post-vaccination transects and (B) school-based surveys versus whether coverage exceeded 70% (green) or were less than 70% (blue) based on (C) post-vaccination transects and (D) school-based surveys.

On the whole, many more dogs were recorded by transects than other methods. For example, fewer than 10 dogs were counted during household surveys in Chake chake district on Pemba, while 182 dogs were counted during transects. Transects surveys are therefore more likely to generate more precise estimates of coverage than the other methods even in areas with fewer dogs. However, at the village-level dog counts even from transects were often very low and therefore village-level coverage estimates would be expected to be imprecise. Although transects could be carried out for longer periods of time, this might also result in recounting of dogs and would make them more expensive to conduct. Overall, transects were affordable and generated more precise estimates of district-level coverage than questionnaire-based surveys that were affected by sampling. But the costs of transects accrue as more villages are surveyed, so in very large populations (with lots of villages) the costs of transects increase.

Priorities in terms of vaccination campaign evaluation typically change over time (Lembo and Partners for Rabies Prevention, 2012). During initial stages of national control programs, the priority, for example, is likely to be planning for dog vaccine procurement, with estimates needed of the dog population size. Human census data are almost universally available and can be used with HDRs to provide a baseline for vaccine procurement (Gibson et al., 2016). HDRs for a range of settings in Africa and Asia are a useful starting point (Knobel et al., 2008, Davlin and VonVille, 2012, Gsell et al., 2012). However, these data should not be considered sufficiently reliable to provide a denominator for generating vaccination coverage estimates. Indeed, our experience in southeast Tanzania was that dog population estimates derived from HDRs substantially overestimated dog populations and reassessment of vaccine procurement was required in subsequent years. But, in general, it was better to overestimate the dog population at this stage than underestimate it.

Consecutive vaccination campaigns should generate data on vaccine doses delivered at the village level. We therefore, recommend post-vaccination transects be used in conjunction with monitoring vaccine doses delivered during campaigns to guide vaccine procurement for future campaigns. This approach may mean that once baseline levels of coverage have been established through accurate records of dogs vaccinated in each village/vaccination station, post-vaccination transects may not be required every year, but could be completed less frequently. In our experience, local government authorities in Tanzania do not have resources or incentives to invest in monitoring and evaluation, and their priority, understandably, is on vaccinating dogs. A further advantage of post-vaccination transects is that local paravets, community-based health officers, local community members, and volunteers can be rapidly trained to conduct transects and therefore provide relatively independent coverage data.

A major obstacle when approaching elimination is the need to address difficulties in program implementation in hard-to-reach populations (Klepac et al., 2015). Post-vaccination transects could be used to troubleshoot the performance of vaccination coverage in stubborn foci. For example, vaccination programs across Latin America have achieved tremendous success in controlling dog rabies with average levels of coverage estimated to exceed 70% based on HDRs (Schneider et al., 2007). However, in localized areas, canine rabies persists, likely due to gaps in coverage or overestimation of routine coverage achieved (Ferguson et al., 2015). Transects could be used to identify areas in need of improved vaccination, where delivery was poor (for example in Figure 2-4). More generally, transects have proven to be effective in measuring the immediate success of vaccination campaigns in settings in both Asia and Africa (Putra et al., 2013, Muthiani et al., 2015, Tenzin et al., 2015b, Gibson et al., 2016, Léchenne et al., 2016).

Our transect surveys require further improvements to adequately address some concerns: transect routes were not pre-defined, which may have resulted in recounting of dogs. But efforts were taken to avoid recounting dogs, as we aimed to go from the outskirts to the centre of sub-villages and vice versa. Our transect surveys were paper-based, however, the developments in mobile phone technology to direct (guide) enumerators could greatly overcome this challenge and advance transect surveys (Gibson et al., 2015). Additionally, transect enumerators (observers) were the one who delivered dog vaccinations, which could cause observer bias. Another concern is the loss of collars of vaccinated dogs which have a significant impact on interpretation of vaccination coverage (Cleaton et al., 2019). We overcame this limitation by conducting transects immediately after vaccinations. In our study, some enumerators cycled rather than walked transects, but enumerators were trained to cover routes slowly, so we expect that any differences due to this would have been negligible. Simple tools are available to evaluate the performance of vaccination programs.

capturing the spatial variation that transects provide, which could also address these concerns (Gibson et al., 2015, Gibson et al., 2016).

Patterns of dog ownership in Tanzania are very heterogeneous. As such, district-level coverage estimates from household or school-based surveys tend to be more imprecise than estimates from transects. To obtain estimates with comparable precision would require considerably increased sampling efforts and increased costs. The issue of precision exists for all sampling methods, but transects overcame this issue because they were conducted in all villages (and therefore had a much larger sample size) while other methods (school-based surveys and household surveys) were conducted in just six sampled villages per district regardless of the geographical size of the district. The relatively lower precision of the estimates from households and school based surveys, and higher precision of estimates from transects may be at least in part because different sample sizes for these method. Post-vaccination evaluation methods that are precise are very important for long term evaluation of a program. Therefore, the focus should be precision of the methods, assuming that accuracy is sufficient and can be validated.

Moreover, from transects we were able to estimate village-level coverages. This can be useful when aiming to eliminate rabies as gaps in coverage can be detected, and therefore campaigns can be strengthened to effectively interrupt transmission. With the wide availability of mobile phones, real-time data on vaccinated dogs and coverage estimates from transects can easily be submitted by enumerators (Gibson et al., 2016, Mtema et al., 2016). We therefore recommend transects as a relatively cheap method to estimate village-level coverage that can be conducted at scale, in comparison to other methods where high levels of sampling are required that are cost prohibitive.

In this comparison, we could confirm that transects perform better than other methods as relatively cheap, comprehensive evaluations are needed. In future works, evaluation is needed to confirm: 1) the minimum number of dogs that need to be counted during transects surveys for inclusion in analysis, 2) what are the limitations of single-day transects (compared) to 2-days transects? 3) what is the required detection rate? and is two hours sufficient in both communities with low or high dog ownership? Obtaining quality data will entail trade-offs (e.g. costs vs.

detection rate). Because all methods have limitations, the intent of a practical evaluation is to strive for precise estimates.

Chapter 3 Estimating the Size of Dog Populations in Tanzania to Inform Rabies Control

3.1 Abstract

Estimates of dog population sizes are a prerequisite for delivering effective canine rabies control. However, dog population sizes are generally unknown in most rabies-endemic areas. Several approaches have been used to estimate dog populations but without rigorous evaluation. We compare post-vaccination transects, household surveys, and school-based surveys to determine which most precisely estimates dog population sizes. These methods were implemented across 28 districts in southeast Tanzania, in conjunction with mass dog vaccinations, covering a range of settings, livelihoods, and religious backgrounds. Transects were the most precise method, revealing highly variable patterns of dog ownership, with human/dog ratios ranging from 12.4:1 to 181.3:1 across districts. Both household and school-based surveys generated imprecise and, sometimes, inaccurate estimates, due to small sample sizes in relation to the heterogeneity in patterns of dog ownership. Transect data were subsequently used to develop a predictive model for estimating dog populations in districts lacking transect data. We predicted a dog population of 2,316,000 (95% CI 1,573,000–3,122,000) in Tanzania and an average human/dog ratio of 20.7:1. Our modelling approach has the potential to be applied to predicting dog population sizes in other areas where mass dog vaccinations are planned, given census and livelihood data. Furthermore, we recommend post-vaccination transects as a rapid and effective method to refine dog population estimates across large geographic areas and to guide dog vaccination programmes in settings with mostly free roaming dog populations.

3.2 Introduction

Dog-mediated rabies is a serious zoonosis responsible for at least 59,000 human deaths every year, primarily in low-income countries in Asia and Africa where rabies is endemic (Hampson et al., 2015). In these areas, over 95% of human rabies deaths result from bites by domestic dogs. Empirical data and mathematical modelling have shown that annual dog vaccination campaigns that achieve a coverage of 70% are sufficient to eliminate rabies (Coleman and Dye, 1996, Hampson et al., 2009). The global call for the elimination of dog-mediated human rabies by 2030 (Abela-Ridder et al., 2016), has prompted many countries to invest in dog vaccinations. For example, Tanzania has developed a National Rabies Control and Elimination Strategy, aiming to control dog rabies and eliminate human rabies in the country by 2030 (Mpolya et al., 2017). However, in low-income countries, dog population sizes are usually unknown, or hard to estimate, making it difficult to implement and evaluate dog vaccination campaigns (Lembo et al., 2010).

In most low-income countries where rabies is endemic, owned dogs are not registered by local authorities, dogs are free to roam, and dog censuses are not conducted. Insufficient knowledge of dog population sizes for planning of vaccination campaigns was reported as one of the limiting factors for ineffective rabies control in Africa (Lembo et al., 2010). This lack of knowledge prevents countries from forecasting vaccine procurement needs, and hinders assessment of the effectiveness of mass dog vaccination campaigns. It is, therefore, important to develop practical methods for estimating dog population sizes.

Approaches for estimating dog population sizes include extrapolation from human/dog ratios derived from household surveys and from transects with counts of dogs differentiating unvaccinated and vaccinated dogs marked with collars or paint sprays (Kongkaew et al., 2004, Knobel et al., 2008, Gsell et al., 2012, Downes et al., 2013, Tenzin et al., 2015a, Tenzin et al., 2015b, Rinzin et al., 2016). The accuracy of these methods has been questioned, as they generate very different population estimates from the same geographical areas, and surveys can be imprecise unless large numbers of households are sampled (Downes et al., 2013, Sambo et al., 2017). Household surveys are restricted to assessing owned dogs, while transects capture only free-roaming (observable) dogs. In Tanzania, over 78% of dog owners reported that their dogs roam freely all the time (Sambo et al., 2014), and therefore, the majority of dogs can be observed during transects. In settings where the vast majority of dogs are owned, such as Tanzania (Lembo et al., 2010, Sambo et al., 2014), a complete dog census, whereby each household in a community is visited, is the gold standard method to estimate the dog population, but requires considerable investment of time and resources.

Dog ownership patterns are not uniform across all communities. The distribution of dogs in different settings is linked to religious, cultural, geographical, and socioeconomic factors (Kongkaew et al., 2004, Knobel et al., 2008, Bardosh et al., 2014). For example, there tend to be fewer dogs in predominantly Muslim communities than in Christian communities (Kongkaew et al., 2004, Knobel et al., 2008). Tools to accurately estimate dog populations that take into account local cultural norms could, therefore, support the scaling up of mass dog vaccination programmes.

Our overall aim is to provide practical and effective approaches to estimate dog populations in different settings. Our first objective was to compare methods to determine which provides the most precise dog population estimates, and explain why estimates differ according to method. From this comparison, we identified that post-vaccination transects, which involve counting both vaccinated and unvaccinated dogs, provide more reliable dog population estimates than either household or school-based surveys. Our second objective was to identify factors that predict dog ownership in different settings in Tanzania, using our estimates of dog population size from transects. The aim of identifying these factors was to enable prediction of dog population sizes and densities in other parts of the country not yet subject to vaccination campaigns, which was our third objective. We assessed the performance of these factors from known populations in our study, and finally used these factors together with nationally available human census data to predict dog population sizes throughout Tanzania. Our findings should be valuable for both Tanzania and other countries as they develop, implement, and monitor their national rabies control programmes.

3.3 Methods

3.3.1 Study Sites

The study was conducted in the area already described previously (Chapter 2 (2.2.1)).

3.3.2 Data Collection

Since 2010, dog rabies vaccinations have been conducted in villages across the study districts using a central point approach (Kaare et al., 2009), whereby owners bring their dogs to a centrally located vaccination point within their village. At the vaccination points, all dogs that were vaccinated were fitted with temporary plastic collars around their necks. We used the number of vaccinated dogs in each district as the minimum possible dog population size from which to compare the performance of our estimates. Data from three different approaches were used to estimate dog populations: post-vaccination transects, household surveys, and school-based surveys. These methods are described in full elsewhere in Chapter 2, and outlined briefly below.

3.3.3 Post-vaccination Transects:

Since 2013, following vaccination campaigns, post-vaccination transects have been conducted (Sambo et al., 2017). Transects were walked (or occasionally cycled) on the same day as campaigns from 16:00 to 18:00, when dogs were active and visible, counting all marked (vaccinated) and unmarked (unvaccinated) dogs. In rural areas, transects were conducted in two randomly selected sub-villages per village (villages ranged in size from 2 to 10 sub-villages, with a median of 4), aiming to representatively sample each village. In the first sub-village, enumerators started at the sub-village centre and headed to the outskirts, while in the other, enumerators walked from the edge toward the centre. Each transect was conducted by one enumerator for 1 h per sub-village, taking 2 h to complete the village. In urban areas, enumerators covered the jurisdiction of a street (a geographical area defined by the National Census, which covers a neighbourhood with several roads). Enumerators selected the direction at the start of transects, at the border of sub-villages/streets and at road junctions by spinning a pen. Numbers of vaccinated dogs per district were compiled from dog vaccination registers and used in conjunction with the transect data to estimate coverage achieved and numbers of dogs in each district. In Serengeti district in northern Tanzania, data from mass dog vaccinations and transects that were conducted in August 2015 were used to validate the performance of transects. Data from a complete census of dogs (covering all 35,867 households in Serengeti district), undertaken from 2008 to 2015, were used to calculate the pup/adult ratio of dogs. Since every household was visited (large sample size) in Serengeti district, I used this district to calculate for puppies to adult ratio (PAR).

3.3.4 Household Surveys:

Household surveys were completed in all 28 study districts between July and August 2011, with the aim of obtaining an initial assessment of coverage from the first phase of vaccination campaigns conducted between February and April in 2011. Six villages were randomly selected from all villages in each district. In each selected village, a landmark was identified (preferably a school, otherwise a dispensary, church, or mosque). From this starting point, interviewers randomly chose a direction for selecting households for interview by spinning a pen. Every third household was sampled, and interviews conducted until 30 households were completed in each village. For households that owned dogs, the questionnaire captured details of dogs owned (adults and puppies <3 months) and their vaccination status on the basis of owner recall.

3.3.5 School-Based Surveys:

School-based surveys were conducted from June 2014 to February 2015, in the two months following dog vaccination campaigns in each district. The surveys were conducted in 24 districts (4 districts were missed) and were used to ask questions on the number of adults and children (<18 years of age) in households, as well as the number of dogs and puppies (<3 months of age), and their vaccination status. Six primary schools (one per village; most villages in Tanzania have a primary school) were randomly selected from each district but logistic and financial limitations meant that surveys were not conducted in four districts and were conducted in fewer than six schools per district as initially planned. We used total population purposive sampling with a target to interview 100 pupils per school (Teddlie and Yu, 2007). Standard VII pupils (ages from 13–15 years) were selected to complete the questionnaire. If more than one pupil from a household was recruited, the oldest pupil was selected. If the school had fewer than 100 standard VII pupils, pupils were recruited from lower classes (Standard IV–VI, ages from 12–14 years). Schools were selected from the same villages where household surveys were conducted.

3.3.6 Characteristics of Study Districts

Human demographic data for the study were extracted from the 2012 national population and housing census, including district-level population sizes, annual population growth rates, average household sizes (persons/household), numbers of livestock keeping households, and the percentage of the population living in rural areas (National Bureau of Statistics, 2012). Human populations were projected from the 2012 census to 2014, using annual growth rates for each district. The census also included district-level information on employment status among the working population (defined as those aged 10 years or over), which showed that the most frequent occupations were farming and livestock keeping. We, therefore, also extracted the number of workers in each district employed as peasants (farmers who only grow crops) and livestock keepers, respectively. To examine whether geographical setting was associated with dog ownership, districts were also categorized as (1) *Inland*, comprising 14 districts from the mainland that did not border the ocean; (2) *Coastal*, comprising 14 districts that bordered the Indian Ocean, including both Tanzania mainland coastal districts and the four districts from Pemba island; and (3) *Island*, covering the four districts from Pemba island. We extracted the geographical area of each district from data obtained from the National Bureau of Statistics (National Bureau of Statistics, 2012), using the *unionSpatialPolygon* function from the *maptoolspackage* in R (Bivand and Lewin-Koh, 2014), excluding water bodies and protected areas. These variables are summarised in Table 3-1 for study and non-study districts.

Table 3-1: Characteristics of study and non-study districts in Tanzania. Continuous variables are summarised by the mean (range) and categorical variables by the number (%). Variables were either extracted from the national census (National Bureau of Statistics, 2012) or from district shapefiles from the Tanzania National Bureau of Statistics (NBS) website. These variables were tested using ordinary least squares regression to assess the best variables for predicting numbers of dogs in districts.

Variable	Study districts (n = 28)	Non-study district (n = 140)
Human population size	307,676 (70,209, 1,775,049)	257,188 39,242, 807,619)
Annual % human population growth rate	2.3 (-1.0, 7.0)	2.6 (-3, 7)
Number of households	75,452 (16,892, 441,240)	50, 636 (9,027, 134,608)
Average household size (persons per household)	4.2 (3.5, 5.5)	5.1 (3.8, 7.8)
Area (km^2)¥	4,375 (15, 28,000)	4,375 (18.6, 28,244)
Setting:		
Inland	14 (50%)	128 (91%)
Coastal‡ [including Island]	14 (50%) [4 (14%)]	12 (9%) [6 (4.7%)]
Number of livestock-keeping households	18,317 (4,771, 35,829)	24,168 (2,258, 71,335)
Proportion (%) of persons employed* as:		
Peasants	60 (3, 88)	64 (4, 93)
Livestock keepers	1 (0, 6)	1 (0, 65)

¥Excluding protected areas and water bodies. ‡Coastal districts were defined as districts that border the Indian ocean. *Defined as the main occupation on which persons aged 10 years and above spend most of their working time.

3.3.7 Statistical Analysis

Estimation of dog population sizes: For transects, which involve counting both vaccinated and unvaccinated dogs, estimates of dog vaccination coverage, and their 95% confidence intervals (CIs), were obtained from binomial generalized linear mixed models (GLMMs) with normally distributed (on the logit scale) random intercepts allowing coverage to vary among villages. Dog population estimates for each district were calculated by dividing the numbers of vaccinated dogs by the coverage estimates. Puppies under the age of three months are not often vaccinated during campaigns (Durr et al., 2009, Minyoo et al., 2015), and are less likely to be counted than adult dogs during transects (Minyoo et al., 2015, Arief et al., 2017, Sambo et al., 2017). In Thailand, puppies comprised approximately one-quarter of the dog population (Kongkaew et al., 2004). Estimates of dog population sizes from transects therefore require further adjustment. We calculated the ratio of pups/adult dogs (1:3.81) from the dog census conducted in Serengeti district in northern Tanzania (Sambo et al., 2017), and adjusted our dog population size estimates accordingly. We used transect and mass dog vaccination data collected between November 2014 to January 2015 for these calculations. Transect data were collected from 27 districts (we were unable to collect transect data in Ilala district, and it was not included in our analysis). To assess year-to-year variation of the estimated dog population sizes, we compared these data (November 2014 to January 2015) with data that were collected from September 2015 to December 2016.

The total number of dogs across the 27 districts was calculated as the sum of the dog population estimates in each district. A 95% confidence interval for this total was estimated as the 2.5% and 97.5% quantiles from 100,000 bootstrap samples, where bootstrapped samples for each district were generated by first sampling coverage estimates from a normal distribution with the mean being the estimated log odds of coverage and the standard deviation being its estimated standard error, and second, converting these coverage estimates to total dog population sizes, with adjustment for undercounting of puppies, as described above. The formula for this was: dog population size=(count of vaccinated dogs/coverage) multiplied by pup to adult ratio.

For household and school-based surveys, we estimated dog population sizes by multiplying the mean number of dogs per household (MDH) recorded during these surveys (all recorded dogs and people in 6 sampled villages/district per method) by the total number of households within each district according to the 2012 national census. The MDH is less popular than the human to dog ratio (HDR), but it has been recommended as a reliable method (Rinzin et al., 2016). For each district, the mean number of dogs per household and profile likelihood 95% confidence limits were estimated from a negative binomial GLMM, where the response was the number of dogs in each household, and the only fixed parameter was the intercept. Confidence limits were not calculated for districts where too few (≤3) surveyed households owned dogs to provide reliable estimates of uncertainty. We explored fitting a random effect to account for variation in dog numbers among villages, but omitted it because, for the majority of districts, the model either failed to converge, suggesting insufficient information in the data to estimate the variance, or gave zero variance estimates and, therefore, identical estimates and confidence intervals to the model, with no random effects. The district-level estimates from the household and school-based surveys were summed to estimate the overall dog population size in the study districts. Confidence intervals for these estimated totals were calculated by parametric bootstrapping, similarly to the transect methods above, by sampling from a normal distribution with the mean being the log mean number of dogs per household, and the standard deviation being its standard error estimated from the GLMM. Where too few households owned dogs to allow the GLMM to be fitted, the standard error was assumed to be zero.

Prediction of dog population sizes: We used a linear regression model to achieve our second objective of identifying factors (those considered are shown in Table 3-1) associated with dog population sizes, and our third objective of estimating the number of dogs in each district. Here, we motivate our approach to modelling dog numbers.

First, rather than modelling dog numbers directly, we modelled the dog:human ratio, then multiplied estimated dog:human ratio by human population size to estimate dog numbers. A simple model for predicting the ratio of the number of dogs (D_i) to the number of humans (P_i) in district *i* is $\frac{D_i}{P_i} = K\varepsilon_i$, where every district is predicted to have the same dog: human ratio, K, from which individual districts are allowed to deviate by means of district-specific residuals, εi, where $\varepsilon i > 0$ with geometric mean 1. We can add flexibility to this model by introducing continuous variables that are potential predictors of the dog: human ratio, for example the proportion of the population employed as livestock keepers, L_i/P_i, such that $\frac{D_i}{P_i} = K\left(\frac{L_i}{P_i}\right)^{\beta_1} \varepsilon_i$, where β_1 is a coefficient governing the influence of L_i/P_i on D_i/P_i. The model can be further extended to allow differences in D_i/P_i between categories of district, such as between districts with and without a coastline: $\frac{D_i}{P_i} = K\left(\frac{L_i}{P_i}\right)^{\beta_1} \exp(\beta_2 C_i)\varepsilon_i$, where C_i is a binary indicator variable with the value 1 for coastal districts and 0 otherwise, so that $\exp(\beta_2)$ represents the ratio (coastal dog: human ratio):(mainland dog:human ratio). Taking the natural log shows that this model can be viewed as a linear regression model: $\log\left(\frac{D_i}{P_i}\right) = \log(K) + \beta_1 \log\left(\frac{L_i}{P_i}\right) + \beta_2 C_i + \log(\varepsilon_i)$, where $\log(\varepsilon i) \sim \text{Normal}(0, \sigma 2)$. Further continuous and binary variables (listed in Table AB-2) were added in the same way (continuous variables were logged and categorical variables fitted as binary indicator variables) to give the full model prior to filtering using the variance inflation factor.

We used this ordinary least squares regression model to assess whether any of the variables that we collated were useful for predicting numbers of dogs. We partitioned our data into two sets of districts: a model-building set, which we used to develop the model, and a prediction set, for which we aimed to predict dog numbers from the model. The model-building set comprised the data from the 28 study districts where we collected data, whereas the prediction set included all districts in Tanzania (including the 28 study districts). The response variable (D_i/P_i) was the estimated number of dogs per 1000 people in each of the study districts, log-transformed to fit the modelling assumptions of linearity and homoscedasticity. Before fitting the model, we conducted data exploration to detect collinearity among the variables using pairwise scatter plots and the variance inflation factor (VIF) as described by Zuur et al. (Zuur et al., 2010). The variable with the highest VIF was removed and VIFs recalculated, repeating this process, stopping when all VIF values were below 5. The remaining variables were taken forward to model selection.

The aim of model selection was to identify the best-fitting model, that is, the model that most accurately predicted district dog population sizes. The best model was selected by fitting all possible subsets of the six candidate variables as main effects, and choosing the model with the lowest corrected AIC (AIC_C (Wagenmakers and Farrell, 2004)). The predictive power of the best model was assessed by calculating R^2_{FPE}, where FPE stands for final prediction error (Rousson and Goşoniu, 2007). The R^2_{FPE} is the useful stat to show the importance of variable. The interpretation of R^2_{FPE} is similar to classical R^2 and adjusted R^2, except that unlike these two statistics, R^2_{FPE} does not overestimate predictive power (Rousson and Goşoniu, 2007). We also calculated adjusted R^2 for comparison. The contribution of each selected variable to the predictive power of the best model was gauged by calculating partial R^2_{FPE}, which estimates the proportional reduction in prediction error when a given variable is included in the final model. Partial R^2_{FPE} is calculated as $1 - (1 - R^2_{FPE})/(1 - R^2_{FPE}{}^*)$, where R^2_{FPE} is calculated from the best model, and $R^2_{FPE}{}^*$ is calculated from a reduced version of the best model, where the variable under investigation has been dropped.

Two methods were used to assess the validity of the final model. First, we assessed the propensity for the model selection procedure to select spurious variables ("false discoveries"). We permuted the response variable 1000 times to simulate 1000 datasets in which none of the variables are associated with the response. We applied the model selection procedure to each dataset and calculated the mean number of variables selected. The ratio of mean number of false discoveries to the actual number of variables selected is a permutation-based estimate of the false discovery rate (FDR; (Efron, 2004)). Second, we used bootstrapping to assess the stability of the selected variables to sampling error. We performed the model selection procedure on 1000 bootstrapped datasets (datasets of equivalent size but sampled with replacement from the original dataset), recording the proportion of datasets from which each variable was selected. The final model was then used to predict the dog population size, density, and 95% prediction interval for each district in Tanzania.

To assess year-to-year variation in our estimates, we compared dog population sizes estimated from data that were collected in 2014–2015 against those estimated from 2015–2016 data.

When making predictions from the models of coverage and the number of dogs per 1000 humans, it was necessary to back-transform from the linear predictor scale using a nonlinear inverse “link” function (inverse logit for coverage and exponential for dog numbers). Since these models have normally distributed errors, predictions would be biased, potentially severely, if calculated simply by back-transforming without adjusting for the error variance, as a consequence of Jensen’s inequality (Nakagawa et al., 2017). Log-scale predictions from the model of district dog population size were adjusted for Jensen’s inequality by back-transforming using $\exp(\mu + 0.5\sigma^2)$, and logit-scale predictions of vaccination coverage were back-transformed using $\text{logit}^{-1}(\mu + 0.5\sigma^2 \tanh(\mu(1 + 2\exp(-0.5\sigma^2))/6))$, where μ is the link-scale prediction and σ^2 is the total error variance (Von Tress, 2003).

All statistical analyses were conducted using R version 3.4.1 (R Core Team, 2017). GLMMs were fitted using the *lme4* (Bates et al., 2014) and *glmmTMB* packages (Magnusson et al., 2017). Models selection was performed using the *dredge* function from the *MuMIn* package (Barton, 2009).

3.4 Results

During the 2014–2015 mass dog vaccination campaigns, 86,361 dogs were vaccinated in the 28 study districts, and 86,142 dogs were vaccinated in the 2015–2016 campaign. The following data collection activities were completed: (i) post-vaccination transects in ~2100 villages in 2014–2015 and in ~2600 villages in 2015–2016; (ii) household surveys in 4488 households in 2011, from 160 randomly selected villages; and (iii) school-based surveys of 8254 primary school pupils (each representing a unique household) within 115 randomly selected schools following the 2014–2015 campaign. During the 2014–2015 transects, 18,436 dogs were counted, of which 63% were observed with collars, indicating that they were vaccinated. From the school-based surveys, 2198 owned dogs were reported, corresponding to a mean of 0.7 dogs per household, and from the household surveys, 731 dogs were recorded, corresponding to a mean of 0.6 dogs per household (Table AB-2).

Estimation of dog population sizes: The overall dog population estimated in these study districts varied according to the survey method used (Figure 3-1). From transects, we estimated a total dog population in the 27 study districts of 164,000 (95% CI 163,000–169,000 reported to three significant digits) and an overall human/dog ratio of 53.6:1 in the study districts. The estimated dog population size leads to a vaccination coverage estimate of 52% (86,000/164,000), which is lower than the direct coverage estimate from transects (63%), due to adjusting for unobserved and unvaccinated pups. By contrast, using household and school-based surveys, we estimated the dog population in the study districts to be 412,000 (CI 348,000–544,000) and 403,000 (CI 341,000–531,000), respectively. We compared the predicted and estimated dog numbers per each district (Figure 3-1). There was minimal year-to-year variation in the estimated number of dogs in each district from the data that were collected in 2014–2015 versus those collected in 2015–2016 (Figure A3-2).

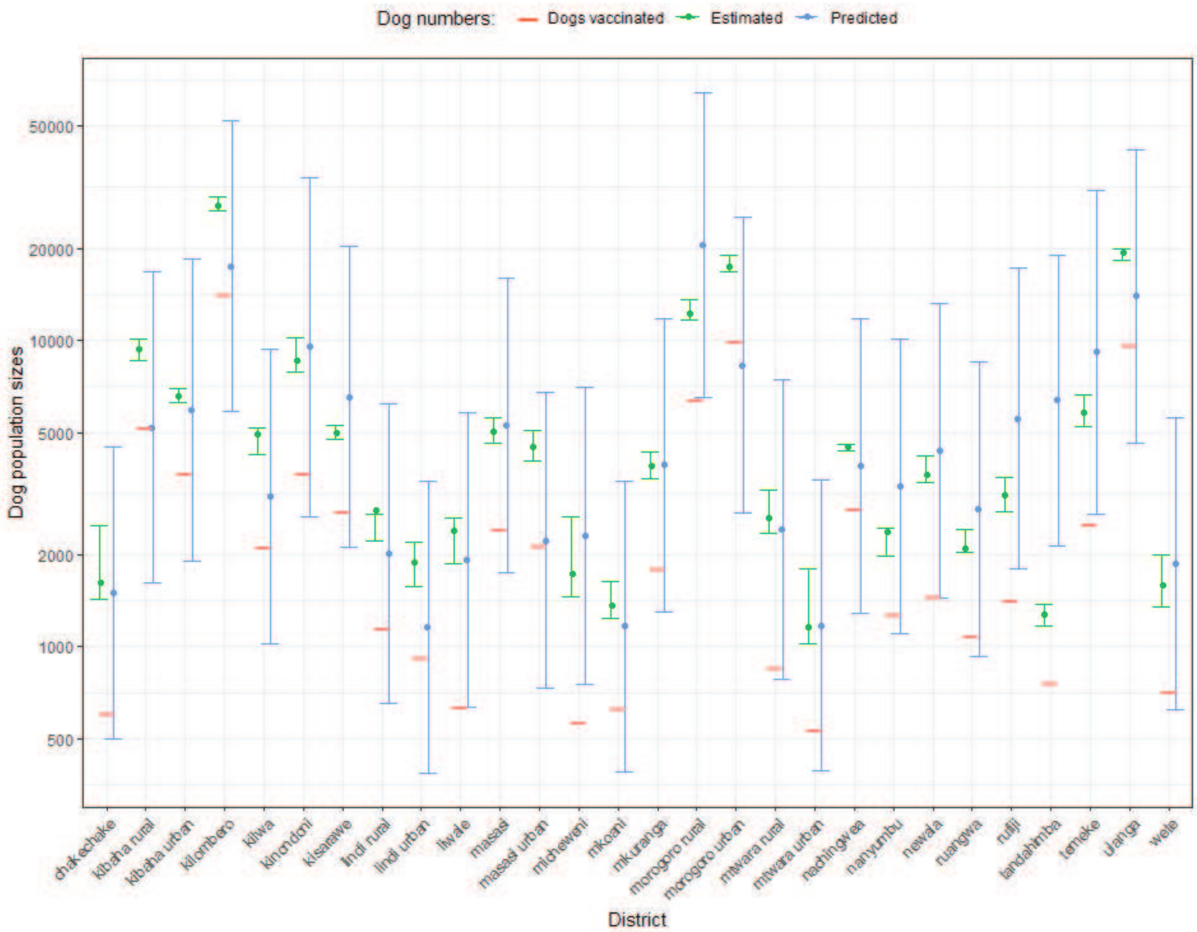


Figure 3-1: Comparison of the estimated and predicted number of dogs in the 28 districts. The number of vaccinated dogs from the 2014–2015 campaign is also plotted as a horizontal line for each district.

Prediction of dog population sizes and densities: using our transect estimates, we investigated the influence of district-level variables on dog population sizes. The pairwise plots between the log-scale continuous variables investigated showed that the number of households was highly correlated with the human population (Pearson's r = 0.96). We therefore dropped the number of households from the model. A further two variables, the number of people living in rural areas and the number of livestock-owning households, were dropped in order to reduce all VIFs to below 5 (Table A3-1). These variables were also highly correlated with human population size.

All 64 possible models were fitted from the combination of the six retained variables and the models were ranked by δAIC_C (Table 3-2). The top three models were almost equivalent in predictive power (R^2_{FPE} = 58%), and were very close in

δAIC_C, which ranged from 0–1.27. Our best fitting model retained three variables: the proportions of livestock keepers and of peasants, and the geographic setting (inland versus coastal and island). The proportions of livestock keepers and peasants were both positively associated with the dog/human ratio: a doubling of the proportion of livestock keepers was associated with 28% (95% CI: 14%, 44%) larger dog populations, while the equivalent effect for the proportion of peasants was 36% (95% CI: 13%, 65%), all other characteristics being equal. We also found that there were 103% (95% CI: 21%, 120%) more dogs per person in inland districts than in island and coastal districts.

Two predictor variables: the proportion of livestock keepers and the geographic setting (inland versus coastal/island) were consistently retained in the best-ranked models (Table 3-2). Dropping either the setting variable or the proportion of persons employed as peasants also reduced the variance explained by 16% (R^2_{FPE} fell from 58% to 42% in both cases, giving a partial R^2_{FPE} of 27%). Excluding the proportion of persons employed as livestock keepers in the final model reduced R^2_{FPE} to 30%, showing the substantial predictive power of this variable (partial R^2_{FPE} = 39%).

Table 3-2: Regression coefficients and model fit statistics for models predicting dog populations in Tanzania. Statistics are shown for all models with $δAIC_C < 4$, ranked in order of decreasing fit as gauged by $δAIC_C$. We report the predictor variable regression coefficient estimates, model fit statistics including the partial R^2_{FPE}, the $R^2_{FPE'}$, adjusted R^2, the degrees of freedom (df), the log-likelihood (LL), delta AIC ($δAIC_C$), and akaike weights. We also report the importance of each predictor variable (variable robustness).

Regression coefficient estimates							**Model fit statistics**							
Intercept	***Area (km²)***	***Inland vs Coastal & Island***	***Mainland vs Island***	***Number of people***	***Employed as livestock keepers***	***Employed as peasants***	***R^2***	***Adjusted R^2***	***Df***	***LL***	***AICc***	***$δAIC_C$***	***Weight***	***R^2_{FPE} (%)***
5.60		-0.708			0.358	0.448	0.658	0.724	5	-18.65	50.03	0.00	26.0%	57.6%
9.51	0.124	-0.758		-0.447	0.303		0.688	0.763	6	-17.49	50.98	0.94	16.2%	58.0%
8.07		-0.760		-0.219	0.335	0.300	0.682	0.760	6	-17.65	51.30	1.27	13.8%	57.5%
9.99		-0.907		-0.412	0.281		0.640	0.757	5	-19.39	51.52	1.48	12.4%	55.3%
11.03		-0.767	-0.422	-0.489	0.302		0.661	0.703	6	-18.54	53.08	3.05	5.7%	54.7%
Variable robustness	33%	91%	13%	51%	97%	49%								

We used permutations and bootstrapping to assess the reliability of the selected best-fitting model. Using 1000 permutations, we estimated an FDR of 28%. Bootstrapping the model selection procedure showed that two of the three variables were highly robust: proportion of livestock keepers and coastal setting were selected in 97% and 91% of bootstrapped models, respectively (Table 3-2). However, despite their robustness, a model containing these two predictor variables alone performed substantially worse than the best-fitting model, as evidenced by its relatively low R^2_{FPE} of 42% and its selection as the best model in only 6% of bootstrapped datasets. Two other variables were selected with around 50% frequency, proportion of the population employed as peasants (49%), and human population size (51%). Based on δAIC_C, R^2_{FPE} , and the reliability analysis, we concluded that two of the three variables selected are highly robust, and that at least one other variable is required to maximise predictive power. Since the top three models are almost equivalent in terms of predictive power (R^2_{FPE}) and δAIC_C, we selected the one with only three variables selected, which also happened to be the best-fitting model. This combination of three variables (the proportions of livestock keepers and of peasants, and geographic setting) chosen for our final model was used to predict the dog population across Tanzania.

From our final model, we predicted considerable variability in dog population sizes across all 168 districts in Tanzania (Figure 3-2). Dog population estimates ranged from just 630 dogs in Kusini district on the island of Zanzibar, to 45,000 dogs in the inland district of Nzega. Overall, the final model predicted a dog population of 2,316,000 (95% CI 1,573,000–3,122,000) in Tanzania in 2014–2015. In 2014, a human population of 47,831,000 was projected from the Tanzania population census (National Bureau of Statistics, 2012). Taken together with our predicted dog population size (2,316,000 dogs), we obtain an overall human/dog ratio of 20.7:1 in Tanzania. Generally, the highest dog ownership was predicted from inland districts, especially those dominated by rural livestock keepers. Human/dog ratios for each study district are presented in (Table 3-2).

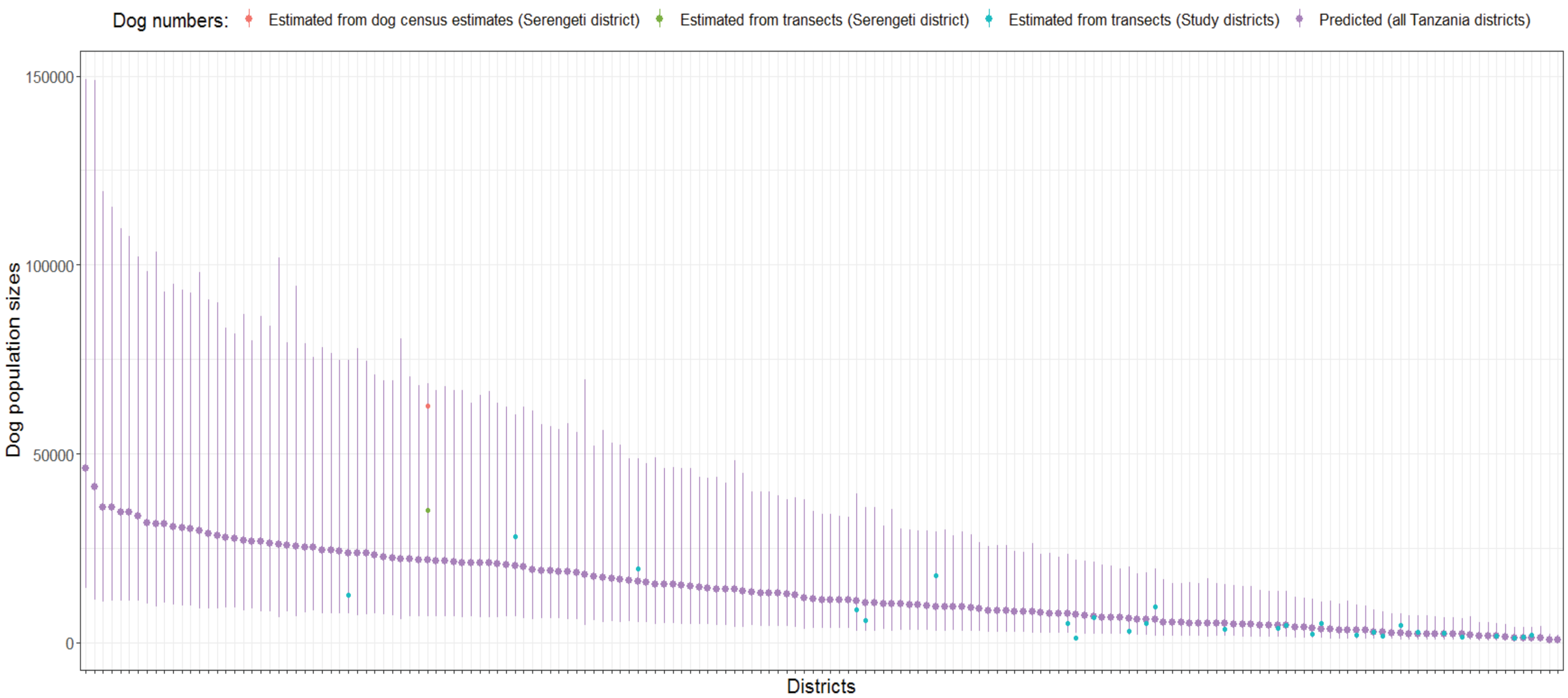


Figure 3-2: The predicted number of dogs in districts across Tanzania. The predictions and prediction intervals are shown in blue and compared to the dog population estimated directly from transects for a non-study district (Serengeti, in red) and for the study districts. Most of the green points (27 out of 28) from the model-building set were within the prediction intervals, suggesting that the fit of the model is reasonably good, with no outlier districts for whom the model is making poor predictions. Districts are ordered according to those with the largest (left-hand side) to the smallest predicted dog population (right-hand side). District names are shown in Figure A3-2. Serengeti transects were conducted in August 2015. PVT = post-vaccination transects.

Dog density from the predicted dog population sizes for each of the 168 districts also varied greatly, ranging from 0.14 to 113 dogs per square kilometre (Figure 3-3). Liwale district (an inland study district which has an area of ~15,000 km2) had the lowest dog density of 0.14 per km2, while Bukoba urban (an inland district with an area of 30 km2) had the highest dog density of 113 dogs per km2. Based on Tanzania's total land area and predicted dog population, we determined the mean density of dogs to be 8.81 per square kilometre (interquartile range: 2.24–9.23 per km2). Predicted densities were highest in northern and north-eastern Tanzania, and lowest in the southern and central-west parts of the country (Figure 3-3).

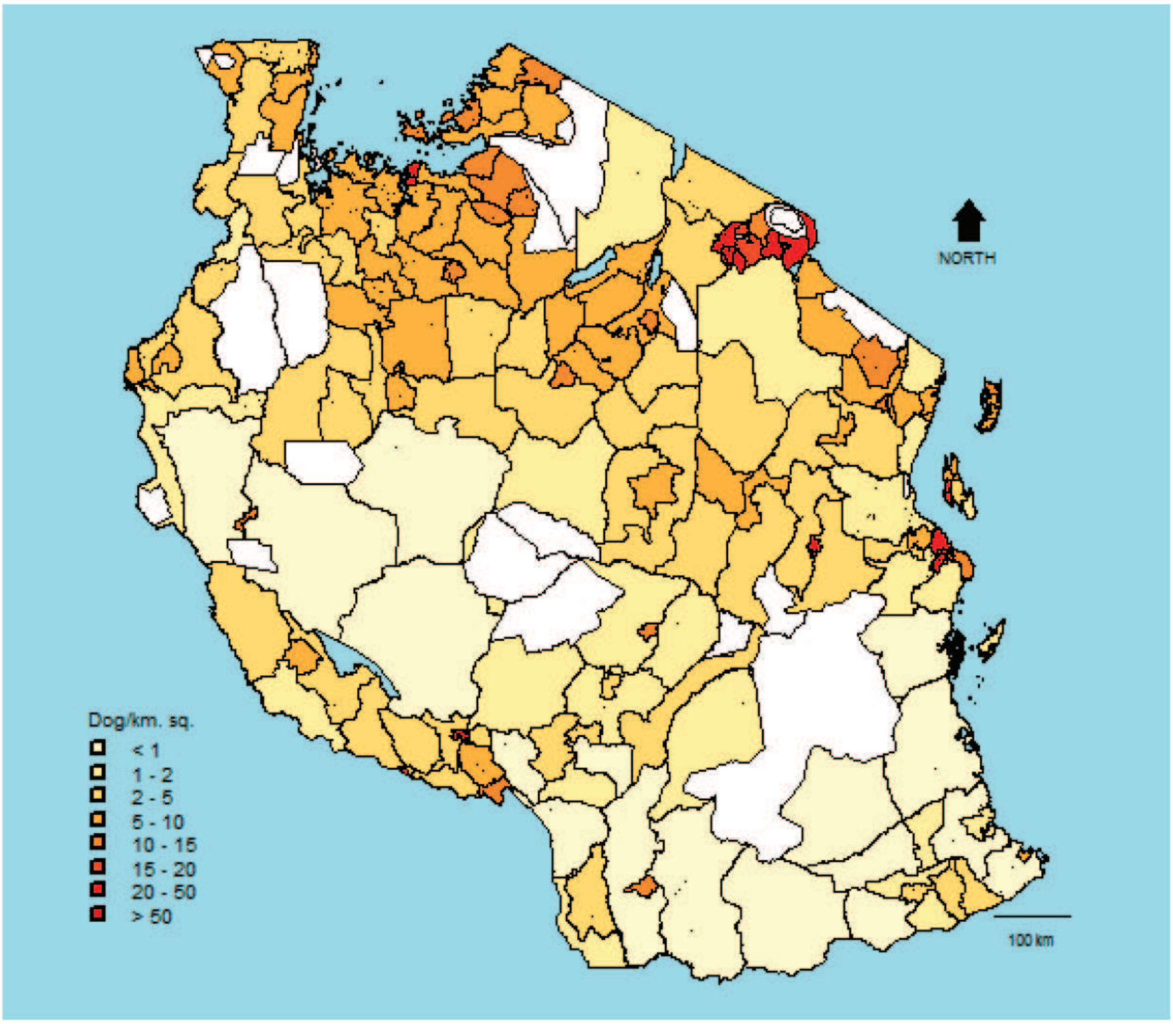


Figure 3-3: Estimated dog densities in districts across Tanzania. White areas represent water bodies, forest reserves, or wildlife-protected areas.

3.5 Discussion

Knowledge of the size of dog populations is critical for the planning and implementation of effective canine rabies control strategies. Before the implementation of vaccination campaigns, this information is useful for determining the personnel required, and for the procurement of vaccines and other supplies. After implementation, this information is required to evaluate the intervention in terms of the vaccination coverage achieved. Our study uses data from well-studied dog populations in Tanzania, where vaccination campaigns have been conducted to predict the size of dog populations in new areas, and where vaccination campaigns will hopefully be scaled up in the future.

Although several methods have been used to calculate the size of dog populations (Davlin and VonVille, 2012), these methods have not been comprehensively compared to assess which generates the most precise dog population estimates. From our comparison, we found that post-vaccination transects generated more precise and reliable estimates than either household or school-based surveys in Tanzania. Transects are, however, only reliable if all dogs (owned and unowned, free-roaming or restricted) have an equal chance of being counted. In many sub-Saharan countries, most owned dogs are free-roaming, so this assumption would hold. In a previous survey in Tanzania, most dog owners reported that they did not tie or cage their dogs. Those who reported restricting their dogs were from urban areas, while in rural areas, the vast majority of dog owners reported that they do not restrict their dogs at any time (Sambo et al., 2014). Hence, transects are appropriate for estimating dog population sizes in Tanzania, but in countries where a large proportion of dogs are kept indoors, this method would not be appropriate.

The imprecision of the dog population estimates from household and school-based surveys was due to their low sampling effort compared with post-vaccination transects (Sambo et al., 2017). Although sample size at the household level was not low (30 households per village and ~100 families per school), only six out of an average of 95 villages per district were sampled, and the precision of estimates from hierarchical sampling designs is expected to be dominated by sample size at the highest level (Maas and Hox, 2005, Snijders, 2005). The overall proportions of the population surveyed were also small (4488/441,000 households from household surveys versus 8254/441,000 households from school-based surveys), despite the large numbers of surveys conducted, whereas for the post-vaccination transects, ~2500 villages were sampled. The practical consequence of imprecision in the estimates from household and school-based surveys for the implementation of mass dog vaccination is that the upper bound of the range of plausible dog population sizes is, on average, 3 times the lower bound, compared with 1.18 for transects.

In addition to being imprecise, estimates from household and school-based surveys were often inconsistent (Figure 3-1), either with each other (for example, Kisarawe and Wete districts), or with the number of dogs vaccinated (for example, Mkuranga and Chakechake districts). The dog population may, therefore, be either over- or -underestimated by projecting from the mean number of dogs per household, given limited sampling and considerable house-to-house variation in dog ownership. For example, Kinondoni district in Dar es Salaam has over 400,000 households with 0.32 dogs per household estimated from the household survey, which would suggest a dog population of 141,197, a large overestimate. However, when we used the mean number of dogs per person (as estimated from SBS) multiplied by number of people in Kinondoni district, the number of dogs was 46, 977 which was much lower than the estimated above 141,197 using mean dogs per household (Table AB-2). When mean number of dogs per person (from SBS or HHS) extrapolated to district level using known human population was estimating fewer dogs compared to estimates of dog number from using mean number of dogs per household (Table AB-2). The mean dog/household tend to throw away a lot of information which we accept as the limitation in this study. However, this is finding should be interpreted with caution. In Bhutan, the number of owned dogs estimated from the mean number of dogs per household was lower than those estimated from mean number of dogs per person (Rinzin et al., 2016). The number of vaccinated dogs (numerators), together with the size of dog populations derived from household and school-based surveys (denominators), were used to calculate the vaccination coverage, and compared against coverage estimated directly from these surveys. We found large discrepancies depending upon the method used. For example, in 2014–2015, around 86,000 dogs were vaccinated, but school-based surveys estimated a dog population of 399,000, which would have led to just 22% coverage (Table AB-2). By contrast, direct estimates of dog vaccination coverage from school-based and household surveys were both around 56% (Table AB-2). In some districts, the discrepancy was clearly implausible, for example, in Chake Chake, Pemba, where more than double the number of dogs estimated from school-based surveys were vaccinated (Table AB-2). These discrepancies have practical impacts on rabies control, and demonstrate the need for careful post-vaccination evaluations, without reliance on dog population survey estimates only.

Our multivariable regression analysis identified the proportion of livestock keepers and geographical setting as robust variables for predicting dog population sizes, consistent with previous studies on factors influencing dog ownership in different parts of the world (Kitala et al., 2001, Acosta-Jamett and Cleaveland, 2010, Davlin and VonVille, 2012). In most African countries, dogs are reported to play a role in protecting livestock, explaining why livestock keeping was such an important variable (Knobel et al., 2008, Bardosh et al., 2014). Other factors reported to influence dog ownership in Africa include socioeconomic status, livelihood (which could include livestock keeping), culture, and religious beliefs linked to different settings (Bardosh et al., 2014). The reason for fewer dogs in Tanzanian coastal and island areas could be linked to the predominantly Muslim communities in these areas, as Muslims are reported to own fewer dogs (Knobel et al., 2008, Bardosh et al., 2014). Our study demonstrates the need to consider such factors in planning vaccination campaigns, and in understanding dog rabies incidence, control, and prevention, more generally.

We found that despite the robustness of these two variables (livestock keeping and geographical setting), by themselves, they accounted for only about two-thirds of the predictive power of the best-fitting model. A third variable was also needed to improve predictive power. Our model validation showed that the proportion of peasants or the human population were almost equivalent in the final model (R^2_{FPE} values of 58% and 55%, respectively). If applying this model to new settings, the decision as to which variable to use will depend on the availability of data on either of these variables. In settings (countries) that do not have data on peasants, they can use human population sizes that are generally available from the census. In this study, I didn't evaluate poverty and human population density or human development index (HDI) which have been reported as a strong predictor of dog ownership (Wallace et al., 2017). I also do not propose evaluating campaign success by working backwards from the total dog population estimates derived from this predictive model, because the uncertainty in this estimate is inflated from the large variation in district population sizes. To evaluate coverage across districts, we would suggest estimating mean coverage directly from the village-level transect measures. District-level estimates of dog populations (Figure 3-1), which are based on these coverage estimates, are quite precise, as are directly derived district-level estimates of coverage ((Sambo et al., 2017), 58–65% not adjusted for puppies).

Our study was consistent with previous findings in Tanzania, which reported more dogs in mainland compared to island and coastal areas (Knobel et al., 2008, Sambo et al., 2017). However, our overall human to dog ratio estimate of 20.7:1 was higher than previous studies in Africa, which ranged from 3:1 to 15:1 (Kitala et al., 2001, Awoyomi et al., 2007, El-Yuguda et al., 2007, Knobel et al., 2005, Knobel et al., 2008, Bardosh et al., 2014, Mbilo et al., 2017). This suggests that human/dog ratios extrapolated from household or school-based surveys could be unreliable when extrapolated to district or national level. Initially, the study area was estimated to have about 400,000 dogs (Hatch et al., 2017, Mpolya et al., 2017), based on reported human/dog ratios (Knobel et al., 2008), which was much higher than the number of dogs subsequently estimated with post-vaccination transects (164,000 (95% CI 163,000–169,000). The lower number of dogs in our study suggests that dog vaccine requirements in Africa might be less than previous estimates. A study in Uganda also found lower numbers of dogs than previously estimated (Wallace et al., 2017). If this pattern holds across more countries, the lower number of dogs provides further incentives for African governments to undertake vaccination programmes, as the target of 70% could be more easily achieved (Wallace et al., 2017). However, our data were largely collected from southeast Tanzania, where there are fewer pastoralists who tend to own more dogs (Malele et al., 2011), and from coastal or island districts (~50% of study districts) which tend to have fewer dogs. A consequence of this non-random sampling of districts is that for several districts (the 40 districts at the left of Figure 3-2) the model is extrapolating beyond the range of the training data, and these estimates should therefore be treated with caution. . Additional data (dog vaccination and transect surveys) from other populations (inside and outside of Tanzania) would be valuable to further refine and validate this predictive approach.

Several household surveys have been conducted in Tanzania, generating lower human/dog ratios than we found from transect-based estimates. For example, in Iringa urban, the human/dog ratios were estimated to be 14 (Gsell et al., 2012), versus our transect estimate for Iringa urban of 34. Meanwhile, in Kilombero and Ulanga districts, human/dog ratios were estimated to be 12 and 29, respectively, from households surveys (Bardosh et al., 2014), in contrast to our transect estimates of 21 and 18, respectively. Variation was also reported by geographical setting, with human/dog ratios estimated to on average be 7.6:1 in rural-inland areas, 10.8:1 in rural-coastal areas, 27.1:1 in urban-coastal areas, and 14.4:1 in urban-inland areas (Knobel et al., 2008). These estimates derived from household surveys are likely to be affected by limited sampling. Mark-recapture studies are useful for estimating numbers of dogs (Downes et al., 2013). Our study suggests that transects, when done in association with dog vaccinations at scale, can capture population variability. However, there is still a need for predictive methods for working in areas where dog vaccinations have yet to be conducted, such as the model that we developed.

My predictive model could be used to make preliminary predictions of dog numbers in other countries that are similar to Tanzania, with respect to dog-owning practices i.e., where most dogs are free-roaming and there are very few unowned dogs. This model can give a starting point for settings with no dog population size estimates even prior to any vaccination campaigns (and transects), given available data on the proportions of livestock keepers and of peasants or on human population sizes. Such preliminary dog population estimates could provide a baseline for planning mass dog vaccinations. The wide confidence intervals of these model estimates may initially mean procurement of excess or insufficient numbers of vaccine vials. However, over-procurement should not be problematic, as the vaccines can be stored for long periods (normally three years) for use in future campaigns. For vaccines remained with shorter shelf life (i.e. one year) as a result of donations i.e. from OIE vaccine bank, we recommend these vaccines to be used first followed by vaccines with long shelf life.

Conducting post-vaccination transects in every village is, however, labour-intensive and costly (Sambo et al., 2017). In my opinion, I don't think conducting transects survey every year is a sustainable approach for national rabies control campaigns. I recommend conducting transect in the initial phases of vaccination to get reliably estimate of dog population and coverage. Awareness and participation of dog owners typically increase in the first few years of a rabies control programme (Mpolya et al., 2017), so transects may help to refine estimates in the second or third campaigns. Once baseline levels of coverage have been established through accurate records of dogs vaccinated in each village/vaccination station, post-vaccination transects may not be required every year as substantial changes in dog population sizes are not expected (Figure A3-2). For example in village *X*, the coverages were 70%, 75%, and 74%, after vaccinating 120, 130 and 127 dogs respectively in year 2017,2018 and 2019. Therefore, there is no need to conduct transects in 2020 and 2021 because the baseline data for number of dogs in village *X* has been established. Assume if you vaccinate 100 dogs in 2020, you really know that the 70% coverage is not achieved. However, using my previous example, I recommend do also recommend repeating transects after several years i.e. 2022 or 2023 given dog population growth, and conducting transects in areas where control programmes have been less successful than expected, so that any coverage gaps that may be limiting progress can be identified (Sambo et al., 2017).

Our overall estimates of dog density were higher those reported from elsewhere in Africa (Brooks, 1990, Dye and Cleaveland, 1995, Kitala et al., 2001, Kitala et al., 2002, Knobel et al., 2005). This was probably because we excluded water bodies and protected areas when calculating densities. Our dog density map highlights districts with high dog densities that should be prioritized in the scaling up of dog vaccinations (only two districts, Moshi urban and Zanzibar urban, had densities exceeding 120 dogs/km2, Table AB-2), and districts where dog densities might be too low to support rabies transmission without importation from other districts (Dye and Cleaveland, 1995, Cleaveland et al., 2003, Lembo et al., 2008).

Our study had several limitations. The main limitation was that we could not externally validate our predictive model, due to a lack of reliable data on dog numbers outside the study area, with the exception of Serengeti district. In addition, our study areas did not cover many inland livestock keeping districts. Our surveys were also completed at different times, with household surveys conducted in 2011, transects immediately following dog vaccination campaigns in 2014/15, and school-based surveys within 2 months of these dog vaccinations. These differences may have affected our estimates. The one-day mark-resight were reported to conserve time and financial resources compared to two-days mark-resight. one-day mark-resight could be used as long as researchers acknowledge the assumptions violated and work to correct them (Cleaton et al., 2019). Number of assumptions are required for the mark-resight technique (Lettink and Armstrong, 2003). These assumptions apply to dog population estimations. The first assumption is that marks are not lost and that they are correctly identified. To overcome collar loss our study was one-day mark-resight (same day of vaccination), conducted immediately after collars were fitted (in the evening). However, a study in Bhutan found that there were 17% more sights in morning counts compared to the afternoon counts (Tenzin et al., 2015b). To overcome collar loss, our collars were made of soft plastic materials, which I expect to be durable leading to a low rate of collar loss during the 1-2 hours between vaccination and transect. Since the population size estimator is based on the proportion of marked dogs that are declared re-sights, I took into account the binomial sampling error. However, dogs that were recaptured at the village were reflected in the district’s 95% confidence interval. Counting less dogs during transects was not a problem in this chapter as the aim of my method was to get estimates at the district level and extrapolate from the model to districts with no transect data.

The second assumption is that the study population should be in a closed system. Our study system was not closed and there was a possibility of either recounting dogs from the same village or counting dogs that emigrated from other villages.

The consequences of counting dogs from another village that has not been vaccinated or has lower coverage is underestimation of coverage and consequent overestimation of population size, whereas counting dogs from another village with higher coverage would cause underestimation of population size due to overestimation of coverage. On the other hand, recounting of dogs from the same village could cause overestimating the recapture sample size. Therefore, coverage estimates would be unbiased but over-precise. Only observable dogs were counted from transects, which results in systematic biases, such as poor observation of pups which could under-estimated the number of dogs (Downes et al., 2013). We considered this as another limitation of the design of our study. We assumed that pups are never seen on transects and that no pups were vaccinated. Although registers had information on the age of vaccinated dogs, we only collected the number of vaccinated dogs per vaccination unit (i.e. village) without categorising the age of these dogs, while for transect we only counted observable dogs without categorising their age. This limitation will be overcome through a mobile phone-based system for collection of both vaccination and transect data. Using mobile phones to track vaccinations and post-vaccination evaluation has the potential to improve the accuracy and speed of data collection, reporting and analysis (Gibson et al., 2015). Because of this limitation of excluding puppies in our design, we adjusted our estimates for this bias by using pup/adult ratios in all of our study locations. The pup/adult ratio was calculated from a dog census completed in Serengeti district data between 2008 and 2015. Although this dog census was conducted over multiple years, we do not expect that the dog population age structure has changed very much during this period.

Again, capture heterogeneity could also be caused by counting only free-roaming dogs (excluding confined dogs). Although most of Tanzanian dogs are free-roaming dogs there is a very small fraction of dogs that are always confined inside the houses (Gsell et al., 2012, Sambo et al., 2014). Therefore, in this setting of Tanzania, the transect appears to be the best method. However, in a setting of highly confined dogs like in developed countries, the transect method will not be reliable. However, in places where dog rabies remains endemic, most dogs are free-roaming and unrestrained (Davlin and VonVille, 2012, Sambo et al., 2014) and therefore transect will still be the best method. Additionally, larger villages also require more time to complete and those with more sub-villages were less well-sampled resulting in precludes some individual dogs and therefore less precise of estimates.

Notwithstanding these limitations, we found that transects were fast and relatively low cost to complete at scale, sampling populations more representatively than other approaches that were limited in spatial scope. We recommend that marking of vaccinated dogs (visible markers/collars) should be included as part of mass dog vaccination campaigns, and that transects should be completed immediately after vaccination campaigns, aiming to cover the centre and the periphery of villages, as coverage has been reported to decrease with the distance to the vaccination point (Matter et al., 2000, Kaare et al., 2009, Minyoo et al., 2015, Mazeri et al., 2018). Estimates should also be adjusted to account for not observing pups.

3.6 Conclusions

Our study underlines the importance of knowledge of dog population sizes and distribution in different settings in rabies endemic countries, with methods of estimating the number of dogs needed to plan, monitor, and evaluate the performance of rabies control efforts. We demonstrated that post-vaccination transects, together with dog vaccination data, can be used to rapidly generate and refine dog population estimates in areas with ongoing vaccination campaigns. Using the transect population estimates, we developed models that use demographic and geographical characteristics to generate tentative predictions of dog populations in districts without dog vaccination interventions. We also show that data derived from smaller scale sampling of the dog population could lead to substantial under- or overestimation of the population in areas with considerable village-to-village variation, leading to poor rabies control. We conclude that post-vaccination transects may be a useful tool for rabies elimination, taking advantage of data on vaccinated dogs that are routinely collected through implementation of mass dog vaccinations.

Chapter 4 Scaling-up, monitoring and improving the efficiency of large-scale dog vaccination campaigns against rabies in Tanzania.

4.1 Introduction

Each year, rabies causes approximately 59,000 human deaths worldwide, mostly in Asia and Africa. Ninety-nine percent of these deaths result from the bites of rabid domestic dogs (Knobel et al., 2005). Rabies deaths are 100% vaccine-preventable through two complementary interventions: first, administration of post-exposure prophylaxis (PEP) to people bitten by suspected rabid animals to prevent disease onset; second, sustained mass dog vaccinations (MDV) to eliminate transmission within the main source (reservoir) of infection, domestic dog populations (Cleaveland et al., 2018). Currently, more than 10 million patients are administered with PEP annually (Hampson et al., 2015). While human rabies can be effectively prevented with PEP, the intervention is expensive, with direct expenditure on PEP estimated at 1.70 billion USD per year and indirect costs estimated at 1.31 billion USD (Hampson et al., 2015). The burden of rabies falls disproportionately upon people in remote, rural communities where most rabies cases occur. A case study in Tanzania estimated that a patient in rural area, where most people live on less than USD 1.25 per day, would need to spend over USD 100 to access and complete World Health Organisation (WHO) recommended PEP regimens (Sambo et al., 2013). Many families struggle to obtain PEP, either because they cannot afford it, or because PEP is not stocked or out of stock at local clinics. These barriers lead to poor compliance with PEP regimens, delays in presentation to health facilities, and increased risk of death (Hampson et al., 2008). Human rabies prevention should not rely only on PEP but should focus on investment to control rabies at its source. Dog vaccination is the most effective control strategy to restrict the spread of rabies in the reservoir population (domestic dogs) and prevent exposures. Economic analysis has shown that canine vaccination against rabies is a very cost-effective approach to prevent human rabies and even cost-saving relative to PEP alone (Fitzpatrick et al., 2014).

However, throughout most of sub-Saharan Africa, canine vaccination is limited and rarely implemented with sufficient coverage to achieve these benefits (Lembo et al., 2010).

Dog rabies has been eliminated from industrialized countries in Europe and North America (King et al., 2005, Hampson et al., 2007) and the continent-wide elimination of canine rabies from the Americas is now within reach (Vigilato et al., 2013). Recent research has demonstrated that rabies can be eliminated through mass vaccination of dogs from even the poorest countries (Zinsstag et al., 2017). To draw attention to this neglected disease and efforts to control it, in 2016 the World Health Organisation (WHO), the World Organization for Animal Health (OIE), the Food and Agriculture Organization of the United Nations (FAO), and the Global Alliance for Rabies Control (GARC) established the "United Against Rabies" partnership, which is working towards the goal of "zero human rabies deaths by 2030" (Abela-Ridder et al., 2016). This alliance has brought global momentum to the drive to eliminate canine rabies.

To eliminate the rabies virus from dog populations and consequently prevent human deaths, a MDV programme must be delivered effectively in terms of completeness, coverage, and timeliness. First, MDV campaigns must ensure there is no areas left unvaccinated as "patchy coverage" can lead to persistence (Townsend et al., 2013). Research shows that unvaccinated (incomplete) areas can be a source of incursions and can jeopardize MVD programmes (Townsend et al., 2013). Vaccination campaigns should aim for a geographically uniform across all communities (completeness). Second, MDV campaigns must aim to achieve high coverage. Empirical and theoretical evidence shows that annual vaccination coverage of 70% can interrupt the transmission cycle and if sustained can eliminate rabies from dog populations (World Health Organisation, 2018b). However, in dog rabies-endemic countries of Africa, vaccinating large numbers of dogs at 70% coverage has been challenging (Jibat et al., 2015). Accessibility of free roaming dogs for vaccination is often mentioned as an operational constraint (Lembo et al., 2010). Third, follow-up MDV campaigns must be conducted within a target time interval (timeliness), because coverage declines rapidly following a campaign as vaccinated dogs die, susceptible dogs are recruited, and vaccine-induced immunity wanes. If coverage of 70% is achieved during a campaign, then the next campaign must be completed 12 months later to keep coverage above the ~25% threshold (Hampson et al., 2009).

In 2010, Tanzania started to implement the Rabies Elimination Demonstration Project (REDP), a large-scale intervention coordinated by the World Health Organization and funded by the Bill and Melinda Gates Foundation (Mpolya et al., 2017). These were the first government-led large-scale dog vaccinations to have been implemented in the country. Monitoring the implementation of control programmes should reveal whether campaigns are being delivered well or poorly (Sambo et al., 2017). Therefore, identifying the factors associated with, and potentially influencing, the success or failure of vaccination campaigns may give insights about how to improve rabies control programmes, particularly in communities where dog vaccination is not effectively implemented (Kaare et al., 2009, Mpolya et al., 2017). Together these insights should be used to guide future control efforts and improve their success. In this study, we evaluate dog vaccinations implemented in southeast Tanzania through the REDP from 2010–2017, focusing on the coverage, completeness and timeliness achieved during campaigns, and identifying factors associated with their performance.

4.2 Methods

4.2.1 Study sites

The study was conducted in five regions from south-eastern Tanzania: Lindi, Mtwara, Coast, Dar es Salaam and Morogoro. Dar es Salaam is an urban region, while the others are mixed rural and urban. These regions consist of 25 districts (Table 4-1; Figure 4-3). In Tanzania, regions are sub-divided into districts, and districts into wards. Wards in urban districts are sub-divided into streets, while those in rural districts are sub-divided into villages. Thus, a village (in a rural area) or a street (in an urban area) is the lowest government administrative unit. Villages are generally larger than streets. The study districts comprise rural, coastal and urban settlements, and cover an area of 160,000 km2, 16% of the landmass of Tanzania. According to the last official population census conducted in 2012, these districts had a population of about 8.5 million people, with an average annual growth rate of 2.16% (National Bureau of Statistics, 2012). Most of the population is engaged in subsistence farming for their own or very local consumption. These districts were selected for the REDP to exploit natural boundaries to facilitate the establishment and maintenance of a rabies-free area, including the coastline to the east, the Udzungwa Mountains to the northwest, and the Ruvuma River to the south. The Dar es Salaam–Mbeya highway to Morogoro and the railway line to Kilosa town define the northern boundary of the vaccination zone (Mpolya et al., 2017).

4.2.2 Data collection

Mass dog vaccination campaigns: Five rounds of mass dog vaccinations were carried out in the study districts (approximately annually) from 2010 (Mpolya et al., 2017). In each district, mass dog vaccination campaigns were managed and supervised by the District Veterinary Officer or the Head of the Livestock Department. In urban districts, mass dog vaccinations were carried out at the ward level while in rural districts mass dog vaccinations were carried out at the village level. To avoid confusion, in this study we refer to the area (i.e. ward or village) where dog vaccination was carried out as a vaccination unit.

Pre-vaccination campaign logistics: Before starting each round of campaigns, planning meetings were held in each district to train Livestock Field Officers (LFOs) in dog vaccination. Training was provided by personnel from the Ministry of Livestock, World Animal Protection and Ifakara Health Institute on how to: 1) restrain and vaccinate a dog, 2) maintain the vaccine cold chain, 3) mobilise dog owners to bring their dogs to vaccination points, and 4) prepare and choose vaccination points. Since 2013 meetings were also used to train enumerators in how to carry out transect surveys. During the meeting, challenges on delivery of dog vaccinations were presented and the way forward to overcome challenges were discussed.

Implementation of mass dog vaccinations: The delivery of mass dog vaccination campaigns in rural and urban areas was through a central point (CP) approach (Kaare et al., 2009), whereby owners voluntarily brought their dogs to a centrally located vaccination point/centre within their village. LFOs within the districts communicated with local authorities to inform communities in advance of the campaigns (normally one week before with a reminder the day before the campaign). Various sensitization approaches and methods such as local radios, public address system, posters, and advertisement in notice boards, and public announcements during religious gatherings were used to encourage participation in the vaccination campaign. In some areas mobilization was done through village assemblies' meetings or use of the local community messenger. In urban settings, there was at least one vaccination point assigned to each ward (an urban ward consists of four to ten streets) while in rural areas there was one vaccination point per village. Data on all vaccinated dogs were recorded in registers, including information on the dogs (i.e. name, age, sex, colour, previous vaccinations) and information of the dog owners (i.e. name and the address (village) of the dog owner), location of vaccination centres, operating time, type of vaccine, and batch number of doses used. Dog owners were given signed vaccination certificates to validate the vaccination status of their dogs, and vaccinated dogs were fitted with temporary collars to enable assessment of coverage. All vaccinated dogs were recorded into registers.

Post-vaccination monitoring: Transect surveys were conducted in 1322 (64%) of vaccination units. Transects were conducted immediately after the vaccination campaigns, for all campaigns conducted since 2013 (Sambo et al., 2017). Transects were walked (or occasionally cycled) on the same day as vaccination campaigns from 4 to 6 p.m. when dogs were active and visible, counting all marked (vaccinated) and unmarked (unvaccinated) dogs. Transects were conducted in two randomly selected sub-villages in each surveyed village (villages ranged in size from two to ten sub-villages, with a median of three), aiming to representatively sample coverage within each village. In the first sub-village, enumerators started transects at the sub-village center and headed to the outskirts, while in the other, enumerators walked from the edge toward the center. Each transect was conducted by one enumerator for one hour per sub-village.

Vaccination costs: The cost of the dog vaccines and consumables such as syringes and needles were excluded in this analysis as information on their costs were not available. This is because consumables and dog vaccines were procured internationally by the international project coordinator at the World Health Organisation (WHO) headquarters who then arranged shipment to the WHO country office in Tanzania (Mpolya et al., 2017). However, district officials received funds from the WHO country office in Tanzania. District officials were expected to use money for: 1) conducting vaccination campaigns (allowance and transport), 2) planning and training vaccinators, and 3) campaign advertisement (community sensitization on the vaccination campaigns). These costs were compiled from the National Rabies Coordinator and were used in our analysis.

Dry and wet season: In our analysis, we considered Tanzania to have two seasons, the dry and the wet season. We used the study by (Koutsouris et al., 2016) to assign months to dry and wet seasons. March to September, including transition months (i.e. from the dry to the wet season, July to September), were considered to fall in the dry season, whereas October to February, including transition months (wet to the dry season, December to February), were considered to fall in the wet season.

Other data: Demographic and geographical data for the study districts were extracted from the 2012 national Population and Housing Census (National Bureau of Statistics, 2012). For each vaccination unit, we extracted data on the area and human population size. We also extracted district-level population sizes, annual population growth rates, average household sizes (persons/household) and numbers of livestock keeping households. Human population numbers from 2010 to 2017 were projected backwards and forwards from the 2012 census using annual growth rates for each district (Table 4-1). From census data, vaccination units were categorised as rural or urban, and the straight-line distance from the vaccination unit to the vaccination campaign headquarters (HQ), which was the district veterinary office or livestock office, was calculated.

Table 4-1: Descriptive characteristics of the study districts where mass dog vaccination and post-vaccination transects were conducted since 2010.

District	No of VUs	Mean distance (km) from HQ to VUs (SD)*	Estimated dogs	Human populat-ion (1000s)	Proportion of households owning livestock	Growth rate (%)	Total number of households	District area (km^2)	Average MDV budget (TZS 1,000,000s)	Number of vaccinators . (LFOs)
Ilala	26	10.5 (9.3)	8179	1,221	26,671	7	297,750	364.7	12.7	58
Kibaha Rural	50	35.9 (18.6)	9327	70	4,771	3	16,892	1500.8	10.2	25
Kibaha Urban	53	13.7 (8.5)	6596	128	7,650	5	31,092	705.3	10.3	47
Kilombero	80	62.5 (49.8)	27599	408	34,427	2	93,331	7994.8	12.3	59
Kilwa	100	56.5 (26.5)	4961	191	20,507	1	42,596	14545.4	8	29
Kinondoni	34	9.6 (8.7)	8618	1,775	35,829	5	441,240	537.1	12.3	71
Kisarawe	77	45.2 (23.1)	5010	102	12,275	1	25,475	4514.3	10,4	38
Lindi Rural	133	43.9 (14.7)	2788	194	21,931	-1	52,821	5971.5	8.6	69
Lindi Urban	18	7.08 (7.8)	1876	79	6,500	7	22,344	1063	6.8	19
Liwale	76	30.9 (26.9)	2386	91	10,582	2	21,084	15634	7.2	25
Mkuranga	116	27 (13.3)	3891	223	17,610	2	51,101	2825.4	9.8	55
Morogoro Rural	140	41.7 (19.6)	12292	286	31,160	1	67,671	8267.7	11.8	100
Morogoro Urban	19	3.7 (3.2)	17476	316	12,060	3	76,039	288.3	11.8	50
Mtwara Rural	156	38.2 (18)	2635	228	21,651	1	58,602	3629.5	8.2	58
Mtwara Urban	15	5.7 (3)	1160	108	5,034	2	27,968	169.9	5.8	14
Nachingwea	118	23.8 (23)	4477	178	21,726	1	48,145	5971.8	8.5	29
Nanyumbu	89	32.8 (13.5)	2364	151	13,474	1	40,746	5200.4	6.7	18
Newala	153	23.2 (12)	3630	205	28,279	1	58,035	1951.3	7.7	37
Ruangwa	89	22.5 (12.2)	2095	131	17,605	1	37,326	2513.8	8.2	22
Rufiji	115	45.9 (19.3)	3128	217	14,973	1	48,164	9383.8	10.5	29
Tandahimba	155	20.4 (11.3)	1269	228	26,595	1	60,872	2047.3	7.3	33
Temeke	30	8.1 (8.8)	5819	1,369	22,150	6	344,391	728.2	12.5	38
Ulanga	65	44.8 (27.9)	19256	265	22,460	3	53,290	14476.8	12	41
Masasi	147	36.2 (14.6)	5027	248	30,565	1	67,872	4003.2	5.7	25
Masasi Urban	12	7.3 (5.6)	4504	103	28,279	2	28,222	752.8	5.7	21

SD=standard deviation, HQ=District headquarters, VU=Vaccination units, TZS=Tanzanian shillings.

4.2.3 Statistical analysis

The aim of this analysis was to determine if the vaccination campaigns achieved their intended goals. The goals of REDP were to conduct vaccination campaigns in every vaccination units, achieve dog vaccination coverage of 70% and conduct annual vaccination campaigns. Additionally, we carried out an analysis to learn about factors associated with success/failure of vaccination goals.

Vaccination completeness: This was measured as the proportion of vaccination units reached by vaccination campaigns in each round of vaccination. During the initial campaigns (i.e. round one and two of vaccinations), data collection protocols were not well understood by district officials, and numbers of vaccinated dogs were aggregated at district level instead of at vaccination unit level for some districts. We did not get the names of vaccination units for the data that were aggregated at district level, and thus dropped these districts from our completeness analysis.

Vaccination coverage: To estimate vaccination coverage in vaccination units, it was necessary to first estimate dog population at the vaccination unit level for the years 2010-2017, as follows. Provided that the number of vaccinated dogs observed during a transect through a vaccination unit was non-zero, the dog population at the time of the transect could be calculated as per (Sambo et al., 2018):

$$D=V_C/(V_T/(V_T+S_T))*(1+PAR)$$

where V_C is the total number of dogs from the vaccination records, V_T is the number of vaccinated dogs (dog with collars/marked dogs), S_T is the number of unvaccinated dogs (dog without collars /unmarked dogs), and PAR is the ratio of pups to adult dogs (estimated from a census of the dog population conducted in Serengeti district between 2008-2016. The value of PAR that was used in this analysis was 0.256. Multiplication by (1+PAR) corrects the estimated dog population based on the assumption that vaccination campaigns fail to reach the majority of pups, and that without this correction, dog populations estimated based on campaign data would be underestimated (Sambo et al., 2018).

Post-vaccination transects where only small numbers of dogs were observed are unlikely to provide accurate population estimates, so we did not use data from transect surveys where fewer than five dogs were observed. Transect-based dog population estimates were available for at least one vaccination round for 63.4% of vaccination units (up to three rounds of estimates were available in some cases).

Missing population estimates, in rounds where there was no transect data, were obtained using three approaches. (1) If the missing round lay between two known estimates, an exponential dog population growth rate was estimated from the two known estimates, and used to project the population in the intermediate year. 2) If the missing year did not lie between two known estimates, but there was either a preceding or subsequent estimate, a human:dog ratio was calculated based on this estimate and the associated human population size projected from the 2012 human census. A dog population in the missing year was then obtained by dividing the human population in that year by the human:dog ratio. (3) For the 36.6% of vaccination units where no transect-based dog population estimates were available, estimates for all years were obtained by taking the projected human populations for those years and dividing by district-level human:dog ratios (Sambo et al., 2018).

The total number of dogs vaccinated was divided by the dog population estimate (calculated as above) for each vaccination unit in each round to get estimates of vaccination coverage. In vaccination units and rounds where dog population estimates were not available from transect surveys, some of these coverage estimates exceeded the proportion of the dog population expected to be adult based on the Serengeti dog census (79.6%), and the values were corrected to this assumed maximum value. The annual dog death rate was estimated using data from Northern Tanzania (Czupryna et al., 2016). These longitudinal data allowed us to calculate the probability of a given dog dying in each year, (0.45), and thus estimate a dog birth/death rate of 0.595 $year^{-1}$.

Vaccination timeliness: Campaign timeliness was measured as the vaccination intervals between vaccination campaigns. Campaign timeliness is an important determinant for the success of the campaign. Between campaigns, 70% initial coverage (P_{target}) is required to keep coverage above critical immunity threshold (P_{cri}t (estimated at 20%)) by the time of the next campaign after one year (Hampson et al. 2009). We therefore evaluated the performance of the REDP on timeliness. However, where initial coverage is less than 70%, the interval to the next campaign should be less than one year to keep coverage above P_{crit}; therefore, we estimated the required time interval to the next campaign based on coverage and dog population data. To evaluate the performance of the campaign on timeliness, we estimated monthly vaccination coverage through time (January 2010 to January 2017 (total=85 months)) in each district. Vaccination coverages for each month between campaigns were projected using the following equation (Townsend et al. 2013):

$$V_t = V_0\, e^{(-(1/v+b)t)}$$

where V_t represents vaccination coverage at time t, V_0 represents the number of vaccinated dogs at the time of the preceding vaccination campaign, *v*=mean duration of vaccine-induced immunity (assumed to be 3 years (Ferguson et al., 2015)), and *b* = birth/death rate (year^{-1}), assuming constant population size which we set *b* = 0.595 year^{-1}.

To estimate the required time interval between campaigns, we used coverage data that were estimated directly from the transect surveys. Coverage values obtained from transects could be overestimated as puppies are rarely observed on transect surveys (Sambo et al., 2017). We therefore decided to use P_{crit} of 30% (which adjust for over-estimation of coverage). We then compared P_{crit} of 20% and P_{crit} of 30% against the P_{target} coverage of 70%. Therefore, from the above equation, we derived *t* from the above principle (Ferguson et al., 2015), to calculate for the timing (campaign interval) of vaccination campaigns, Δt, in months. Then P_{crit} denote the V_0 and P_{target} stand for V_1.

$$\Delta t = -\log_e(P_{crit} / P_{target}) / ((1/v+b)/12)$$

Factors associated with rabies vaccination completeness and coverage: We investigated eleven factors hypothesized to influence dog vaccination completeness and coverage (Table 4-2) by fitting them as predictors in binomial generalized linear mixed models (GLMM). We estimated the strength of their associations with completeness and coverage as odds ratios (ORs) with 95% confidence intervals. We developed separate models for completeness and coverage. For completeness, the response variable was the binary outcome of whether a dog vaccination campaign was conducted (coded as 1) or not conducted (coded as 0) in each of the vaccination units in each round. For coverage, the response variable was the binomial outcome of the number of dogs vaccinated (marked with collars) out of the total number of dogs observed in each vaccination units in each round during the transect surveys (round 3 to round 5 of vaccination). Because many of the continuous predictors were right skewed, and because we generally expect multiplicative relationships between these predictors and completeness and coverage, we log-transformed all the continuous predictors by log2, choosing base 2 to aid the interpretability of the odds ratios.

Table 4-2: Summary statistics of explanatory variables hypothesised to be associated with completeness and coverage, separately for vaccination units with and without completed vaccination campaigns, and with low and high coverage.

	Completeness (N=8959)		Coverage (N=6198)	
Predictors	No vaccination (N=1548)	Vaccination (N=7411)	Low coverage <70% (N=3677)	High coverage ≥ 70% (N=2521)
Cost (in TZS) per head per vaccination unit, Mean (SD)	45.5 (20.9)	49.2 (24.5)	42.4 (20.5)	54.9 (28.8)
No. of vaccinators per 1000 people, Mean (SD)	24.4 (30)	16.8 (19.8)	19.3 (23.5)	15.4 (17.6)
Distance (km) between district HQ and vaccination unit's centroid, Mean (SD)	30.6 (22.6)	34.6 (25)	33.5 (24.3)	33.1 (23)
No. of the estimated dogs per VU, Mean (SD)	50.2 (91)	92.4 (187)	87.4 (193)	92 (188.3)
Geographical area of vaccination unit in km^2, Mean (SD)	48.8 (294.2)	88.9 (413)	77.4 (404)	73.1 (308.1)
Number of vaccination units, Mean (SD)	114 (37.2)	107.4 (38.8)	115.4 (40.2)	101.4 (37.6)
Mean household size (SD)	4 (0.4)	4 (0.4)	4 (0.4)	4 (0.4)
Number of people per vaccination unit, Mean (SD)	3387.5 (9599.6)	3638.4 (9852)	4498.8 (12243.4)	3390.4 (9095.5)
Type: Urban (vs Rural), N (%)	112 (7)	466 (6)	299 (8)	163 (6)
Prop. of households owning livestock, Mean (SD)	39.6 (11)	40.3 (10.6)	39.7 (11.3)	40.2 (10.2)
Season: Wet (vs Dry), N (%)	741 (48%)	4190 (57%)	2230 (61%)	1435 (57%)

N=number; TZS=Tanzanian shillings;VU=vaccination unit;HQ=headquarters; SD=standard deviations.

We carried out univariable regression analyses assessing the association with the response of each predictor in isolation, before fitting the predictors together in a multivariable model where their associations with the response would be mutually adjusted. Before fitting models, we conducted data exploration to detect collinearity among the predictor variables using pairwise scatter plots and the variance inflation factor (VIF), as described by (Zuur et al., 2010). Predictors with VIF values greater than or equal to 5 were assumed to be collinear and were removed. This process was repeated until all VIF values were below 5. The resulting variables were fitted in a multivariable model, which was refined by a single round of model selection by dropping non-significant ($P > 0.05$) predictors. All models, including the univariable models, were adjusted for the effects of spatial (vaccination unit, district and region) and temporal (round of vaccination) factors. These factors were fitted as random effects, with the exception of round, which was fitted as a fixed effect because it has too few levels (five in the completeness model, three in the coverage model) to be fitted as a random effect (Bolker et al., 2009). Additionally, an observation-level random effect to account for overdispersion was fitted in the coverage model (Harrison, 2015).

All models were fitted using the glmer function of the lme4 package (Bates et al., 2014). All statistical analyses were conducted using R version 3.5.1 (R Core Team, 2017).

4.2.4 Ethical considerations

The study protocol was approved by the Medical Research Coordinating Committee of the National Institute for Medical Research of Tanzania (NIMR/HQ/R.8a/Vol.IX/2109), the Institutional Review Board of the Ifakara Health Institute and the Tanzania Commission for Science and Technology (COSTECH).

4.3 Results

Mass dog vaccinations: During 2010-2017, mass vaccination campaigns were carried out that vaccinated 349,000 dogs in 2066 vaccination units. The number of dogs vaccinated increased over the five rounds of campaigns (Figure 4-1). In all districts, the number of vaccinated dogs increased from year to year until round four and then remained fairly stable for round five (Figure 4-2), when the vaccination campaigns were completed within all districts during a 4-month period. A total of 2, 573 transects were conducted from the study areas. Out of this, 1197 transects counted greater than or equal 5 dogs which were included for the analysis.

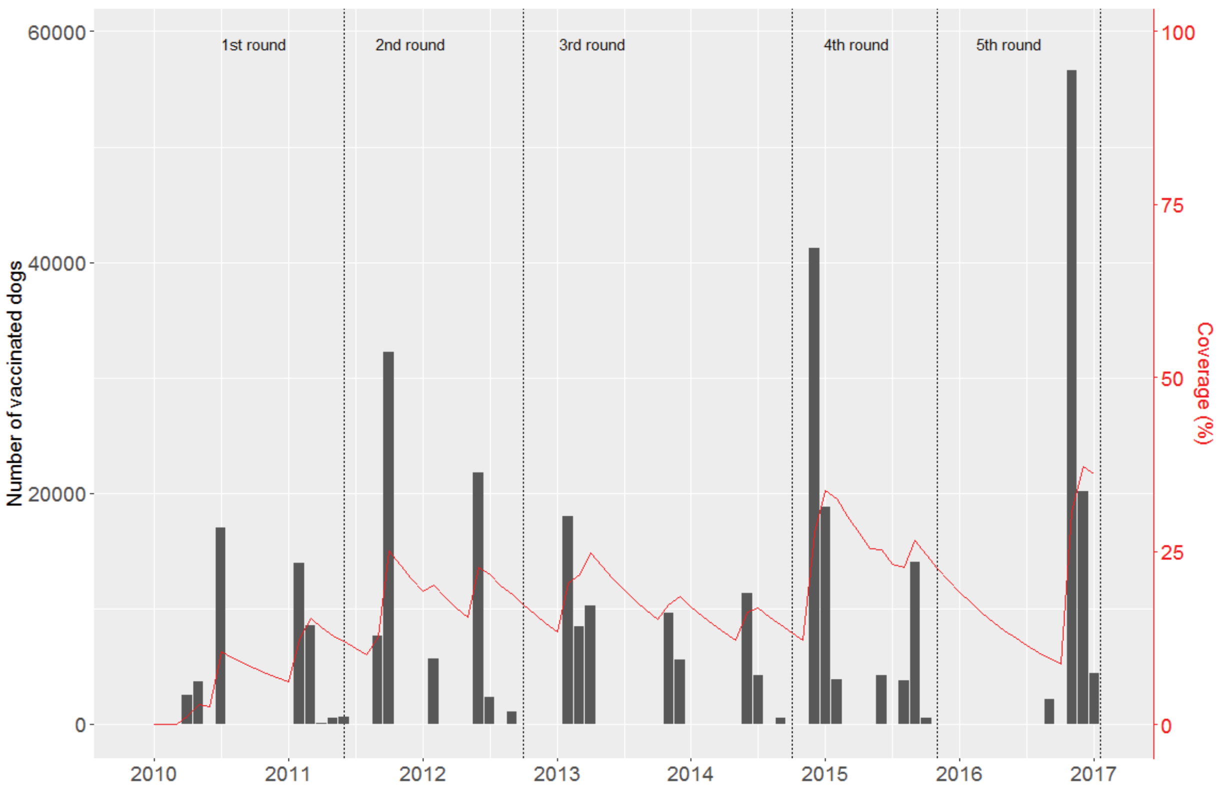


Figure 4-1: The number of dogs vaccinated during each year of project implementation. Coverage was calculated from the total number of dogs vaccinated in each month from all of the study areas (all the study districts with vaccination campaigns in that month) divided by the dog population estimates per respective month as shown by the red line.

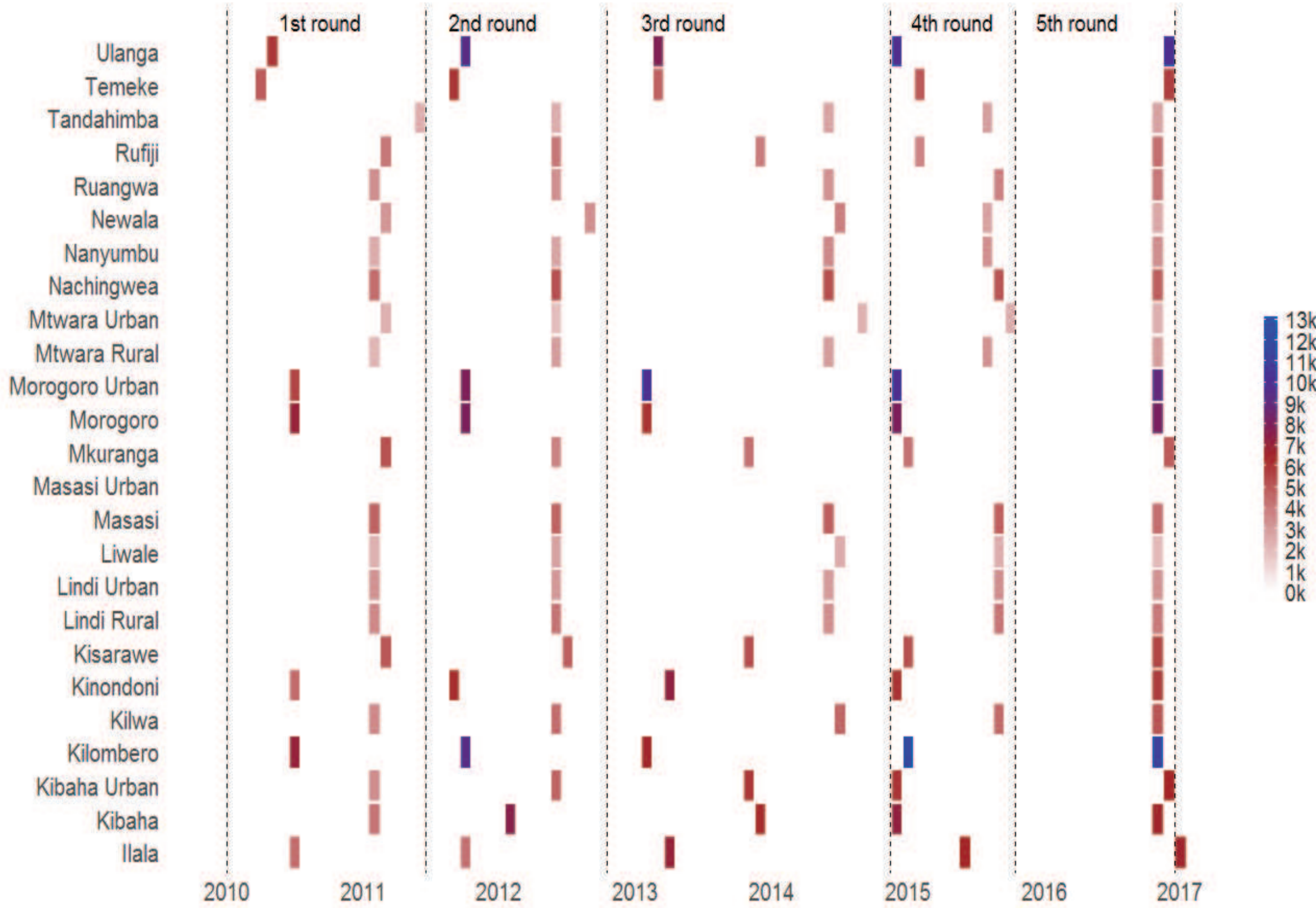


Figure 4-2: Figure 2. The number of dogs vaccinated in each district by month from 2010-2017. The number of dogs vaccinated in each district during campaigns ranged from 0 to 13 thousand dogs, indicated by the “heat intensity” of the colours from salmon red (low numbers) to blue (high numbers).

Vaccination coverage: At the local level, patterns of vaccination coverage varied markedly across the study area (Figure 4-3). Over the three rounds (3, 4 and 5) when coverage was being monitored, on 19-21% of vaccination units achieved the recommended coverage threshold of 70% (Table 4-3). At the district level, overall, vaccination coverage increased with the implementation of vaccination campaigns across districts (Table 4-3). The mean coverage across the three rounds of vaccinations ranged from 42% in Masasi Township to 71% Nachingwea district (Figure 4-4). When looking at the mean coverage across the three rounds of vaccinations, the analysis shows that only four of 25 districts were consistent in achieving the coverage target of 70%.

Table 4-3: The performance of vaccination campaigns in terms of completeness, coverage and campaign timeliness for the 25 study districts over the five rounds of vaccinations from 2010-2017.

Performance indicator	Calculation	Round 1 (Mar 2010)	Round 2 (Jun 2011)	Round 3 (Sep 2012)	Round 4 (Aug 2014)	Round 5 (Sep 2016)
Completeness*	Prop. of districts with 100% (90%) of VU vaccination,	13% (20%)	11% (26%)	17% (42%)	28% (64%)	28% (68%)
	Median completeness (range)	77% (51-100%)	78% (33-100%)	84% (57-100%)	95% (56-100%)	96% (62-100%)
Coverage✧	Proportion of districts >70% coverage	N/A	N/A	33%	27%	36%
	Median (range) coverage	N/A	N/A	60% (56-70%)	62% (55-70%)	65% (58-72%)
Coverage	Proportion VUs >70% (>60%) coverage	N/A	N/A	21% (37%)	19% (35%)	21% (38%)
	Median (range) coverage	N/A	N/A	53% (0-80%)	55% (0-80%)	56% (0-80%)
Timeliness	% districts revaccinated in ≤13 (≤18) months	N/A	8% (100%)	0% (40%)	16% (72%)	4% (56%)
	Median (range) interval in months	N/A	16 (12-18)	22 (16-27)	15 (12-26)	15 (13-24)

✧=coverage was calculated directly from the transect surveys and did not account for pups adult ratio (PAR), * =excluding districts with incomplete data, N/A=either not applicable or no data, VU=Vaccination units.

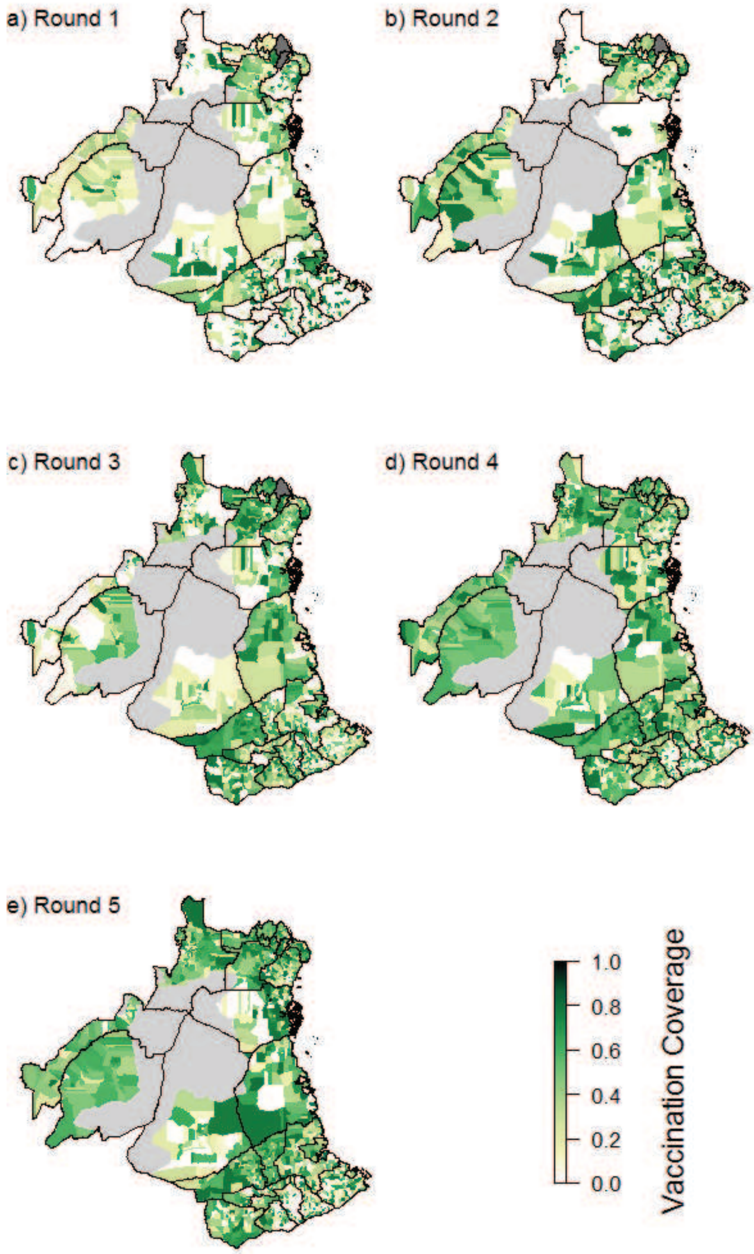


Figure 4-3: Village-level (vaccination unit level) coverage achieved in the five rounds of vaccination campaigns. Coverage for rounds 1 and 2 was calculated using projected dog population estimates, while for rounds 3-5 coverage were either estimated directly from the transects or were projected as explained from the Methods (i.e. when transects weren't available). Darker shading (dark green) corresponds to higher vaccination coverage while white shading indicates that no vaccination campaign was undertaken. Grey shading represents forest reserves or wildlife-protected areas.

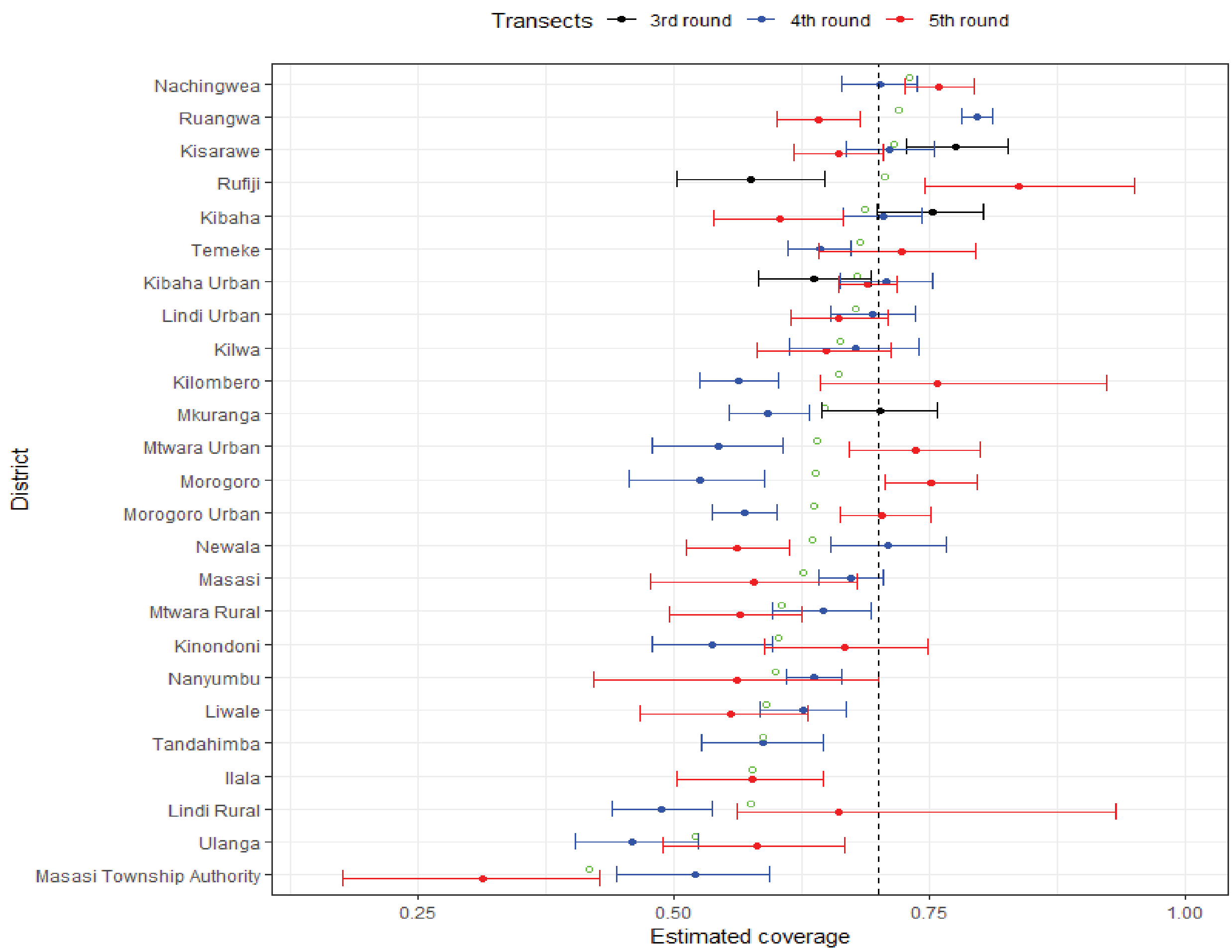


Figure 4-4: Coverage achieved during campaigns in each district from 2013 to 2017 (third to fifth round of vaccinations) calculated directly from transect surveys and did not account for pup:adult ratio (PAR). Green circles represent mean coverage across the three rounds. The black dashed line represents the target 70% vaccination coverage threshold.

Factors associated with the performance of rabies vaccination: In both coverage and completeness models, the predictor variables cost per head and vaccinators per 1000 people were highly correlated, therefore I omitted vaccinators per 1000 people. After omitting vaccinators per 1000 people, the remaining predictors met the criteria for low multicollinearity, with VIFs in the range of 1–5. Four predictors that were not significant were dropped in the multivariable completeness model: number of villages, proportion of livestock owning households, setting (rural versus urban), and household size. For the coverage model, only four predictors were significantly associated with coverage and were retained in the model: number of the people in the vaccination unit, estimated number of dogs per vaccination unit, number of people, and season.

In the multivariable regression analysis, we found that vaccination units with larger geographical area were associated with better campaign completeness OR: 1.24; 95% CI: 1.19, 1.30 (Table 4-4). Similarly, larger distance from the district livestock offices was associated with better campaign completeness OR: 1.11; 95% CI: 1.04, 1.19 (Table 4-4). Completeness in round 2 was significantly lower than in round 1, then increased significantly from round 2-3 and from 3-4, with no significant change from 4-5. Overall, completeness was substantially higher in rounds 4-5 than in rounds 1-3 (Table 4-4).

Our model investigating vaccination coverage indicated that there were significant differences in coverage between villages located near and far from district headquarters (HQ), with villages located far from HQ having better coverage than those located near HQ (Table 4-4). However, the strength of the association was weak, with a doubling in distance being associated with only a 5% increase in the odds of a dog being vaccinated (OR: 1.05; 95% CI: 1.02, 1.08). The model indicated that vaccination units with more dogs had lower coverage than vaccination units with fewer dogs (OR: 0.86; 95% CI: 0.83, 0.89). The number of people (human population size) was positively, but weakly, associated with coverage (OR: 1.04; 95% CI: 1.00, 1.09). Additionally, campaigns conducted during the wet season had better coverage than those conducted during the dry season (OR: 1.17; 95% CI: 1.03, 1.33).

Table 4-4: Factors associated with the success of rabies vaccination coverage and completeness based on univariable and multivariable mixed effects models.

	Completeness OR (95% CI)		Coverage OR (95% CI)	
Predictor	Univariable	Multivariable	Univariable	Multivariable
Area (km^2)	1.32 (1.27, 1.38)	1.24 (1.19, 1.30)	1.01 (0.99, 1.03)	-
Distance from HQ to the vaccination units (km)	1.26 (1.18, 1.34)	1.11 (1.04, 1.19)	1.05 (1.02, 1.08)	1.05 (1.02, 1.08)
Estimated dogs per vaccination unit	1.37 (1.29, 1.47)	1.12 (1.04, 1.20)	0.87 (0.85, 0.90)	0.86 (0.83, 0.89)
Cost per human head (Tanzanian shillings)	1.60 (1.19, 2.14)	2.29 (1.69, 3.09)	1.12 (0.98, 1.29)	-
Number of vaccination units per district	0.36 (0.21, 0.61)	-	0.94 (0.71, 1.24)	-
Household size	4.02 (0.33, 48.63)	-	1.13 (0.37, 3.47)	-
Number of people in vaccination unit	1.53 (1.40, 1.66)	1.41 (1.29, 1.54)	0.96 (0.92, 0.99)	1.04 (1.00, 1.09)
Proportion of households owning livestock	1.49 (1.04, 2.13)	-	-	-
Category (urban versus rural)	0.64 (0.30, 1.37)	-	0.66 (0.49, 0.89)	-
Season (wet versus dry)	1.44 (1.17, 1.78)	1.40 (1.14, 1.72)	1.15 (1.01, 1.32)	1.17 (1.03, 1.33)
Second round	0.38 (0.31, 0.46)	0.43 (0.35, 0.54)	-	-
Third round	1.69 (1.37, 2.08)	1.78 (1.44, 2.20)	-	-
Fourth round	3.10 (2.48, 3.89)	3.50 (2.76, 4.43)	1.19 (1.09, 1.30)	1.20 (1.09, 1.31)
Fifth round	3.41 (2.71, 4.28)	2.94 (2.29, 3.77)	1.20 (1.09, 1.33)	1.10 (0.97, 1.25)

HQ= district headquarters; Rounds of vaccinations 2-5 (for completeness model and 3-5) were more of a design variable that I was interested to see the variation of completeness and coverage over time (round) therefore rounds were not subjected to model selection.

Campaign timeliness: Vaccination campaigns were not all completed annually. Vaccination intervals varied greatly between rounds, which led to further declines in vaccination coverage before the next campaigns were implemented (Figure 4-5). For example, the median campaign intervals between the first and second round of vaccination was 16 months and ranged from 12-18 months (Table 4-3).

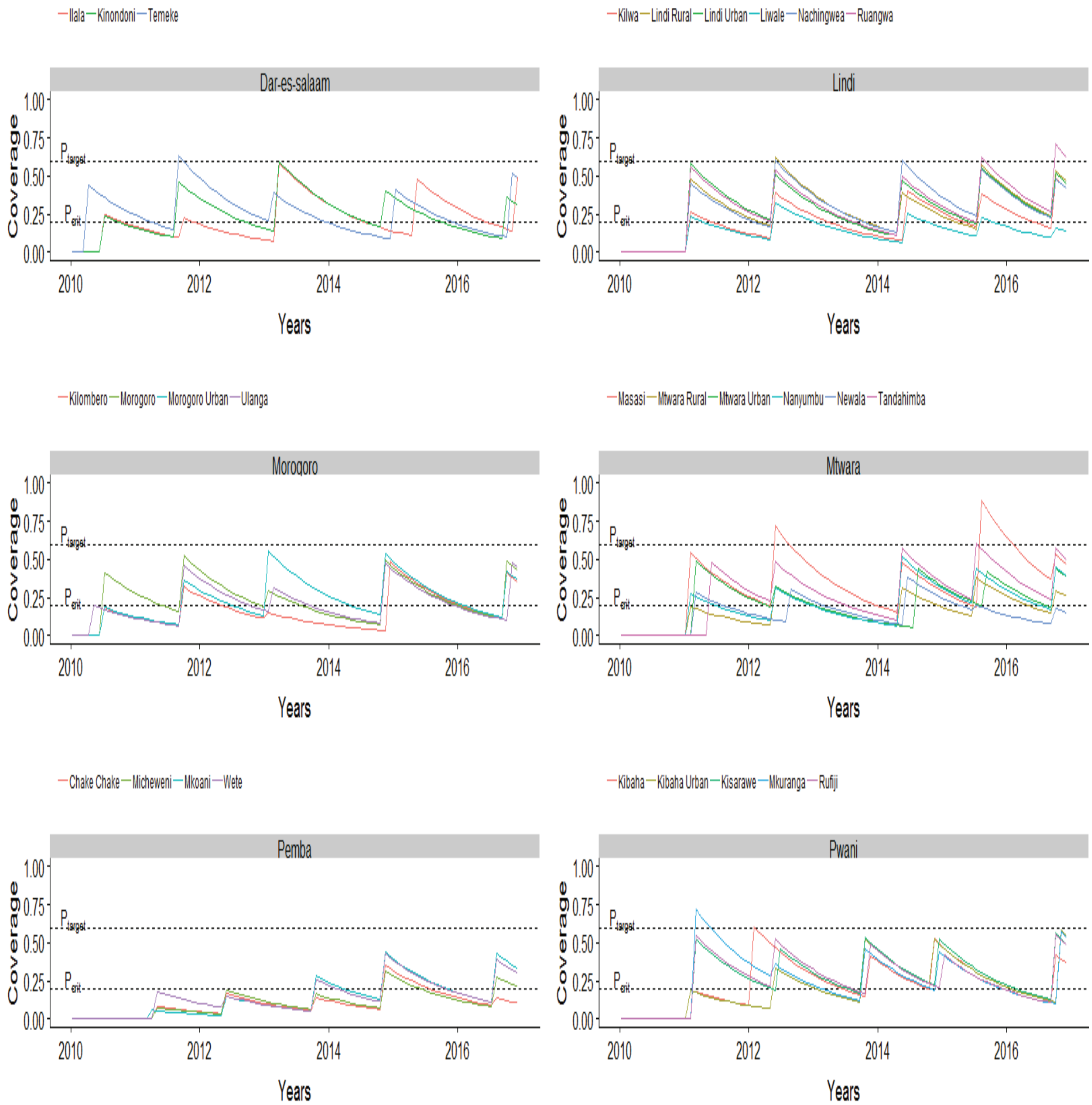


Figure 4-5: Projected dog vaccination coverage in each of the 25 districts from 2010 to 2017. High coverage (P_{target}) was not achieved in all districts; and between campaigns coverage declined due to dog population turnover. When annual campaigns achieved high coverage, coverages were sustained above the critical immunity threshold (below-dashed line labelled P_{crit}) for approximately 12 months. Although some districts achieved the target coverage of 70%, the time lag between campaigns (up to >20 months), caused coverage to decline below P_{crit}. Coverage was calculated from the number of vaccinated dogs divided by number estimated dogs per each district per each month.

Timing (interval between vaccination campaigns): To eliminate dog rabies, a certain proportion of the susceptible population (P_{crit}; critical proportion) has to be vaccinated. The threshold level can be calculated based on the basic reproductive number (R0; the average number of secondary infected cases initiated by one infected individual in a fully susceptible population). It is recommended to keep the vaccinated proportion of the dog population above the critical threshold, otherwise natural turnover in the dog population leads to drops in coverage that allow sustained rabies transmission. My analysis to determine interval between vaccination campaigns found that, in dog populations with high birth rates and death rates such as in Tanzania, timely annual vaccination campaigns are required in order to prevent the herd immunity declining below the critical immunity threshold. By vaccinating annually, vaccination of at least 66% of dogs is required to keep waning coverage above the 30% critical immunity threshold (Figure 4-6).

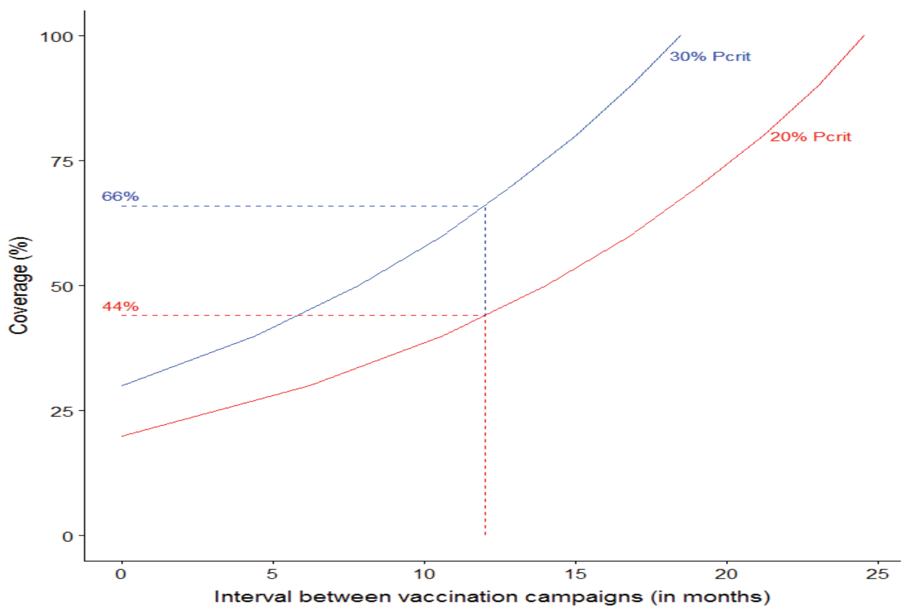


Figure 4-6: Guidance in choosing the most suitable timing (interval between campaigns) of vaccination campaign. For effective control and elimination of canine rabies, sufficiently high herd immunity level must be achieved and maintained. For example, in Tanzania, to keep the herd immunity above a Pcrit of 30% (adjusted Pcrit), our data show that the annual campaign must reach ≥ 66% coverage.

4.4 Discussion

My finding showed that campaigns did not achieve the vaccination targets. Only few districts achieved 100% vaccination completeness. Whereas, 19-21% of vaccination units achieved the WHO's recommended coverage threshold of 70%

between round 3 and 5. This suggests that 70% coverage is achievable and static central point vaccination is a feasible strategy for delivery of dog vaccinations in Tanzania. During the initial vaccinations (round 1 and 2), campaign completeness was poor as a result lower number of dogs were vaccinated.

Initially, organisational and operational challenges delayed the implementation of the MDVs (Mpolya et al., 2017). For example, the Coordinator and District Livestock/Veterinary Officers in Tanzania had no previous experience in planning and delivering large-scale dog vaccination campaigns, resulting in delayed implementation and phased campaigns in some districts (Mpolya et al., 2017). Financial resources were distributed equally to all 25 districts irrespective of geography, infrastructure and dog populations (Bardosh, 2018). As a result, some districts were well resources and others particularly large districts were under-resourced. This caused field staff to operate within resource constraints, for example when there was insufficient fuel to reach all villages (Bardosh et al., 2014, Bardosh, 2018). When they started the implementation of dog vaccinations, the first challenge was the placement of vaccination points. For example, 16% of respondents from a population-based survey of 750 dog-owning households conducted in two study districts reported that vaccination points were too far from their homestead (Bardosh et al., 2014). The second challenge was lack of training. some vaccinators lacked proper training on dog management during vaccinations, such as how to handle or restrain aggressive dogs (Bardosh et al., 2014). This is not only a challenge for vaccinators but also for dog owners. A study in northern Tanzania found that over a third of respondents (39%) claimed that they could not handle their dogs (Minyoo et al., 2015). To overcome this challenge, we learned from our experience delivering dog vaccinations in the study areas that campaign advertisements should advise dog owners to bring dogs on leads and cats in sacks.

The third challenge was the organization of the vaccination sessions. For example, dog owners complained that vaccinators did not stay in the village for enough time. They complained that the sessions often ended either before or just after school finished, therefore children (pupils) failed to bring their dogs (Bardosh et al., 2014). It has been recommended that timing of campaigns should therefore take account of agricultural cycles and school holidays (Cleaveland et al., 2018).

Once these challenges had been overcome, there was a large increase in the number of vaccinated dogs, particularly after the introduction of post-vaccination transects in 2013 to monitor the performance of campaigns. Since 2013, prior to the commencement of MDV activities, district-level meetings were held to share experiences on the delivery of vaccinations. From these meetings, lessons learned were incorporated into subsequent campaigns.

Our first aim of this study was to measure the coverage in the study areas. As we found in previous chapters, coverage estimates can vary greatly by the source of the data and analysis formulation. Therefore, when measuring coverage important aspects are: source of data, place (area, geography), time period, and jurisdiction (administrative unit). For example, in Figure 4-1 we measured coverage by using the number of vaccinated dogs per month divided by the estimated number of dogs in that month (data were from all of the study areas). This coverage was slightly different from figure 4-5, which was estimated using number of vaccinated dogs per month divided by estimated dogs in that month per each district. In Table 4-3, coverage was calculated directly from the transect surveys and did not account for pups:adult ratio (PAR), and in this table, the jurisdiction was vaccination unit and district level.

Our second aim of this study was to learn the demographic, resource and geographical factors that affect campaign completeness and vaccination coverage. I found that campaigns conducted during the wet season had better completeness and coverage. This finding was contrary to my hypothesis that vaccinations conducted during the dry season when most of the roads are passable and peasants are not occupied by farming activities have better completeness and coverage. This may be due to the seasonal migration of pastoralists in some districts, affecting the availability of dogs for vaccination during dry season. Pastoralists migrate away from village centres for pasture and water, which probably hindered them from bringing their dogs for vaccinations in village centres. Secondly, our categorization of seasonality may have influenced this finding. Pastoralists recommend June as the ideal month for vaccination while farmers recommend August or September (Bardosh et al., 2014). For, effective rabies control, timing of campaigns that will take place outside of harvesting or planting season (for peasants) and not nomad season (for pastoralists) might help to further increase coverage. Otherwise, alternative approaches such as door to door or outreach vaccination campaigns are necessary to achieve the target coverage. Additionally, our finding shown that vaccination units with more dogs had lower coverage (versus vaccination units with fewer dogs). This could be linked to pastoralists or agro-pastoralists who tend to own more dogs that peasants (Sambo et al., 2018). This data shown that most of these people (pastoralists and agro-pastoralists) were not well reached by the campaigns. It has been reported that remote livestock keepers (pastoralist) were not well covered by vaccination campaigns in a previous study (Bardosh, 2018).

Campaign completeness has been shown to be an important factor in the success of large-scale vaccination campaigns (Townsend et al. 2013, Ferguson et al., 2015). Despite the improvements in numbers of vaccinated dogs from year to year, we found that campaigns were not conducted in each of the vaccination units. Even during the fifth round of vaccination, some vaccination units were not vaccinated and only 28% of districts had 100% completeness (Table 4-3). In most cases, completeness is tied to district-level planning and incompleteness with issues around leadership or external financial constraints.

Our data showed that spending more (increased budget) resulted into better campaign completeness. However, our vaccination costs excluded dog vaccines and consumables as these data were not available. We consider, this a weakness for our predictor. A study evaluated the costs of implementing dog rabies control found that the cost of the dog vaccine in Tanzania constituted 6% of the total cost of vaccinating a dog while consumables and equipment constituted 29% (Elser et al., 2018). These costs were not included in our analysis. Most LMIC countries including Tanzania will not be able to fund sustainable mass dog vaccinations due to budget constraints. For elimination of rabies external funding will be crucial. External funding will allow countries to secure sustainable dog vaccines. We also found that vaccination units with more dogs had better completeness than those with fewer dogs, possibly because district officials considered these high priority areas for vaccination campaigns. This also could be the reason why completeness increased positively with area. To our knowledge, vaccination units from rural areas tend to have larger geographical areas and contain a higher proportion of dogs than those from urban areas. Therefore, district officials considered these villages as high priority areas for vaccination campaigns as a result they have high campaign completeness than vaccination units with small geographical areas. Additionally, larger human populations were associated with better completeness and previous studies have linked dog ownership with human population size (Knobel et al., 2008, Davlin and VonVille, 2012). We also do not know why campaign completeness was associated with areas further from the district headquarters, which was not our expectation. We also found that completeness was improved with rounds of vaccination with the fifth round has better completeness than initial rounds of vaccination. This could be linked with increased training, experience, and lessons learned in delivering dog vaccinations improved completeness.

Although, we found that long distance from district headquarters associated with better coverage, their effect size is not big OR= 1.05 (CI 1.02, 1.08). The recent research from Malawi reported that distance to the closest city appeared to produce a negligible effect on coverage (Sánchez-Soriano et al., 2020). We also found that coverage decreased with levels of dog population sizes. This is supported by the fact that it is easy to achieve higher coverage in areas with fewer dogs than in areas with higher number of dogs. Additionally, we found that livestock keeping household (pastoralists) was associated with decreased odds ratios of vaccinating a dog (although it was not significant).

It has been reported that dogs owned by pastoralists are less used to handling and restraint by their owners and families often absent during dry season due to transhumance movements. As a result, our central point strategy achieved only a low coverage (Bardosh et al., 2014, Kaare et al., 2009). However other strategies such as door-to-door and strategy and community-based animal health workers reported achieving the necessary coverage (Kaare et al., 2009). However, these approaches were reported to be time consuming and expensive compared to central point strategy (Kaare et al., 2009).

Since most of the delivery of vaccination in the project was through central points approach whereby owners voluntarily brought their dogs to a centrally located vaccination point. The vaccination coverage was tied to the ability/willingness of dog owners to bring their dogs to vaccination points. Dog vaccines could available, vaccinator could be available but if the dog owners did not bring dogs coverage will be poor. This could probably be the reason why very few variables were retained in the multivariable analysis.

Timeliness is another essential component for control and elimination of dog rabies. Rapid dog population turnover causes population-level protection to fall in the interval between vaccination campaigns. In this study, the longest interval between campaigns was 27 months. Bureaucratic leadership caused delays in timely procurement of dog vaccines and therefore campaigns (Mpolya et al. 2017). In contrast, delays during the initial rounds (between round 1 and 2) were negligible as dog vaccines were available due to overestimation of dogs (Mpolya et al. 2017). Between round 1 and round 2 of vaccination, the vaccination interval in all of the study district was within 18 months. The delays of vaccinations for round 2 was not caused by shortages of dog vaccines but by delays in reimbursement of financial resources (Mpolya et al. 2017). Additionally, in the 2016 round of vaccinations (the fifth and last round), the campaigns were conducted in a much more timely manner compared to previous campaigns, and largely synchronized across all districts as vaccines (procured for fourth and fifth round) and financial resources were available. In most cases, timeliness is tied to the national level, i.e. the ability of the Ministry of Livestock to plan, procure and distribute dog vaccines and disburse funds to districts on time. To overcome this challenge of the long interval between campaigns (vaccination delays), countries must develop strong procurement systems. For example, bulk procurement of high-quality vaccines, through for example OIE rabies vaccine banks, are a means to ensure consistent availability of affordable, safe and effective vaccines.

In Africa and Asia, dog rabies control programs typically operate under financial constraints. Biannual campaigns would be even more challenging than annual campaigns. In these settings, biannual vaccinations would not only be financial and logistical challenges but also vaccinations might be ended by vaccinating the previously vaccinated dogs but not the new susceptible. Therefore, vaccination units with poor coverage should be identified through post-vaccination transects and prioritised for rapid remedial vaccinations.

Our study investigated demographic, resource (human and financial resources) and geographical factors that affect campaign completeness and vaccination coverage. We cannot modify geographical factors but we can learn from this and troubleshoot on how we can improve the performance of the campaigns. For example increase placement of the central point, increase frequency of advertisement for the campaign. However, our study did not investigate socioeconomic or cultural factors which are known to be the barriers to dog vaccination and can therefore affect coverage (Bardosh et al., 2014, Kaare et al., 2009, Mazeri et al., 2018). Social factors like socioeconomic status are always important with regard to willingness to pay or vaccinate dogs. We found in this study that coverage varied greatly from village to village and district to district. We suspect that unequal access to information about vaccination campaigns (advertising issues) is the cause of this difference in coverage. It was reported that 23% of the 113 dog owners were not aware that the campaign was taking place (Bardosh et al., 2014). We also did not investigate the religious factors, 14 (50%) of our study areas were island or coastal areas which are dominated by Muslim communities who do not prefer to contact with a dogs (Bardosh et al., 2014). Our estimates of completeness in urban districts were also biased as the vaccination unit was considered at ward level. Some urban wards had 2 or 3 vaccination centres while in rural districts, the vaccination unit was considered at village level.

Another limitation of the study, was due to low detection rate, where transect surveyors counted very small numbers of dogs which potentially biased our coverage estimates. However, in our analysis, we excluded transect data that counted <5 dogs per village.

The success of the dog vaccination campaign is determined by its impact on disease incidence assessed through disease surveillance. A dog vaccination campaign must aim to achieve at least 70% coverage of susceptible dog population in every vaccination in order to interrupt rabies transmission. Another limitation of this study is that I was able to measure village level coverage but unable to evaluate the outcome and impacts of vaccinations in term of incidence of bite-injuries (as a measure of rabies incidence). Monitoring the status of infectious diseases is one of the most challenging problems facing the public health sector in Africa. Very few laboratories in Africa are capable of rabies diagnosis and sample submissions are extremely limited (Lembo et al., 2010). These data on surveillance were not included in this chapter because were not cleaned and were incomplete. However, these data have been recently cleaned and improved by my colleague who is using integrated bite case management (IBCM (Lushasi et al., 2020)). In future, these data from this thesis together with data from IBCM are potentially needed to inform policy-makers be on the performance of these campaigns.

4.5 Conclusion

As we are fast approaching the 2030 deadline for achieving “zero dog-mediated human rabies deaths”, it is essential for rabies-endemic countries to learn and promote the most efficient strategies to control and eliminate rabies. This chapter provides a way in which the dog vaccination performance of can be more accurately measured. Our evaluation showed that Tanzania’s Rabies Elimination Demonstration Project did not reach 100% of the project targets, districts were not consistently achieving 70% coverage, campaigns were not 100% completed in each of the vaccination units, and there were serious delays of vaccinations between campaigns. Long interval between campaigns were not ideal, this lengthy was caused by insufficient dog vaccines. This indicated that vaccination campaigns need a specific action plan before the beginning of the campaign. Transect surveys are useful in providing important operational guidance as to how vaccination coverage may be improved. Dog demographic data and coverage data can help to forecast dog vaccines for future vaccination activities. We conclude that completeness, coverage and campaign timeliness are essential scales if rabies control and elimination goals are to be met.

Chapter 5 General discussion

5.1 Discussion

The World Health Organisation (WHO) has set its sights on elimination of dog-mediated human rabies deaths by 2030 (Abela-Ridder et al., 2016). Dog vaccination is a crucial component of efforts to achieve this goal and vaccination programmes are now underway around the world. However, most low-income countries, particulary in sub-Saharan Africa, still have limited investment in dog vaccination programmes (Hampson et al., 2015). This research will directly benefit control programmes in low-income countries by providing guidance on the implementation of vaccination campaigns, including guidance for evaluating vaccination coverage using transect surveys.

This thesis investigated the best way to implement, monitor and assess the success of campaigns. We found that campaigns must be carefully planned and coordinated to ensure that large number of dogs are vaccinated to reach the recommended coverage threshold. Because the true dog population numbers will likely not be known, we demonstrated the best approach to estimate dog population sizes. Understanding the dog population size is important for campaign planning (e.g., number of dogs to vaccinate, dog vaccines needed, number of vaccinators needed) and evaluating the effectiveness of intervention. Major research findings generated in Chapter 2 and Chpater 3 are useful for planning of the implementation of dog vaccinations.

To eliminate rabies, vaccination coverage must achieve be 70% of susceptible domestic dogs during annual mass vaccination campaigns (Coleman and Dye, 1996). It is therefore important to measure the vaccination coverage that was achieved during vaccination campaigns; however, there is no specific guidance for the most accurate and efficient methods for estimating coverage in different settings. In chapter 2, I compared and assessed three methods that are commonly used to estimate dog vaccination coverage, namely post-vaccination transects, household surveys and school-based surveys. I compared the effect of sampling on the precision and accuracy of coverage estimation against a complete census of the dog population that also recorded dog vaccination status. From this comparison, I demonstrated that transects, which involve the counting vaccinated and unvaccinated dogs in communities soon after campaigns, are cheap, quick, and provide precise coverage estimates, in contrast to household or school-based surveys. Although transects provide rapid estimates, these need to be adjusted because they generally do not include puppies. However, this adjustment is straighforward by incorporating the ratio of pups to adult dogs. I demonstrated that transects are cheap, rapid generate precise estimates and therefore are more appropriate for routine monitoring of vaccination campaigns than household or school-based surveys.

I further compared the practicability and scalability of these methods to identify coverage gaps. My results showed that household and school-based surveys are not suitable for spatial resolution unless all villages are sampled, which is impractical. I demonstrated that transects are essential to identify problematic areas that require repeat vaccination campaigns. With this result, I suggest that transects can be used to troubleshoot stubborn foci areas for countries close to elimination. For example, vaccination programs across Latin America the Caribbean have achieved tremendous success in controlling dog rabies, with average levels of coverage estimated to exceed 70% based on HDRs (Schneider et al 2007, Vigilato et al. 2013, Seetahal et. al 2018). However, rabies persists in some countries in Latin America, such as in Bolivia, and a few remaining foci in Brazil, Peru, and Guatemala (Vigilato et al. 2013). In some of these countries, the ongoing circulation of rabies suggests that vaccination coverages have been over-estimated. Identifying the remaining pockets of susceptible individuals is essential for focusing control and elimination efforts, as these pockets can delay elimination during the endgame (Klepac et al. 2013). Tools such as transects that are cheap and quick to complete, can potentially detect the remaining pockets of susceptible individuals and could be used to guide implementation during the last mile to elimination.

When aiming for eliminating dog rabies in endemic transmissions, campaign must consistently achieve at least 70% vaccination coverage of susceptible dog and ensure that there is no areas left unvaccinated (Townsend et al. 2013). Aiming for a geographically uniform vaccinated dog population with no areas left unvaccinated is important since a patchy coverage might cause persisting disease due to “unvaccinated pockets” (Townsend et al., 2013). This is because unvaccinated pockets can hinder progress to elimination. An important result from this thesis was that transects can detect poor performing communities with low vaccination coverage. These communities with no vaccination campaigns or poor vaccination coverage could be targeted for remedial vaccination to improve both their completeness and their coverage. Transects could not detect unvaccinated pockets missed by routine vaccination campaigns. However, transects could help managers to monitor their campaigns and use thorough planning and assessment to ensure areas are not missed.

When problematic areas are detected, careful planning of tailored vaccination delivery approaches such as remedial vaccinations can be applied to these areas with no vaccination campaigns or poor vaccination coverage. Continuous vaccinations using remedial strategy could improve both completeness and coverage. This study demonstrated that random sampling of villages is not enough to detect unvaccinated pockets, we therefore, recommend to conduct transects for two or three consecutive years in every vaccination units, monitoring coverages in these vaccination units. Transects together with records of vaccinated dogs will help to refine dog population sizes in each vaccination units. When reliable estimates of dog population size is established i.e. after two or three years of consecutive dog vaccinations, transects will be no longer required. We know doing transects in every villages can greatly increase the sample size and generate precise coverage estimates but their implementations are expensive. We still recommend to countries to budget for transects if the goal is to eliminate dog-transmitted human rabies. Important lesson campaign completeness could be learnt from other diseases whereby “Reaching Every District” (RED) strategy was demonstrated to be successful in reducing gaps in immunization coverage (Vandelaer et al., 2008, Ryman et al., 2010).Additional lesson can be learnt from large-scale delivery of mass public health interventions including drug administrations for lymphatic filariasis, using mop-up campaigns, where millions of drugs were administered in different parts of the world. For example in Tanzania, administration of drug administrations for lymphatic filariasis increased from 86% in 2013 to 93% in 2014 following additional mop-up campaigns (Mwingira et al., 2016). Another drugs delivery approach to the problematic areas has been through the outreach/supplementary campaigns. For example, 84 mobile outreach teams delivered 2,979,000 supplemental doses of oral polio vaccine to children younger than 5 years in 18 months in Nigeria (Bawa et al., 2019). Another vaccination delivery approach was through the use the local communities. Experience shows that involvement of the community in delivering drugs (community-driven interventions) in very remote areas speeded up the control efforts of neglected tropical diseases, and if intensified can contribute to the elimination of disease (Amazigo et al., 2012). For example, the elimination of rinderpest was achieved by using thermo-stable vaccine which was delivered through community-based animal health workers (CBAHW(Roeder et al., 2013)).

The above “mop up” delivery approaches could be applied in dog vaccinations. The availability of a thermotolerant rabies vaccine would allow the investigation of community-led dog vaccination delivery approach (Lankester et al., 2016). Community-based interventions could be used in problematic areas that are poorly served by vaccination interventions. However, research is required to investigate cost, logistical and practical challenges associated with dog vaccination delivery through these approaches. The cost of vaccinating a dog using static central point vaccination was estimated to be $1.7 ($0.8-$2.7) in agropastoral areas in Tanzania (Kaare et al., 2009) and $1.3-$1.8 in urban areas in Chad (Kayali et al., 2006). On the other hand, door-to-door strategies to achieve the necessary coverage in pastoralist areas were time-consuming and expensive, with costs estimated at $5/vaccinated dog (Kaare et al., 2009). If local communities will be allowed to deliver dog vaccination campaigns, the cost vaccinating a dog might be lower than the previous estimated.

The results from my thesis showed that fine-scale transect data allows the assessment of the performance of vaccination campaigns. Coverage data from transects will show areas where the number of vaccinated dogs were below the estimated target of 70% of the susceptible dog population in each area. There are two reasons on why a vaccination campaign can fail to achieve the recommended coverage of 70%: First, campaign was never done, perhaps due to poor planning, and second, campaign was done poorly and needs remedials (re-doing). I recommend remedial vaccination due to the following reasons. First, empirical evidence show that shows outbreaks in villages according to coverage (Hampson et al., 2009). Second, experience from Bali in Indonesia who did implement remedial vaccination coverage which resulted into substantial declines in rabies incidence and spread (Putra et al., 2013). Third, experience from Pemba island showed that initial vaccinations covered just 25% of the population, subsequent campaigns across the entire island locally eliminated dog rabies. Rabies reintroduced after suspension of dog vaccinations (Lushasi et al., 2017).

Additionally, I carried analysis to determine the interval between vaccination campaigns. We found that the levels that was achieved by the majority of districts were low and potentially required biannual vaccination campaigns. Since it is expensive to conduct biannual campaigns in LMICs, I presume planning and doing everything properly is cheaper than doing biannual campaigns. This should rapidly increase protective "herd" immunity and will give enough time (i.e. 12 months vaccination interval) for rabies project managers to prepare (i.e. procuring vaccines) for the next vaccination campaign.

Since in the study areas in Tanzania where I worked, remedial dog vaccination campaigns were not conducted, my recommendation raises four important areas for further discussion: first, how should these remedials be considered in terms of costing into national plans? Future studies are needed to compare the cost per dog vaccinated between remedial and routine campaigns. These costs need to be incorporated into national vaccination plans. Second, how quickly should remedial vaccinations be conducted after routine dog vaccination campaigns i.e. after one day/one week or one month? Third, which geographical areas should be targeted by remedial campaigns to achieve maximum impact to interrupt rabies transmission i.e. geographical high-risk areas or is reaching all problematic settings feasible, and fourth, how long will it take to complete remedial campaigns in comparison with routine dog vaccination campaigns? This study demonstrated that transect surveys generated fine scale resolution data that can be used to identify gaps in coverage but were paper-based, which does not allow rapid analysis to be carried out. Since transects are urgently needed by program managers to track the progress of their vaccination campaigns, methods are needed to more rapidly record and summarize these data, such as the use of mobile health (*mHealth*) technology. For example, In Malawi, Mission Rabies vaccinated more than 35,000 dogs in 20 working days and used a mobile phone application to evaluate the coverage achieved (Gibson et al. 2016). In different parts of the world, introduction of *mHealth* technology has greatly facilitated the real-time monitoring of mass dog vaccination campaigns, with over one million dog vaccinations recorded using this application (Gibson et al 2018). This application of *mHealth* innovations allow more efficient capture of extensive data, rapidly analyse and report the community level coverage, these systems, are now replacing the commonly used paper-based surveillances that are prone to data entry errors and cannot allow real-time analyses (Gibson et al. 2015). When gaps are detected rapidly, coverage can be improved through prompt remedial vaccination (Gibson et al. 2015).

Estimates of dog population sizes are a prerequisite for delivering effective dog rabies control. However, dog population sizes are unknown in most rabies-endemic areas. In Chapter 3, I compared three post-vaccination methods to assess which provides the most accurate estimates of the dog population size. I found sampling had effect on estimating dog population sizes and could lead to substantial under or overestimation of the population particularly in areas with considerable village-to-village variation, leading to inaccurate dog population size estimates, which could result into poor rabies control. Using dog population estimates from transects, I further developed a statistical model (from the 27 study districts) to predict dog numbers and distribution in other parts of Tanzania (i.e. 142 districts) where no data on dog numbers are available.

My results showed that there are lower number of dogs in coastal and island areas than in mainland areas, and that pastoralists tend to own more dogs than farmers (peasants). These findings were consistent with previous findings that have been reported elsewhere in East Africa whereby dog keeping is much less common in coastal areas with a predominantly Muslim population and in households without livestock (Knobel et al 2008, Kitala et al. 2001, Gsell et al. 2012). In these settings with lower numbers of dogs, little financial and human resources are required to undertake vaccinations. This provides further incentives to undertake vaccination programmes in these areas as the target of 70% could be more easily achieved. The data on the size of dog populations in Tanzania generated from this thesis has been incorporated into the Tanzania National Rabies Control Strategy, which lays out a roadmap for elimination of rabies in Tanzania by 2030. The modelling approach presented in this thesis that is used to estimate the size of dog populations in Tanzania could be potentially transferable to other parts of Africa.

Moreover, this thesis demonstrated practical approaches for monitoring the implementation of mass dog vaccination campaigns in different settings, which could guide policy in Tanzania and Africa as a whole. One of the key questions in designing vaccination campaigns is the delivery mechanism that will ensure campaigns reach the entire dog population. A key lesson that can be learnt from this chapter is that vaccination campaigns must be constantly and consistently monitored through improved survey methods. This study found several reasons why campaign monitoring is important. First, monitoring the performance of vaccination campaigns allows assessment of their effectiveness in terms of preventing rabies. My findings showed that vaccination campaigns significantly improved over time from when transects were introduced in 2013 for monitoring vaccination programmes. A lesson can be learned that countries could spend money on transects to increase awareness and increase coverage. In each of the study districts, the number of vaccinated dogs increased leading to an increase of vaccination coverage. Campaign monitoring helps rabies project managers to find out whether the target coverage was reached or not, and, if not, they can troubleshoot why not. Project managers can then link poor coverage with reasons that have been reported as barriers for dogs vaccinations (Kaare et al. 2009, Bardosh et al, 2018, Castillo-Neyra et al. 2017 & Mazeri et al 2018). Second, campaign monitoring helps in identifying areas where vaccination campaigns were poor or missed entirely. For example, lessons can be learned from campaigns to eliminate lymphatic filariasis. Lot Quality Assurance Sampling (LQAS) surveys in each of the implementation units was used to identify problematic areas with low coverage (Maroto-Camino et al. 2019). LQAS was used to determine three factors:

(1) a target percent coverage for an indicator (the upper threshold); (2) a percent coverage below which a lot is considered unacceptable (the lower threshold); and (3) the tolerable levels of misclassifying failures and successes i.e. the alpha and beta errors, respectively (Robertson and Valadez, 2006). Third, campaign monitoring motivates district officials and vaccinators to improve their campaigns. The experience from Tanzania showed that the results from transects provided useful feedback for the staff implementing the campaigns (i.e. Livestock Offices and District Veterinary Officers). We observed that when feedback-sharing meetings were conducted resulted into an increased motivation for districts that achieved lower levels of coverage to increase vaccination coverage in subsequent campaigns.

Our finding indicates that to ensure that vaccination coverage in dogs does not drop below the critical threshold, vaccination intervals should not be longer than one year. Many districts in the study areas faced substantial challenges in achieving timely (annual) vaccination campaigns due to the shortages of dog vaccines. These delays were linked to national-level planning and administration. Therefore, to overcome delayed vaccinations, countries must accurately forecast dog vaccine needs.

5.2 Future work

The overall aim of evaluation is to find out information about a programmes' activities, characteristics, and outcomes. This thesis evaluate only activities and characteristics of the vaccination programmes but did not evaluate the outcomes (impacts) of vaccination programmes on bite incidence. Further work is required to incorporate dog bite incidence to explore the impact of mass dog vaccinations on bite incidence. This could be done by exploring the relationship between levels of coverage (that were estimated in Chapter 4) and bite incidence. In addition to that, future work is needed to explore if there is any relationship between rabies incidences and dog population sizes (that were estimated in Chapter 3). This will improve our understanding on whether rabies is dog population based on not.

Additionally, future work is needed to investigated the impacts of reported gaps in coverage on rabies control.

In Chapter 3 of this thesis, I developed a model to predict dog numbers in districts without dog vaccinations. Investigating the performance of my model in other LMIC countries is therefore important as most of LMIC countries do not have reliable data on dog numbers. Dog numbers in LMICs are needed for global initiatives for rabies elimination. For example, Gavi, the Vaccine Alliance, is considering the investment in rabies vaccines (World Health Organisation, 2018a). However, to be eligible for Gavi investment, countries need to demonstrate plans and delivery of mass dog vaccinations and dog population sizes will fit for the purpose.

Future geospatial modelling analysis is required to develop highly specific prediction models regarding to which geographical clusters will be at risk for rabies outbreak. I would like to incorporate bite incidence data, transect data, and geographical data (i.e. altitude, roads, waterways, railways and water bodies) into my model. Geospatial modelling would provide timely identification of geographic clusters of unvaccinated communities and assess the risk reintroduction of rabies from these clusters. This would allow us to explore the potential association between landscape (i.e. physical barriers such as lakes, rivers, elevation, and habitat) and vaccination completeness and vaccination coverage.

5.3 Conclusion and general recommendations

If the goal to end human deaths from dog-mediated rabies by 2030 is to be achieved, mass vaccination of dogs will need to be scaled up and sustained across LMICs in Asia and Africa. Based on the results from my PhD thesis, I recommend the following:

- ✓ It is important for dog vaccination campaigns to include post-vaccination evaluations. Therefore, countries that are implementing dog vaccinations should also set a budget for transect surveys. Monitoring in vaccination campaigns helps to detect gaps in vaccination coverage. The detected gaps can be targeted for remedial vaccination campaigns to boost coverage as biannual campaigns are impractical in LMICs. Detection of coverage gaps and conducting remedial vaccinations help to interrupt rabies circulation, generate herd immunity, and accelerate progress towards rabies elimination (Chapter 2).

- ✓ Assessing dog population sizes is extremely helpful when planning vaccination campaigns (i.e. budgeting for human and financial resources that will be incurred) and evaluating their effectiveness (i.e. to calculate vaccination coverage (Chapter 3)).

- ✓ Small scale sampling of the dog population could lead to substantial under- or overestimation of dog population sizes in areas with considerable village-to-village dog variation, leading to poor rabies control. Population size estimation using transects is a useful alternative tool to support the global initiatives for rabies elimination, taking advantage of data on vaccinated dogs that are routinely collected through implementation of mass dog vaccinations (Chapter 3).

- ✓ The assessment of vaccination coverage at vaccination unit level showed that most of vaccination units in the study areas in Tanzania had not attained the threshold of 70% vaccination coverage. Therefore, efforts should be made to maintain and increase the current vaccination coverage to reach the threshold of 70% coverage by increasing campaign completeness, conduct remedial vaccinations in poor performing communities and conduct annual vaccinations (Chapter 4).

- ✓ A focus on the campaign timeliness could be an effective strategy to enhance the effectiveness of the vaccination campaigns. Due to high dog population turnover in most rabies endemic countries, a one-year interval between vaccination campaigns is needed to maintain sufficient coverage for transmission to be interrupted. Dog vaccine procurement was a major constraint for timely vaccination in Tanzania and affects the efficiency of dog vaccinations. Allocating at least six months for vaccine tendering and procurement is necessary. Over-procurement of dog vaccines is not a problem, because dog vaccines can be used for vaccination campaigns in subsequent years (Chapter 4).

- ✓ Our data supports that 70% vaccination coverage should remain the coverage target in countries with high dog population turnover (Chapter 4).

Appendix A

Evaluating Vaccination Coverage in Dog Populations: a guide for practitioners and rabies programme managers

Background: Each year tens of thousands of people die from dog-mediated rabies, mostly in Africa and Asia (Hampson et al., 2015). The most effective way to prevent rabies is to interrupt transmission in dogs through vaccination (World Health Organisation, 2018b). Rabies can be eliminated by achieving and sustaining comprehensive vaccination coverage of 70% through annual dog vaccination campaigns (World Health Organisation, 2018b). The United Against Rabies collaboration recently set its sights on reaching the global goal of “zero human deaths by 2030” (Abela-Ridder et al., 2016). Mass dog vaccination is the cornerstone of these elimination efforts. Monitoring and evaluation (M&E) are required to assess the performance of mass dog vaccination programmes (Sambo et al., 2017). Here we provide guidance on approaches to evaluate coverage, with a focus on transect surveys.

Why is it important to monitor and evaluate vaccination coverage?

M&E in public health is used for assessing interventions over time and for identifying where delivery needs improving (Reynolds and Sutherland, 2013). Monitoring is conducted continuously to check progress against targets and allow for regular adjustments, whilst evaluation is periodic, usually carried out at specified milestones to check the programme is having the desired and stated impact. M&E involves measurement of ‘indicators’ chosen to reflect important components of the programme at different stages. Useful performance indicators for dog rabies control programmes are: vaccination coverage, timeliness and completeness. With the launch of the ‘Zero by 30’ campaign, one hundred countries are projected to scale up dog vaccinations over the next ten years (Minghui et al., 2018). As countries scale up it will become increasingly important to monitor whether their campaigns are on track.

There are three main reasons for conducting post-vaccination transects:

- To measure the performance of vaccination campaigns and whether the vaccination coverage target was reached. If coverage was poor, it is important to identify reasons for this, so that specific remedial actions can be planned and the situation avoided in future. Barriers to vaccination are typically related to planning and include: poorly located or timed vaccination stations, advertising issues, insufficient procurement, mistrust from communities, and lack of responsible dog ownership. Through monitoring, vaccination coverage gaps can be detected. Monitoring can therefore help to highlight both problems and successful elements of interventions.
- To evaluate the effectiveness of the programme by relating coverage to impact: i.e. coverage versus bite incidence, demand for post-exposure prophylaxis (PEP) and rabies cases in animals and humans. Through monitoring, we can demonstrate if interventions are achieving their aims.
- To estimate or revise estimates of the dog population size. Vaccination coverage assessments together with dog vaccination campaign information enable dog population estimates to be adjusted as improved data becomes available, which can inform vaccine procurement requirements.

This guidance only focuses on transect surveys for M&E of dog vaccination programmes. It is intended to provide guidance for practitioners and rabies programme managers involved in monitoring and evaluating implementation of their regional or national rabies control activities, in order to make any required improvements. The basis for this guidance is the outcome of a workshop on scaling up rabies control, held on 10–11 December 2018, in Geneva, Switzerland. These guidelines aim to assist in the implementation, monitoring and evaluation of vaccination programmes, especially in areas where M&E of the performance of dog vaccination campaigns is neglected. They describe how to choose, establish, and implement an appropriate post-vaccination survey and also the field protocol and analysis of resulting data.

What data do we need to measure vaccination coverage?

Dog vaccination coverage is commonly assessed as the proportion of the total dog population (denominator) that are vaccinated (numerator). In most of Sub-Saharan Africa, dog census or dog registration data (denominators) are not available which makes measuring vaccination coverage a challenge. Denominators are then obtained from human-to-dog ratios (HDRs), which can be used as a preliminary guide on the number of owned dogs. Alternatively, coverage can be obtained from household surveys by asking dog owners to confirm the vaccination status of their dog by memory recall or showing dog vaccination certificates. Coverage estimates obtained from household or school-based surveys and HDRs frequently over- or underestimate coverage in LMICs because of lack of precision due to limited sampling (i.e. small sample size at the household or village level). Another challenge of using these methods is the failure to identify coverage gaps across populations. Transect surveys that involve counting vaccinated (marked) and unvaccinated (unmarked) dogs across communities which are used to measure coverage provide precise and accuracy coverage estimates.

What methods should you use?

Different methods have been used to measure vaccination coverage, such as household surveys, school-based surveys and transect surveys (Table AA-1). Each has advantages and disadvantages and their suitability depends on the setting as summarized in Table AA-1. All the methods miss some part of the dog population, for example households and school-based surveys count only owned dogs while transects counts only free-roaming dogs (both ownerless and owned free-roaming dogs) and tend to miss puppies (dogs under 3 months of age). Critically, household or school-based survey methods do not provide a complete picture of the effectiveness of the campaigns, as they can only detect poor coverage (coverage gaps) in sampled areas because they are typically only implemented in a small geographic area in relation to scaled-up vaccination campaigns. In some parts of the world, HDRs are estimated from household surveys, and are used with human census data to estimate dog populations and coverage achieved during vaccination campaigns. However, this approach suffers from the same problem as they over or underestimating dog populations and coverage. Transect surveys are the most useful method as they generate detailed data across large geographic areas, which can be used to identify spatial heterogeneity in vaccination coverage, i.e. variability, in terms of areas with both low and high coverage. If coverage is low, remedial vaccination should be undertaken. Therefore, we recommend rabies project managers to use transect surveys over other methods for fine-scale monitoring of coverage.

Table AA-1. Comparison of methods to monitor dog vaccination coverage (from (Sambo et al., 2017)).

Method	Applicability in different settings?	Accurate?	Precise?	Geographic coverage and resolution?	Types of dogs that can be counted?	Personnel/ time?	Set-up and implementation costs?
Household survey	Performs poorly in areas with variable dog ownership (e.g. with few dogs such as cities and in mainly Muslim communities).	No, often severely over- or under-estimates coverage	No, confidence intervals (CI) are usually very wide	Poor, conducted usually only in a small random sample of villages	Owned dogs only	2 persons for 2 days per village	$889.05 per district* (cost increases with sample effort, e.g. more villages & households surveyed)
School-based survey	Performs poorly due to variability in dog ownership in different communities (because of sampling fewer numbers of villages).	No, often severely over- or under-estimates coverage	No, CIs are usually very wide	Poor, conducted only in a small sample of schools	Owned dogs only	2 persons for 2 hours per school	$310.60 per district** (cost increases with sample effort, e.g. more questionnaires per school and schools per district
Transect survey	Transects work well in rural and urban settings (because of sampling much larger numbers of villages)	Yes, if adjusted for puppies, which are typically missed during transects	Yes, CIs are narrow	Wide, rapidly conducted in all villages/ vaccinated areas, and used to identify coverage gaps	Free-roaming dogs (both owned and ownerless), but puppies tend to be missed	1 person for 2 hours per village	$1,307.37 per district (average of 79 villages/district)

*based on surveying 30 households per village in 6 villages per district in rural Tanzania (the average human population of districts in Tanzania is 265,000 people). **based on questionnaires with ~100 pupils/school/village.Setting up transect surveys:

Planning: Planning is key to successful vaccination campaigns and should include M&E. Vaccinated dogs must be marked during campaigns, with, for example, a temporary collar or paint mark, and the costs of marking dogs needs to be included in the budget. Transects require consideration of equipment, resources and a timetable, including training. Bare minimum equipment of transects is a notepad, recording sheet/survey form (see the checklist at the end of this guidance) and a pencil or pen. Global Positioning System (GPS) devices and digital cameras are also useful but not essential. For electronic data collection, appropriately configured devices are required for all persons collecting data, and these devices should be fully charged.

Program managers are required to budget for manpower and equipment; working with local officials to identify who will do what, when and where. For example, each district could be assigned a supervisor who will supervise the surveyors. Surveyors can be livestock officers, agricultural extension officers, animal health workers, villagers or volunteers, as long as they are trained. Proper budgeting will ensure that surveys are completed properly and on time. Surveyors must receive training before starting surveys: training and field practice should be completed the week before the surveys, so that surveyors are familiar with the methods and motivated. During training sessions, survey instructions should be distributed to surveyors and supervisors, the survey tools tested, and transect locations (such as villages and streets) assigned to each surveyor.

An important consideration for surveyors is the setting (rural or urban) for their transect, as this will determine the route followed. Surveyors should have knowledge of village and sub-village boundaries to ensure their route passes throughout the targeted areas (sampled sub-villages within a village). Maps with boundaries, human settlements, blocks/streets and major roads in urban areas are usually available through the local councils or government agencies and these should be printed for planning and training purposes. Data can be collected using paper forms or using handheld devices such as a data logger (https://rabiesalliance.org/capacity-building/gdl) or an mobile phone with an App e.g. www.wvsapp.org or a form that can be configured to collect relevant data e.g. www.epicollect.net/. A major advantage of using handheld digital devices to conduct transects is that these data can be vary quickly compiled and reviewed to provide real-time feedback that can guide the implementation of campaigns.

A list of villages and sub-villages to be covered by vaccination campaigns (if possible, together with village maps) should be prepared. To ensure a representative sample (every dog has equal chance of being counted), make sure the transect covers both the centre and periphery of the village in rural areas, or most streets in urban areas. This protocol is well tested in both rural and urban communities in Tanzania, and we have found that completing transects in two randomly selected sub-villages from each village provides useful village-level coverage estimates (Figure AA-2). The same approach, adapted to the local context, has been found to work well in Indonesia (5, 6). The lists of sub-villages and villages and maps (if available) should be shared with surveyors during the training session, checking that they understand the protocols of data collection and are able to discuss with village leaders to identify landmarks for transect starting points, such as a village offices, mosques, schools, churches etc.

Conducting transects: On starting the transect, the surveyor should decide upon a direction to follow by, for example, spinning a pen. The surveyor should alternate between starting transects at the village centre heading to the outskirts, versus starting transects at the sub-village edge (periphery) and heading toward the centre (Figure AA-2). In urban communities, transects should be conducted across the ward, block or borough (in Tanzania one ward contains 3-7 streets or blocks). Maps can be used to help select transect routes within the target area. Maps on mobile phones can help to guide field personnel. In urban areas, select transect routes that intersect with at least half of all streets/blocks of the area, and cover the whole area for a 2-hour period, randomly deciding on a direction to follow when at a junction. Every dog seen during a transect should be recorded (Figure AA-6), noting whether it is marked or unmarked. Dogs should only be counted once. Avoid recounting dogs by ensuring that transect routes are not too close to each other and are within the target area (i.e. village).

Transects should be completed soon after the vaccination campaign, ideally the same day, and should take no more than 2 hours to cover each village/ward regardless of the area involved. In rural areas a good strategy is to spend 1 hour in each sub-village (making 2 hours for 2 sub-villages). Ideally, transects should be conducted in the evening from ~4-6 pm when the temperature is lower and dogs are more likely to be active.

Transects should aim to cover as large an area as possible within the village/ward boundary. Surveys can be done on foot in urban areas. In rural areas that are less densely populated bicycles can help to cover large areas quickly and maximize information-gathering (dogs counted), but avoid cycling at speeds over 20km/hour because surveyors need to travel slowly enough to count and record dogs.

Recording each transect survey.

The main data that have to be collected from transects for assessing coverage are the village name and the counts of marked (vaccinated) dogs and counts of dogs without marks, as well as the date. Other information can also be collected depending on the purpose of the transect (Figure AA-7). For example, name of surveyor, start time, end time, dog age and confinement status can also be recorded but are not essential.

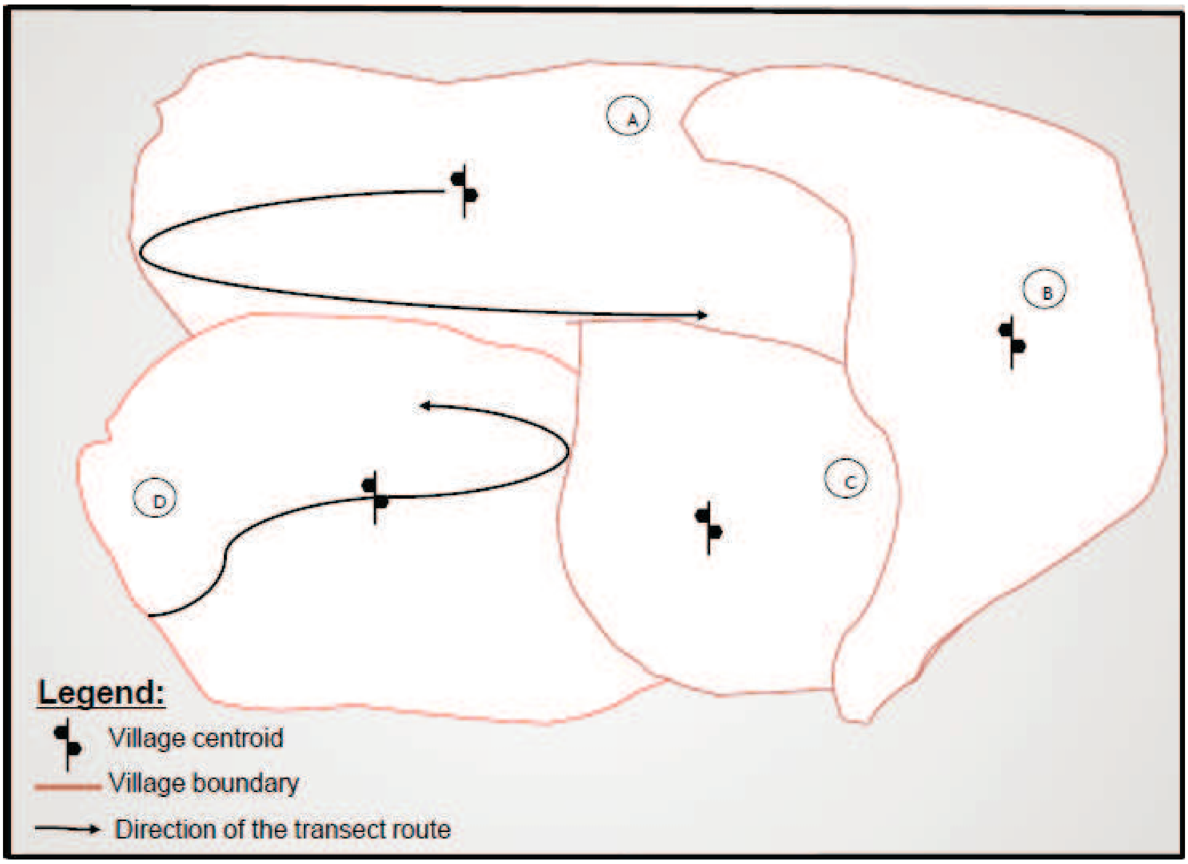


Figure AA-2. Sketch map of a village with four subvillages (A-D), transects covering 2 (sub-village A and C) out of 4 sub-villages. Sub-village A and C were randomly selected for the transect survey. In sub-village A the surveyors started to count dogs from the centre of the sub-village while in sub-village C, surveyors started at the periphery of the sub-village.

Using mobile phones, randomly selected sub-villages can be viewed on Google maps, allowing the surveyor to constantly check while moving if he/she is walking within the sampling area. When transect surveys are completed, data should be entered and stored in a database, containing the following information: name of surveyor, date, village, district (i.e. generally sufficient geographical information to map the location to the administrative unit), count of dogs observed with collars/marks (vaccinated dogs), count of dogs observed without collars/ marks (unvaccinated dogs), and any other relevant information. The quality of the transect data plays a crucial role as data entry errors reduce the precision of the information collected. Ensure that data are examined and verified from the transect form if using paper-based data collection. Issues to look out for include: incomplete (missing counts) or unusually high or low counts, due to data-entry errors. Consult surveyors while their memories are still fresh or have their notebooks accessible. In addition, check if data are unusually high or low counts (out of the required range/ outliers). Validate count data with the number of vaccinated dogs in the village. Some errors cannot be corrected due to lack of appropriate information, and these data have to be deleted.

Data entry from paper-based surveys becomes more time consuming and less reliable as the amount of survey data increases. Use of digital devices to collect and upload standardised data is preferred, especially for large-scale dog vaccination programmes, as these can be used most effectively to rapidly identify coverage gaps (Figure AA-3) requiring remedial revaccination. Mobile technology is widely applied for field data collection, allowing for quick and easy data management, and almost everyone in low-income countries now has mobile phone access.

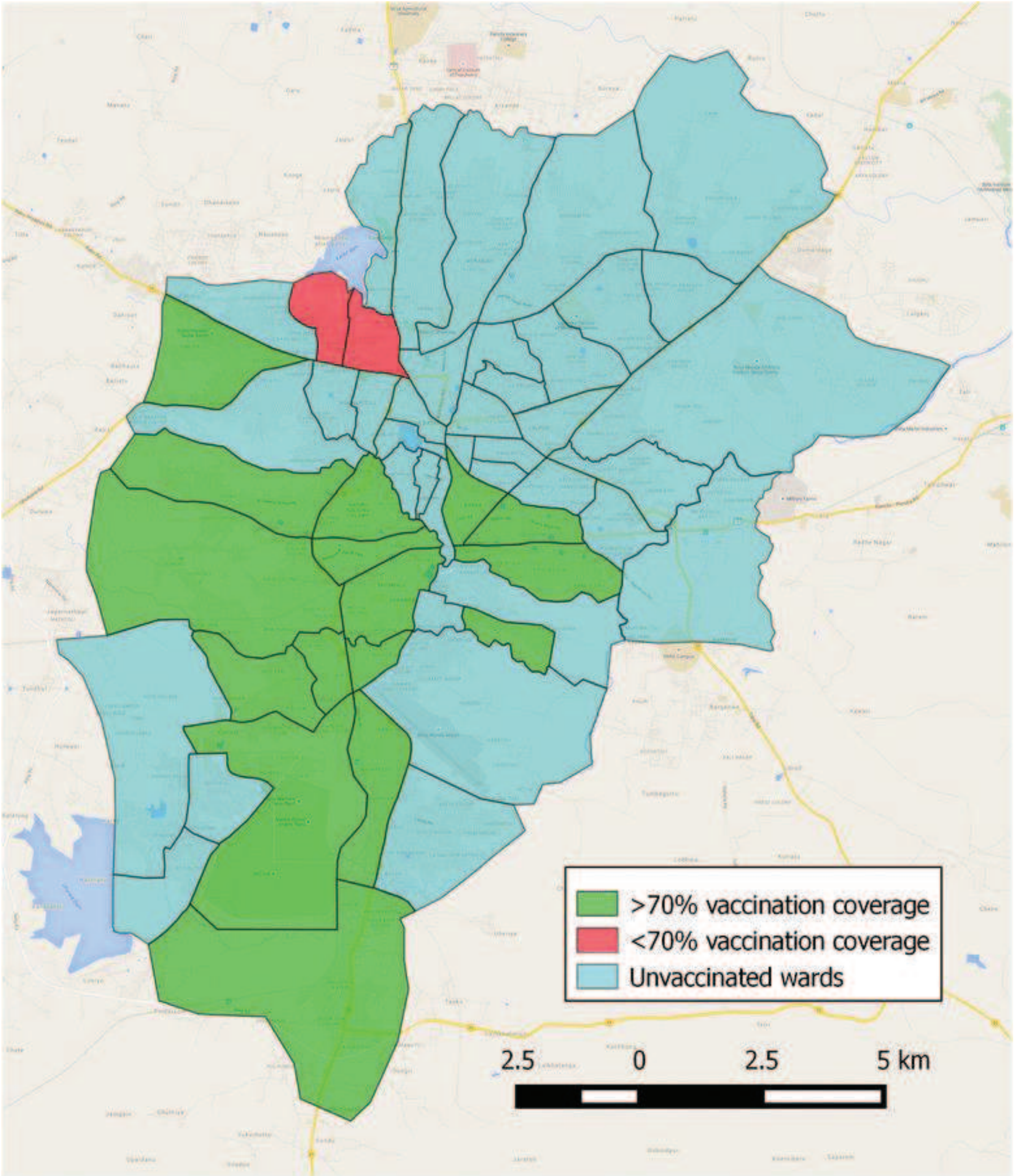


Figure AA-3. Ranchi city in India showing coverage levels in vaccinated wards (from (Gibson et al., 2015)).

Analysis of data

The cleaned data can be analysed using a variety of programmes and summaries of the data displayed to support easy interpretation. Maps can be overlaid with other features, to help visualize what might affect vaccination success.

Vaccination coverage: Coverage is calculated as the number of vaccinated dogs, i.e. those observed with a mark, divided by the total number of dogs observed, i.e. vaccinated dogs with collars and unvaccinated dogs without collars. This estimate needs adjusting because typically puppies are not observed during transects and puppies are rarely vaccinated. Multiplying the coverage estimate by the proportion of dogs that are adult (P) corrects for this bias, which would otherwise be an overestimate (Figure AA-4). P can be calculated from the ratio of pups to adult dogs (PAR) as 1 - PAR/(1+PAR).

$$\text{Coverage} = (1\text{-PAR}) * \frac{\text{Count of marked dogs}}{\text{marked + unmarked dogs}}$$

Figure AA-4. The formula to calculate vaccination coverage, adjusted for unvaccinated and unobserved puppies.). P is the proportion of dogs that are adult, calculated from the pups:adult ratio (PAR) as 1 - PAR/(1+PAR). Example: In Tanzania, the PAR is estimated to be around 1:3.8 = 0.263, so P = 1 – 0.263/(1+0.263) = 0.79. During transects conducted in village A, 20 dogs were observed wearing collars and 10 without collars (unadjusted coverage = 20/30 = 0.67). Vaccination coverage is therefore estimated to be 53%: 20/30*0.79=0.53.

Coverage gaps: These can be identified from transect data using heat maps indicating where remedial vaccination is required. Subsequent monitoring can show the improvement in coverage following remedial vaccination. Figure AA-5, shows areas with >70% coverage, as per WHO’s recommendation, and subsequent improvements.

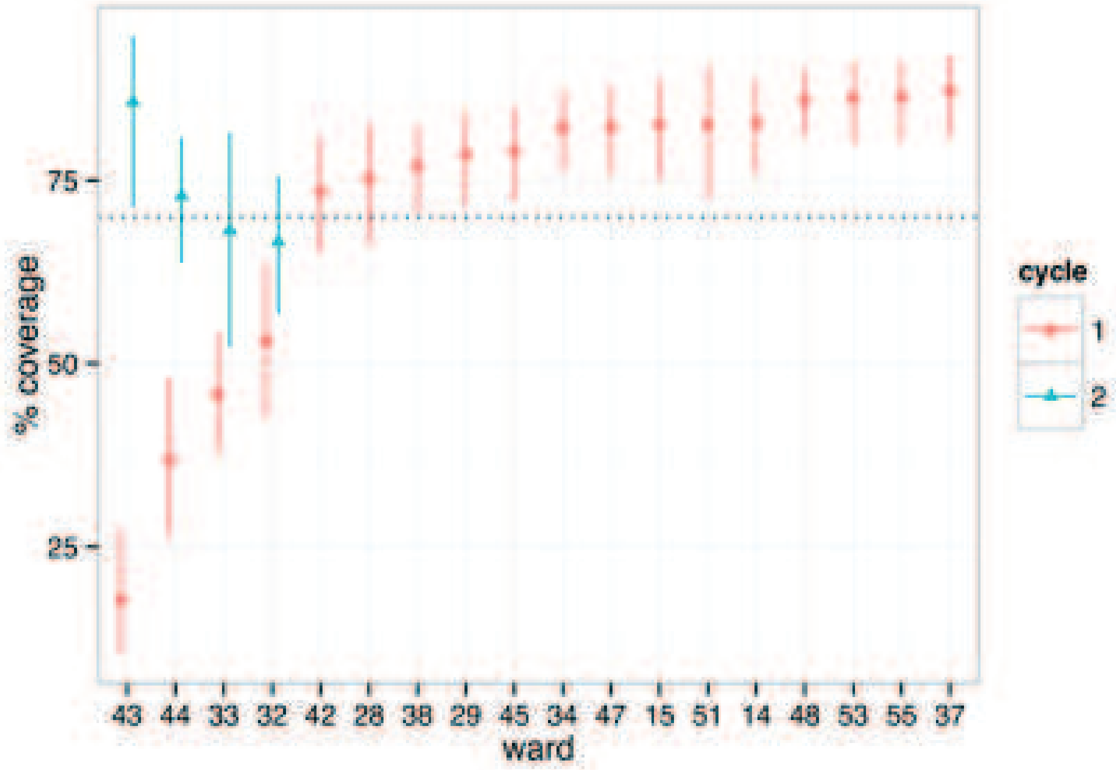


Figure AA-5. Coverage in wards after first vaccination campaign and remedial vaccination. Initial (red) and remedial (blue) coverage estimates are shown, with 95% confidence intervals. 70 % vaccination coverage is indicated by the dotted horizontal line (from (Gibson et al., 2015)).

Dog population sizes: Data on dog population sizes are important for local and national planning and transect data can be used in conjunction with dog vaccination campaign information, to revise (improve) dog population estimates. For example, if 220 dogs were vaccinated in Village A, and 30 dogs observed during the post-vaccination transect, 22 of which had collars, we would get coverage of 0.73 (22/30), an initial estimate of 300 dogs in village A (220/0.73). Adjusting for unobserved puppies (using PAR=1/3.8) would give a total of 381 dogs (220/0.73*(1+1/3.8)). Regression models can be performed to refine (improve) estimates and quantify their uncertainty (Sambo et al., 2018).

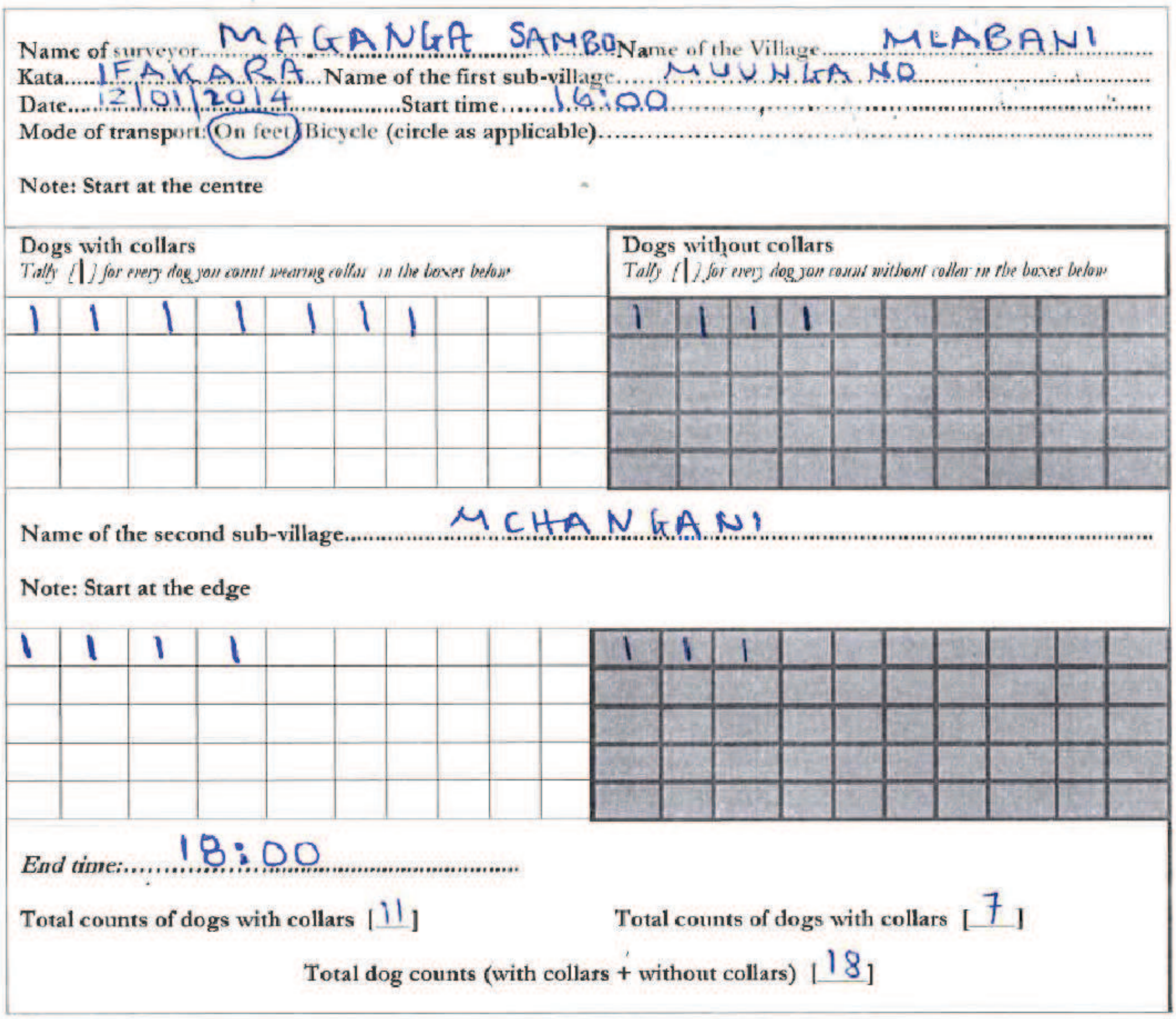
How often should transect surveys be conducted?

At the very start of a vaccination programme, transects should be conducted over consecutive vaccination campaigns to generate baseline data as communities become familiar with the process of vaccination. Once baseline levels of coverage have been established through accurate records of dogs vaccinated in each village/vaccination station, post-vaccination transects may not be required every year, but could be completed less frequently. Many LMICs do not have resources or incentives to invest in M&E, and their priority, understandably, is on vaccinating dogs. Nonetheless we recommend conducting transects at least every four years to monitor longer-term changes in the dog population.

An example of a paper-based form for completing a transect survey is detailed below and an example of a form used from a mobile phone can be accessed via the Mission rabies WSV App (https://www.wvsapp.org)

Paper-based transect survey forms:

Paper-based forms that can be filled out easily by surveyors using a pen or pencil e.g. Figure AA-6. Surveyors should fill all form fields. These field include: name of the surveyor, village name, ward name, name of the first sub village, date (when the survey was conducted), start and end time of the survey, mode of transport and tallies of dogs counted in both the first and second sub villages (each of marked dogs and unmarked dogs in the separate section). At the end of the transect surveyors should count up the tallies.


Name of surveyor...MAGANGA SAMBO Name of the Village...MLABANI
Kata...IFAKARA...Name of the first sub-village...MUUNGANO
Date...12/01/2014...Start time...16:00
Mode of transport: On feet Bicycle (circle as applicable)...

Note: Start at the centre

Dogs with collars
Tally (|) for every dog you count wearing collar in the boxes below

Dogs without collars
Tally (|) for every dog you count without collar in the boxes below

Name of the second sub-village...MCHANGANI

Note: Start at the edge

End time:...18:00

Total counts of dogs with collars [11]

Total counts of dogs with collars [7]

Total dog counts (with collars + without collars) [18]

Figure AA-6: Example of a paper-based transect form.

Paperless transect forms: This can be easily filled out by surveyor on his/her devices by typing requested information into boxes (also known as 'fields') or choosing information from dropdown lists.

Steps to fill the online transect form.

- Contact: epi@missionrabies.com to configure a form and setting up a user ID and password for your study.
- Download WVS APP from the App Store or Google Play store.
- Start filling in your user ID and password.

- The configured transect form with text fields will appear – tap on the active area of the field to type in the text.

Click Start >Select DOG

Next page will open; fill your details accordingly:

- Name of enumerator(Your name)
- Village name (Surveying village)
- Fill sub-village
- Check if the sub-village is the first or the second sub-village
- Start time is option (the system detects starting time)
- Choose the mode of transport from the menu

SAVE & click NEXT

Click START SESSION

Drop in box will pop in and ask start path tracker? SELECT YES (this will trace your routes)

Click a green box written ADD ENTRY

Click new page, the new page titled dog sighting will appear (see figure below named Figure AA-7)

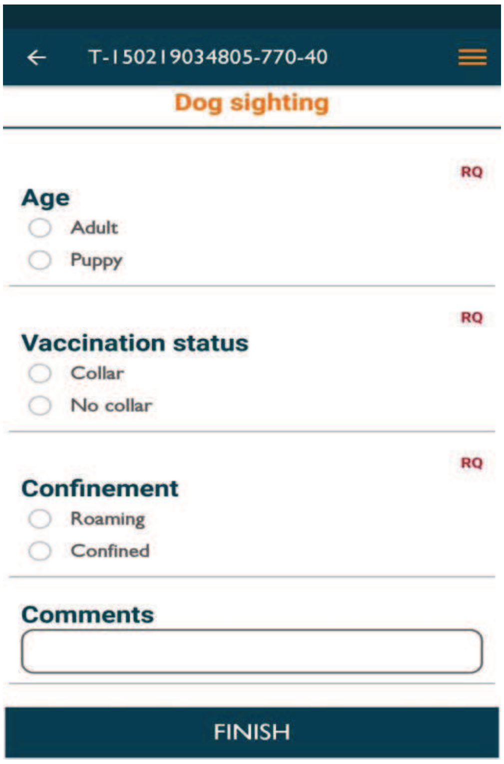


Figure AA-7. Screenshot of survey form using Android- enabled form. ***RQ=required field***

These questions are filled for each sighted dog.

- the age of the sighted dog as you see (puppy or adult)
- the vaccination status of the sighted dog (wearing collar on not wearing collar)
- confinement status of the sighted dog
- any comments (not compulsory)
- Select FINISH

Continue to ADD ENTRY for the next dog until completed.

For technical support of using this App contact: epi@missionrabies.com

Appendix B

Chapter 3: Estimating the Size of Dog Populations in Tanzania to Inform Rabies Control

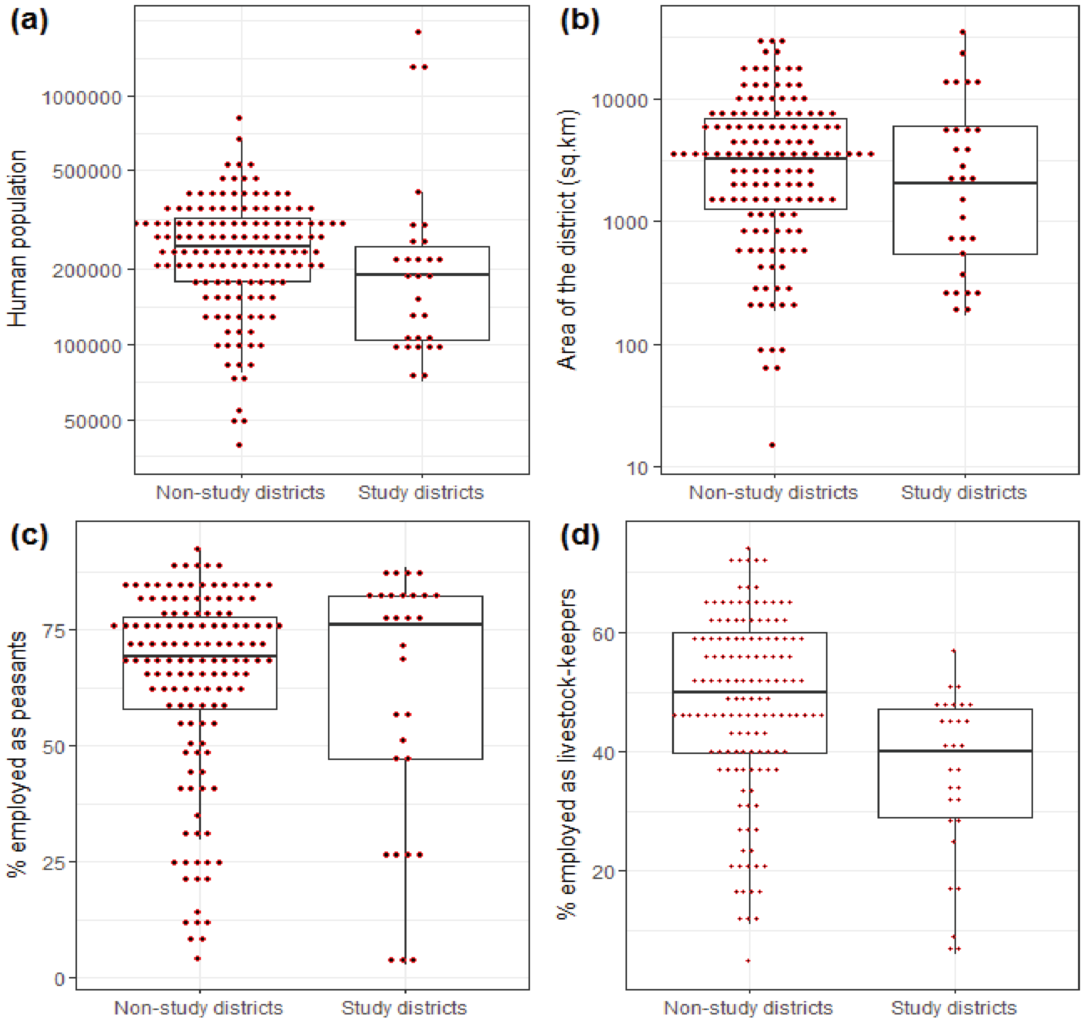


Figure AB-1: The distribution of the non-study districts and study districts in Tanzania. Red points represent data from each district. (A) human population from the National census in 2012 (B) geographical area of the district in square kilometres (C) percentage of population (aged >10 years and above) employed as peasants and (D) percentage of population (aged >10 years and above) employed as livestock keepers.

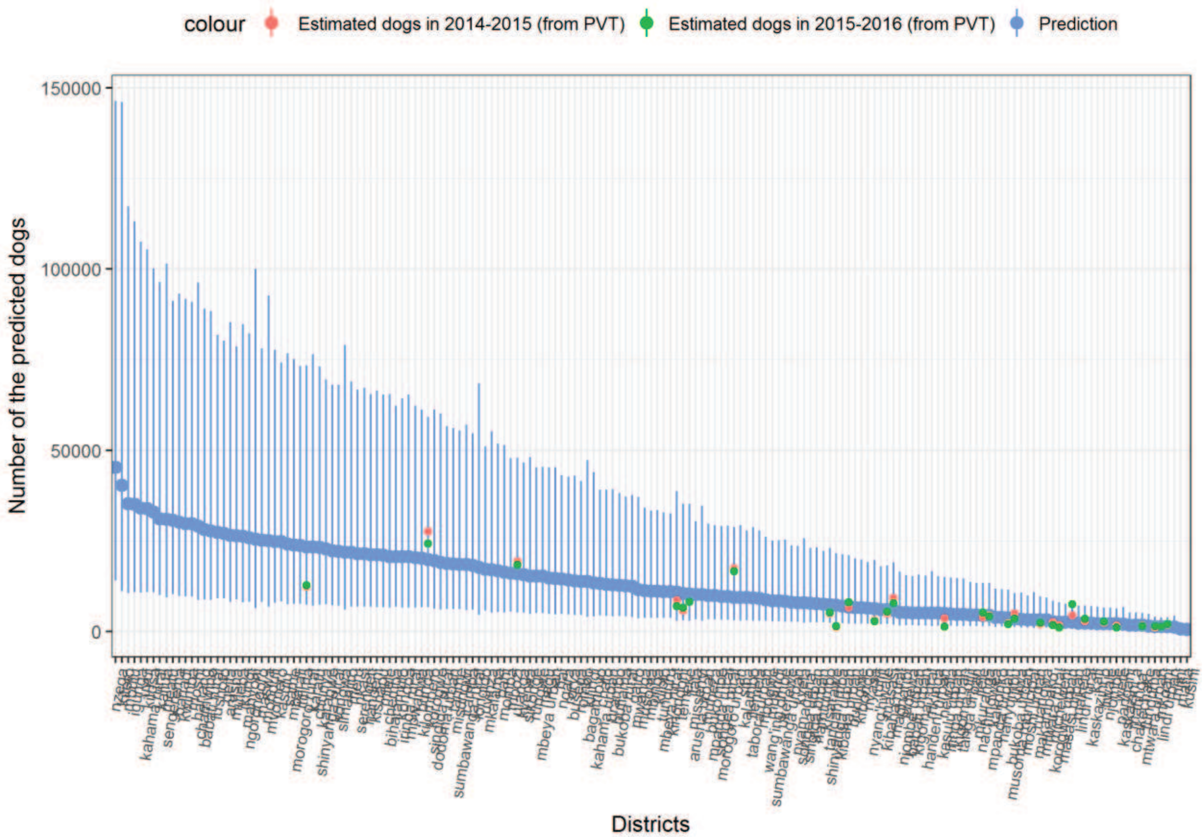


Figure AB-2: The predicted number of dogs in districts across Tanzania. Model predictions (points) and their prediction interval are shown in blue and compared to dog populations estimated directly from transects conducted in 2014–2015 (red points) and in 2015–2016 (green points). This comparison shows that there was minimal year-to-year variation in the estimated number of dogs per district.

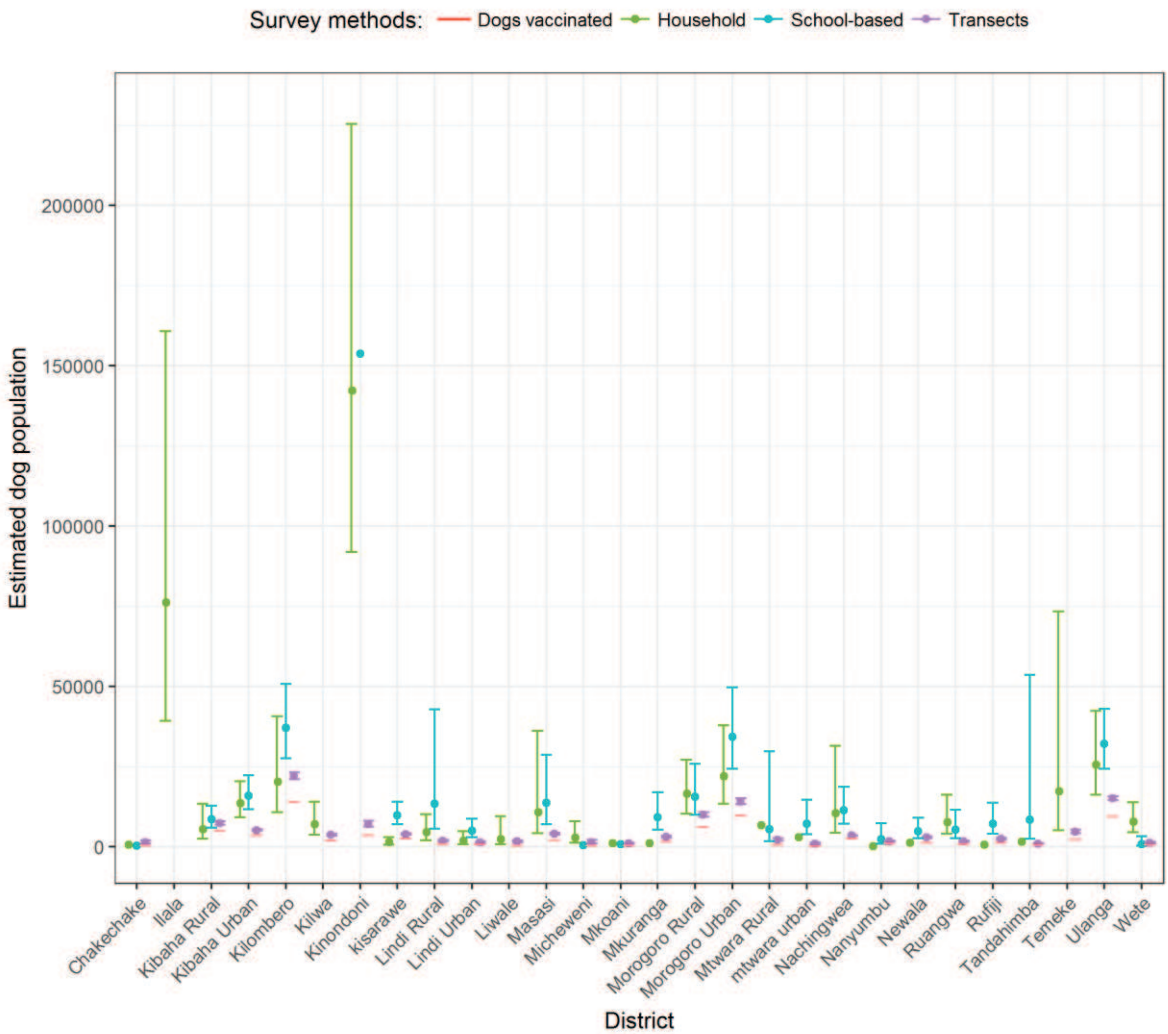


Figure AB-3: Dog population size estimates for the 28 districts (on actual scale). Data for the household survey were collected in 2011 (different dog vaccination campaigns) while school-based survey and transects were conducted in 2014 and 2015 following the dog vaccination campaigns. Points are the mean estimate and error bars show the 95% confidence intervals (CI) around the mean. We did not report CIs for districts which counted less than three dog-owning households or where surveys were not administered.

Table AB-1: A stepwise comparison of Variance Inflation Factors (VIFs) for variables that may influence dog populations in Tanzania. Predictor variables with highest VIF values were removed and the stepwise comparison repeated until all VIF values were below 5. NA=not applicable after the predictor was dropped.

Variables	**VIF after step:**			
	1	2	3	4
Human population in 2014	972.8	9.5	2.4	2.9
Number of people living in rural areas	9.5	NA	NA	NA
Proportion of livestock keeping households	8.8	7.8	5.4	NA
Number of households	948.9	2.9	NA	NA
Proportion of persons employed as livestock keepers	1.6	1.6	1.4	1.3
Setting (inland vs coastal)	1.9	1.9	1.8	1.5
Setting (Mainland vs island)	9.2	5.3	4.7	2.1
Proportion of persons employed as peasant	9.4	8.8	5.4	4.7
Area	8.2	4.3	4.1	3.1

Table AB-2: Descriptive characteristics of the study districts. Number of households and employment status were obtained from the 2012 national census. In household surveys, ~30 households/village were sampled in 6 (range 2-6) villages/district (ranged 93–180 households) per district (Table 2-2). For school-based surveys, ~100 pupils were sampled per school in 6 (range 3–6) schools/district, whereby questionnaires were administered to 152–645 pupils per district. Dogs counted during surveys, mean dogs per household and vaccination coverage were compiled or calculated from household- or school-based surveys. Human: dog ratios (HDRs) were calculated from transects and numbers of vaccinated dogs were compiled from mass dog vaccination campaigns, both conducted in 2014-2015. HHS = Household survey. SBS = School-based survey. CI = Confidence interval. NA = Not applicable.* Calculated by multiplying mean number of dogs per person (from SBS)/district.

			Employment status			HHS		SBS				Estimated dogs		
District	Setting	Number of households (% rural)	Peasants	Livestock keepers	Others	Dogs (mean dogs/ HH)	Coverage (%)	Dogs (mean dogs /pupil)	Coverage (%)	HDR (CI)*	Vaccinated dogs**	HHS Dogs/HH	SBS Dogs/HH	Estimated dogs/people*
Chakechake	Coastal	17,551 (47)	51.1	0.5	48.4	7 (0.04)	0	3 (0.02)	100	59 (20, 177)	608	702	351	216
Ilala	Coastal	297,750 (9)	4	1.2	94.8	34 (0.26.)	50	NA	NA	NA	4,218	77,415	NA	NA
Kibaha Rural	Inland	16,892 (28)	47.2	5.8	47	30 (0.32)	23	199 (0.50)	59	13 (4, 40)	5,226	5,405	8,446	5,148
Kibaha Urban	Inland	31,092 (25)	27.7	2.7	69.6	66 (0.44)	44	237 (0.51)	59	21 (7, 65)	3,684	13,680	15,857	9.079
Kilombero	Inland	93,331 (37)	78.7	0.7	20.6	32 (0.22)	47	218 (0.40)	66	21 (7, 63)	14,208	20,533	37,332	20,819
Kilwa	Coastal	42,596 (48)	71.6	0.4	28	26 (0.16)	15	NA	NA	55 (18, 166)	2,120	6,815	NA	NA
Kinondoni	Coastal	441,240 (8)	2.9	0.8	96.3	59 (0.32)	44	163 (0.35)	52	181(50, 648)	3,696	141,197	154,434	46,977
Kisarawe	Inland	25,475 (48)	78.7	2.3	19	9 (0.05)	89	109 (0.39)	80	14 (4, 43)	2,787	1,274	9,935	5,653
Lindi Rural	Coastal	52,821 (42)	87.2	0.1	12.7	15 (0.08)	60	60 (0.24)	55	83 (27, 257)	1,148	4,226	12,677	7,957
Lindi Urban	Coastal	22,344 (29)	55.8	0.3	43.9	17 (0.10)	41	70 (0.20)	50	68 (23, 205)	930	2,234	4,469	2,597
Liwale	Inland	21,084 (50)	76.2	0.1	23.7	19 (0.11)	16	NA	NA	43 (14, 132)	637	2,319	NA	NA
Masasi	Inland	67,872 (45)	82.2	0.1	17.7	27 (0.15)	30	32 (0.20)	69	42 (14, 127)	4,558	10,181	13,574	8,808
Micheweni	Coastal	19,257 (52)	57.3	1.2	41.5	25 (0.14)	0	4 (0.03)	25	41 (14, 125)	569	2,696	578	312
Mkoani	Coastal	18,067 (57)	26	0.6	73.4	9 (0.06)	100	8 (0.05)	100	75 (25, 224)	631	1,084	903	537
Mkuranga	Coastal	51,101 (34)	68.5	0.5	31	4 (0.02)	100	58 (0.18)	62	52 (17, 157)	1,811	1,022	9,198	5,693
Morogoro Rural	Inland	67,671 (46)	81	3	16	41 (0.24)	56	103 (0.25)	65	12 (4, 39)	6,434	16,241	16,918	9,237

Table AB-2. Cont.

			Employment status			HHS		SBS				Estimated dogs		
District	Setting	Number of households (% rural)	Peasants	Livestock keepers	Others	Dogs (mean dogs/ HH)	Coverage (%)	Dogs (mean dogs /pupil)	Coverage (%)	HDR (CI)*	Vaccinated dogs**	HHS	SBS	Estimated dogs/people*
Morogoro Urban	Inland	76,039 (16)	25.2	0.7	74.1	49 (0.29)	76	225 (0.40)	67	35 (12, 108)	9,968	22,051	30,416	9,237
Mtwara Rural	Inland	58,602 (37)	83.2	0.1	16.7	16 (0.11)	50	31 (0.09)	61	85 (27, 262)	860	6,446	5,274	3,260
Mtwara Urban	Coastal	27,968 (18)	27.7	0.4	71.9	14 (0.09)	64	69 (0.24)	35	84 (28, 252)	540	2,517	6,712	3,919
Nachingwea	Inland	48,145 (45)	85.7	0.1	14.2	37 (0.22)	32	84 (0.25)	8	41 (12, 125)	2,823	10,592	12,036	7,594
Nanyumbu	Inland	40,746 (33)	88.4	0.1	11.5	1 (0.01)	100	28 (0.06)	18	41 (13, 123)	1,281	407	2,445	1,470
Newala	Inland	58,035 (49)	81.2	0.1	18.7	4 (0.02)	100	55 (0.09)	53	42 (14, 128)	1,465	1,161	5,223	2,881
Ruangwa	Inland	37,326 (47)	83.7	0.1	16.2	37 (0.21)	35	24 (0.14)	50	42 (14, 126)	1,090	7,838	5,226	3,240
Rufiji	Coastal	48,164 (31)	77.1	1.3	21.6	2 (0.01)	100	61 (0.14)	49	35 (11, 109)	1,423	482	6,743	4,610
Tandahimba	Inland	60,872 (44)	86.2	0.2	13.6	2 (0.03)	100	24 (0.14)	8	32 (11, 95)	762	1,826	8,522	5,098
Temeke	Coastal	344,391 (6)	4.6	0.8	94.6	8 (0.05)	88	NA	NA	147(44, 496)	2,521	17,220	NA	NA
Ulanga	Inland	53,290 (42)	83.2	1.1	15.7	85 (0.48)	45	326 (0.58)	61	18 (6, 53)	9,645	25,579	30,908	17,918
Wete	Coastal	20,151 (40)	47.2	0.8	52	56 (0.38)	57	7 (0.04)	100	52 (17, 155)	718	7,657	806	545
Overall						731 (0.6)	56	2,198 (0.7)	56		86,321	410,800	398,983	189,154

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