The impact of dog population management on free-roaming dog population dynamics, health and welfare

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The candidate confirms that the work submitted is her own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Abstract

Free-roaming dogs present disease, economic and conservation risks, whilst often experiencing health and welfare problems themselves. Dog population management is widely conducted to mitigate these issues. Recent studies have highlighted the need to assess the impact of different dog population management methods in terms of their effectiveness, efficiency and sustainability. This thesis reports the impact of dog population management methods on free-roaming dog population dynamics, health and welfare. An initial systematic review was conducted, finding that most management methods are associated with a reduction in population size and risks to public health and dog welfare. Methods involving fertility control had the greatest reported effect on dog population size. A follow-up field study collected dog population and public attitude data in focal European countries (Bulgaria, Italy and Ukraine). A mark-recapture study using Pollock's robust design was conducted to determine population size, growth, and rates of recruitment and removal for free-roaming dog populations, finding evidence for effects of sex on removal rates and survey conditions on dog detection probability. The questionnaire found associations between public attitudes and dog ownership practices with gender, religious beliefs, age, education level, reason for dog ownership, previous experience with free-roaming dogs, and country of residence.

Using the field data, a systems dynamics model was developed incorporating an interactive system of dog subpopulations to investigate the impact of population management on dog population size, welfare, and financial costs. Results show that methods incorporating both fertility control and responsible ownership have the greatest potential to reduce free-roaming dog population sizes, whilst being cost-effective and improving overall welfare. This thesis

highlights the importance of identifying the causes of population increase (e.g. abandonment of owned dogs), to ensure that population management efforts create lasting change.

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Abbreviations

%	Percentage
€	Euro currency
ARRIVE	Animals in Research: Reporting *In Vivo* Experiments
C	Coverage of management
CI	Confidence interval; Credible interval; Bayesian confidence intervals or highest density intervals; the 2.5 and 97.5 percentiles of the posterior distribution
CNR	Catch-neuter-release
dogs km^{-2}	dogs per squared kilometre
EE	Error estimate
F	Indicates only female fertility was controlled during an intervention
IZSAM	Istituto Zooprofilattico Sperimentale dell’Abruzzo e del Molise “Giuseppe Caporale”
km	Kilometre
km^2	Squared kilometre
L	Length of management
M	Modelling study
M&F	Indicates fertility control was applied to both males and females during an intervention
Mgmt.	Management
NA	Not applicable
NR	p-value not reported

NS	p-value not significant
O/I	Observational or intervention study
OIE	The World Organisation for Animal Health
OR	Odds ratio
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
R_0	Basic reproductive number
RQ	Reporting quality
spp.	Species (plural)
vs.	Versus

Chapter 1. Introduction

1.1. The ecology of the domestic dog population

The domestic dog (*Canis familiaris*) has a global distribution and an estimated total population size of around 700 million to 1 billion (1,2). It is now generally agreed that dogs were domesticated from the grey wolf (*Canis lupus*) around 16,000 years ago (3,4), although other evidence suggests domestication as early as 34,000 years ago (5,6). Since their domestication, dogs have become closely associated with humans. Dogs take on many roles in their relationship with humans, for example, as working dogs (guarding, herding, hunting, medical support – e.g. guide dogs for the blind, and with the police – e.g. sniffer dogs), companions, and sporting animals.

The dog population can be split into different categories (subpopulations), typically relating to the dog's dependency on humans, their roaming ability, and whether they inhabit rural or urban areas (7,8). For the purpose of this thesis, I define dog subpopulations depending on their association with people (i.e. ownership status) and the level to which their movement is restricted (i.e. roaming ability). Dogs have one of two ownership states—either they are owned, or they are unowned. The owned population is dependent upon humans for food, water, and shelter and may have one or more owners (e.g. "community dogs"). The owned dog population includes both dogs that are restricted in their movement to a limited area (e.g. within a fenced yard or under human supervision on walks), and those that are free to roam unrestricted, without human supervision (9). Unowned dogs (often referred to as stray) do not have an owner but may still depend upon humans directly or indirectly for food, water, and shelter (9). Feral dogs, such as dingoes (*Canis familiaris dingo*), are included in this category, but exist independently of human resources, reverting to an undomesticated state with limited human interaction (7). There are few strictly feral dog populations (8). Similar to owned dogs, the unowned population's movements may be restricted or unrestricted—dogs housed in shelters have restricted movement, but street-dwelling dogs have unrestricted movement. Unrestricted dogs (including owned and unowned) are commonly referred to as the free-roaming or the street dog population (10).

Free-roaming dogs are mainly sustained on food provided directly by people (i.e. deliberate feeding), or indirectly by scavenging on human waste (11–19). Dogs are efficient scavengers of anthropogenic food, including food waste and human faeces (11–19). Free-roaming dogs may also feed on small mammals, birds, insects and livestock (11,14,18,20). Home range sizes vary depending on external factors, such as the spatial distribution of resources, season, environment and geographic location and internal factors, such as sex, neutering status, and age (7,21,22). Range sizes have been reported between 0.27 and 927 hectares (21,23–26). Most free-roaming dogs that live in or around cities and villages are thought to have home ranges on the lower end of this scale (8). These free-roaming dogs are also thought to be more solitary, forming loose social groups, although often observed in close approximation due to the distribution of resources (e.g. food, mates) (27–30). This is compared to feral dogs, which have been observed forming wolf-life packs (28,30).

Approximately 75% of dogs across the world fit into this free-roaming dog category (1). Free-roaming dog abundance varies greatly between countries, relating to the habitat type (urban/rural) and human population (e.g. density and cultural/social factors) ((9); see (1) for review of abundance and distribution). For example, densities of free-roaming dogs have been estimated as 719 dogs km^{-2} in Maharashtra in India (31), 334 dogs km^{-2} in Iringa, Tanzania (32), 76.8 dogs km^{-2} in Brazil (33), and 0.3 dogs km^{-2} in rural parts of Italy (28).

1.2. Dog population management

Free-roaming dogs, particularly those in high densities, present issues for public health (e.g. transmission of rabies and other zoonotic pathogens) (34–36), livestock (20,37–40), and the conservation of wildlife (41–43). Their own welfare states are also of concern (9,44–46). Population management typically focusses on free-roaming dogs (47) to control the population size and—depending on the approach taken—to improve dog health and welfare and mitigate public health and environmental problems (48,49).

1.2.1. The impact of free-roaming dogs on public health

Free-roaming dogs are associated with the transmission of a number of zoonotic pathogens (50–54), dog bite injuries (55–57), and road traffic accidents (9,58). Dogs are responsible for transmitting over 300 zoonoses to humans (2,59). They are perhaps best known in this regard for the role they play in the spread and maintenance of the rabies virus (60). This virus is responsible for an estimated 60,000 human deaths per year amounting to an annual economic cost of 8.6 billion United States dollars (61). Dogs are a primary reservoir host of this virus and account for 99% of human-rabies transmissions (60).

Dogs also play a significant role in transmitting *Leishmania infantum* to humans, the causative agent of zoonotic visceral leishmaniasis (62). *Leishmania infantum* spreads over 79 countries globally causing 20,000-40,000 human deaths annually (63). This pathogen is transmitted by the phlebotomine sand fly vector and dogs are considered the primary reservoir host (64). Other notable zoonoses include *Echinococcus* spp. (*E. granulosus* and *E. multilocularis*) (65), which causes echinococcosis; and *Toxocara canis,* which causes toxocariasis (66).

Additional public health concerns caused by free-roaming dogs include dog bite injuries (55–57) and road traffic accidents as a result of unrestricted dogs on public roads (9,58). The risk of dog attack is greater in children than in adults (67–70), as is the risk of severe injury (for example, a severe face and neck injury) (69,70). The reported annual incidence of dog bites to humans varies between countries, for example, previously reported annual incidence in Haiti was 3.7% (71) and in India, 1.7% (72). A lack of reporting may greatly underrepresent these figures, as methods to estimate dog bite incidence often rely on bites being reported to authorities (69,73,74). Estimates indicate dog bite incidence may be around 50% higher than reported (69,73,74). Victims of dog bites often need to seek medical attention to treat the injury or acquire post-exposure rabies prophylaxis, which contributes to the economic burden of free-roaming dogs (9).

1.2.2. The impact of free-roaming dogs on wild and domestic animals

Free-roaming dogs can compromise the conservation of wild animals through a combination of pathogen pollution (i.e. the spread of pathogens to naive hosts) (41,75,76), predation (77,78), competition (13), and hybridisation (42,79,80). It is estimated that dogs have played a role in the extinction of 11 vertebrate species and threaten the survival of at least 188 more species (43).

In addition to the negative consequences that canine pathogens have on human health, these pathogens can have an important impact on the conservation of endangered species. For example, rabies spread by domestic dogs can threaten the Ethiopian wolf (*Canis simensis*) (41) and African wild dog (*Lycaon pictus*) (75) populations. African wild dogs have the potential to be driven to extinction by rabies due to their small population size and taxonomic similarity to dogs (75,81). Similarly, dog populations seropositive for canine distemper virus can cause epidemics in neighbouring wildlife populations (82); in areas west of the Serengeti National Park, high-density dog populations have acted as a maintenance host for canine distemper virus, causing outbreaks of the virus and mortality in the local lion (*Panthera leo*) populations (76).

The taxonomic relatedness of the domestic dog to other canids, such as dingoes (*Canis familiaris dingo*), grey wolves (*Canis* ssp.), and Ethiopian wolves, is also of concern when dogs are free-roaming. Inter-species breeding can result in hybridisation and threaten species survival (42,79,83–85). In addition, dogs have been responsible for the reduction of other species through predation and competition (1,8,77,78,86). For example, predation by dogs has resulted in the decrease of mountain gazelle (*Gazella gazella gazella*) in Israel (87), puda (*Puda puda*) in Chile (88), and the North Island brown kiwi (*Apteryx australis mantelli*) in New Zealand (89).

Domestic dogs can also be responsible for the killing of livestock (20,37–40); in particular, small- and medium-bodied livestock such as sheep, goats, and donkeys (20,37–40). The numbers of livestock killed by dogs correlate with the number of dogs in the area (40) and the density of the livestock (20). The loss of livestock contributes to substantial economic losses (20). For example, in the United States of America, this amounts to over 620 million United States dollars annually (39). The financial consequences can be particularly problematic in low-income areas (20). Additionally, the loss of livestock can increase human–wildlife conflict, as predation by dogs is often mistaken for that of other species, such as wolves (20,37,40,90) or snow leopards (20,90). For example, in districts of Himachal Pradesh, Suryawanshi *et al.,* (2013) reported that local communities perceived wolves and snow leopards as the greatest threat to livestock, whereas dogs were responsible for the majority of livestock predation (90).

1.2.3. Health and welfare of free-roaming dogs

Free-roaming dogs can often experience conditions leading to poor health and welfare states. In particular, unowned free-roaming dogs may have an inadequate diet and be more at risk of starvation and dehydration (9,46). For example, in India, around 49% of free-roaming dogs are emaciated (91). Unowned free-roaming dogs can still be dependent on humans for resources, either directly through feeding or indirectly through the provision of food in human waste (15). The high prevalence of emaciated body condition states in free-roaming dogs that occur in some areas may be due to low quantities and/or poor quality of food resources, potentially linked also to a high disease burden (91,92). Additional health and welfare risks to free-roaming dogs include injury caused by road traffic accidents, abusive treatment by locals (10), and inhumane methods of removal (e.g. poisoning, electrocution, drowning, or carbon monoxide asphyxiation (93)).

Free-roaming dogs, particularly those that are unowned, lack even basic veterinary care, such as vaccination or antiparasitics, and are therefore more susceptible to disease. A study in the Bahamas found that approximately 70% of free-roaming dogs experience infectious diseases and malnutrition (94). High prevalence of skin conditions and ectoparasites have been reported in several populations (91,94). Canine transmissible venereal tumour disease is also a welfare concern in free-roaming dog populations. The cancerous cells of this disease transfer between dogs during sexual activity, leading to infection and tumour growth. The prevalence has been estimated at around 1% in dog populations in Africa, Asia, South America, and Central America (95), although the prevalence has been estimated to be as high as 15% in female dogs in some free-roaming populations (96). As sexually intact dogs mate more frequently, they are at higher risk of contracting the disease. Free-roaming dogs are often not neutered, potentially leading to a higher prevalence in the free-roaming population (95).

1.3. Methods of dog population management

Dog population management is conducted to tackle the public health, environmental, and animal welfare issues associated with free-roaming dogs. Approaches to manage the dog population include mass culling, reproductive control and the use of shelters to house unowned or unwanted dogs (47,48). Additional strategies are often used alongside these methods, including educating the public about responsible dog ownership and implementing legislation that enforces the registration and identification of owned dogs (47,48). These management methods will be outlined in detail in Chapter Two.

Different methods of dog population management have been employed and there is a need to assess the effectiveness and efficiency of each of these methods when considering the impact they have on free-roaming dog health and welfare, public health, and on wild and domestic animal populations. Dog population management often aims to reduce free-roaming dog population size and stabilise population turnover in order to reduce these risks (49). To reduce population size, methods of dog population management aim to alter sources of free-roaming dog population increase (such as reducing births within a population) or decrease (such as increasing deaths within a population). For example, methods involving fertility control aim to reduce the birth rate, whilst methods such as culling aim to increase the mortality rate.

As described, the dog population can be split into several subpopulations depending on their restriction status and interaction with people. The system of dog subpopulations is interactive and dynamic, dogs may move between subpopulations throughout their lifespan. For example, owned dogs may move from the owned restricted dog subpopulation to an unowned, unrestricted subpopulation through abandonment, leading to an increase in free-roaming dog population size. Assessing the potential impact of population management requires identifying and quantifying the rates of recruitment and removal. Recruitment into a population typically occurs through births and immigration, and removal through mortality and emigration (97). As the dog population involves several subpopulations, recruitment may also occur through immigration from other dog subpopulations (e.g. abandonment from an owned population), and removal may also occur through emigration to other subpopulations (e.g. adoption from the street). As management methods aim to alter rates of recruitment and removal, understanding the contribution of each of these processes to free-roaming dog population dynamics allows the potential impact of different management methods to be evaluated, therefore guiding policy towards methods that are effective and efficient in the long-term.

Understanding public attitudes towards free-roaming dog populations is also key to determining management success (98). Free-roaming dogs can be an important part of a community, providing companionship and protection to people and livestock (9). Public support for management aims (such as a reduction in free-roaming dog numbers) and methods is important in ensuring the success of interventions. It is therefore important to measure public attitudes towards different management methods and public demand for management in order to determine the potential effectiveness of dog population management.

In this thesis, I focus on free-roaming dog populations in focal countries within Europe – in Bulgaria, Italy and Ukraine. There is a lack of data on dog ownership practices, public attitudes, and free-roaming dog population dynamics in Europe. Dog population management in these countries often involves catch-neuter-release (CNR) (Bulgaria, Italy and Ukraine), sheltering (Bulgaria, Italy and Ukraine), and culling (Ukraine) (47,48), in order to reduce risks to public health (99–101), reduce predation on livestock (37) and wildlife (40), and to improve free-roaming dog welfare (47). Bulgaria, Italy and Ukraine were selected as focal countries due to the networks established with this project's collaborating organisations, VIER PFOTEN International and Istituto Zooprofilattico Sperimentale dell'Abruzzo e del Molise "Giuseppe Caporale" (IZSAM). These networks allowed access to historical records of dog population management and provided local knowledge to facilitate data collection. The focal countries are culturally and environmentally distinct, allowing comparison of the collected data between different countries.

1.4. Thesis questions, objectives, hypotheses and structure

1.4.1. Thesis aim

The aim of this PhD thesis is to investigate and compare the impact of dog population management methods on free-roaming dog population dynamics, health and welfare, in terms of their sustainability, effectiveness and efficiency.

1.4.2. Thesis questions

Specifically, four main questions will be addressed in this thesis:

(i) What evidence is there for the effectiveness of dog population management methods?

(ii) What are the public attitudes towards free-roaming dog populations and what might dog ownership practices contribute to the free-roaming dog population?

(iii) What are the sizes, dynamics and health status of dog populations in the focal countries, and how may these factors influence the success of dog population management?

(iv) What are the projected impacts of dog population management, including culling, sheltering, CNR, and responsible ownership on the sizes of street, unowned and shelter dog populations, and the estimated cost and welfare implications of each of the interventions?

1.4.3. Thesis objectives

The thesis questions will be addressed through a combination of data collection approaches and the development and running of a systems dynamics model through computer simulations. The systems model describes the system of dog subpopulations and the collected data will be used to inform model parameters. The systems model will be used to investigate the potential impact of CNR, sheltering and culling, in terms of projected estimates of population size, financial costs, welfare impact to the dog population and threats to public health.

The thesis aim will be met through the following objectives:

(i) To conduct a systematic review to synthesise the existing evidence of the effectiveness of dog population management, describing (i) where and when dog population management has been assessed, (ii) the management methods investigated, and (iii) the recorded effect of dog population management.

(ii) Within the focal countries, to (i) measure the level of dog ownership; (ii) determine public attitudes towards the presence of free-roaming dogs; (iii) determine ownership practices (e.g. prevalence of roaming and neutering); and (iv) compare with demographic information to determine demographic risk factors for ownership practices and attitudes.

(iii) Within two of the focal countries (Italy and Ukraine), to: (i) determine the population size; (ii) population health; (iii) detection probability; (iv) recruitment; and (v) removal processes, and investigate whether there are differences in these parameters for different study locations, sex, and environmental factors.

(iv) Develop a systems model that describes the system of dog sub-populations (unowned free-roaming, owned restricted and unrestricted, and shelter) to assess the impact of dog population management methods, including CNR, culling, sheltering and responsible ownership on the sizes of these populations and to calculate the welfare impacts and financial costs of each intervention.

(v) Run computer simulations to investigate the potential impact of each of the interventions, as well as combinations of interventions, over different periodicity of control (continual versus annual) and at different coverages (i.e. management to different percentages of the population).

1.4.4. Hypotheses

I predict that free-roaming dog population birth rate is the dominant source of free-roaming dog population growth. Therefore, I hypothesise that CNR is more sustainable than other methods of dog population management (sheltering, culling, responsible ownership and combinations of interventions), as it targets the birth rate of the free-roaming dog population. Sustainability is here defined as the ability of dog population management methods to be effective and efficient at maintaining: (i) the free-roaming dog population below an acceptable threshold within a community; (ii) the highest levels of animal welfare for free-roaming dogs; (iii) the lowest levels of public health risk; and (iv) the lowest levels of environmental impact of free-roaming dogs within the community.

Effectiveness will be defined as the degree to which dog population management methods are successful in: (i) reducing the free-roaming dog population size over time; (ii) improving free-roaming dog health and welfare; (iii) reducing environmental impact; (iv) reducing the risks posed to public health (e.g. zoonoses and human injury through traffic accidents and dog bites); and (v) increasing the level of public acceptance for free-roaming dogs within the community.

Efficiency will be described as the extent to which CNR and other dog population management methods achieve the objectives with minimal wasted effort or expense (e.g. financial and temporal resources).

Sustainability will therefore be measured by four indicators, whether the dog population management method is able to:

(i) Maintain the number of dogs km^{-2} below an acceptable threshold (in terms of (a) public acceptance; (b) public health risk; and (c) environmental impact).
(ii) Maintain above a minimum standard of free-roaming dog welfare.
(iii) Maintain below a certain level of risk to public health.
(iv) Maintain below a certain level of environmental impact.

1.4.5. Thesis structure

In this thesis, I provide a background into the reasons why dog population management is carried out and what management methods have been used, and synthesise the existing evidence of the effectiveness of different dog population management methods (Chapter Two). I then investigate public attitudes towards dog population management and determine dog ownership practices in three focal countries: Bulgaria, Italy and Ukraine (Chapter Three). Following this, I determine the size, dynamics, and health status of free-roaming dog populations in study regions within two of the focal countries, namely: Pescara, Italy and Lviv, Ukraine (Chapter Four). Using data collected in the preceding chapters, I use a system dynamics modelling approach to compare the impact of different dog population management methods on the sizes of the street, owned, and shelter dog populations (Chapter Five). I provide a discussion of the findings and implications for future dog population management intervention (Chapter Six).

Chapter 2. The Effectiveness of Dog Population Management: A Systematic Review

2.1. Introduction

As outlined in Chapter One, populations of free-roaming dogs may present issues to humans and other animals by spreading disease (34–36), predating on wildlife (77) and livestock (20,37–40), and by competing and hybridising with wildlife (42,79,80). Free-roaming dogs may also experience poorer health and welfare (9,44–46). Dog population management is carried out to counter these issues.

2.1.1. Responsible groups and motivations for dog population management

Different groups (e.g. researchers, animal welfare organisations, or government agencies) are often responsible for setting up dog population management programs (48). They manage the population in three main ways: culling, long-term sheltering, and fertility control of free-roaming dogs (47,48). In addition, programs may include a focus on public education of responsible ownership and taxation of dog ownership. Different countries, as well as different regions within a country, may vary in their objectives for carrying out dog population management programs (47,48), such as: reducing the number of free-roaming dogs; increasing awareness of responsible ownership practices; or improving the health of the free-roaming dog population. These objectives may be underpinned by: dog-centric motives, such as improving dog health and welfare; human-centric motives, such as the control of zoonotic disease (47) and reduced prevalence of dog bite injuries; and wildlife-centric motives, such as reducing the risk to the conservation of other species.

2.1.2. Methods of managing dog populations

Historically, culling has been the primary method used to reduce numbers of free-roaming dogs (102). Culling is the episodic removal and killing of individuals for the purpose of population reduction. The World Health Organisation published guidelines in 1990 discouraging the use of culling and recommending alternative methods (e.g. registration and identification, vaccination, public education, and sterilisation) (103). Despite these recommendations, many countries continue to use culling as a primary method of population control (48). Injectable barbiturates are more commonly used in high- and upper-middle-income countries (48), whereas poisoning and shooting are often used in lower-middle- and low-income countries (48). National law in some countries (e.g. Bulgaria (104), Italy (105), and Kosovo (106)) prohibits the killing of dogs for the purpose of population control.

In some countries, sheltering free-roaming dogs is the most common method of dog population control. Similar to culling, sheltering aims to reduce the free-roaming dog population size by removal of dogs. Ultimately, sheltered dogs may be: (i) euthanised; (ii) adopted; or (iii) permanently stay in the shelter. Shelters are commonplace globally and may be government-run (public shelters), privately-run, or operated by non-government organisations. The numbers of dogs coming into the shelter are often greater than the number of dogs going out, for example to be rehomed (107–109). This results in either lifelong stays in the shelter or euthanasia (107–109). As national law in some countries prohibits euthanasia of healthy animals, this can lead to long-term sheltering and overcrowding. The use of shelters to house dogs are costly and, as such, more commonly employed in high- and upper-middle-income countries (48). Due to the expense, this method may be unsuitable in lower-middle- and low-income countries (48).

Fertility control can be achieved through surgical or chemical sterilisation or contraception (110). Although surgical sterilisation is the predominant method of fertility control, there has been growing interest in nonsurgical methods, such as hormonal contraceptives and chemical sterilants (111). In particular, there has been increasing interest in the use of immunocontraceptives, such as GonaCon™ (112–114). This injectable contraceptive can be used in conjunction with the rabies vaccine and, unlike surgical sterilisation, does not require invasive surgery or anaesthesia (115). To date, few studies have been conducted on dog populations in the field (111). Surgical sterilisation through the catch-neuter-release of free-roaming dogs is the predominant method of fertility control. This method involves collecting free-roaming dogs and carrying out spay or castration surgery in either a fixed-location or mobile clinic. CNR has been carried out in several countries and states, for example in Italy (116), India (117–119), Bangladesh (120), Sri Lanka (121), and Brazil (122). Surgical sterilisation is generally more socially acceptable than culling. In some locations, there can be conflict between locals and the groups/agencies conducting CNR, as some owned free-roaming dogs are caught and neutered against their owner's wishes (123). In some communities, owners are against the surgical sterilisation of dogs due to their religious beliefs or the misunderstanding that neutering causes undesired behavioural changes (124,125). In addition, CNR has associated expense, as it requires skilled staff, clinical facilities, and medicines.

2.1.3. Study aims

A systematic review was conducted to synthesise the existing evidence of the effectiveness of different dog population management methods. In this review, I describe: (1) where and when the impact of dog population management has been assessed; (2) what management methods have been used; and (3) what effect the management method had on: (i) the dog population size; (ii) dog health and welfare; (iii) public health risk; (iv) public attitude; and (v) risk to wildlife populations. The effectiveness of dog population management depends upon the management intensity (coverage and length of management); therefore, effects in relation to these criteria wherever possible are reported. In addition, the reporting quality of the relevant published studies were evaluated to allow weighting of evidence for future decision-making.

2.2. Materials and methods

2.2.1. Search strategy

An initial literature search was conducted in February 2017, using the following search engines: Web of Science; ProQuest (Applied Social Sciences Index & Abstracts, PAIS Index, Sociological Abstracts, and Worldwide Political Science Abstracts); LILACS; and Google Scholar (results from Google Scholar were limited to the first 50 pages, due to the high volume of returned literature and lack of relevancy). The search used key words relating to dog population management (Appendix A, Table A1). A second search was carried out using the same search engines, keywords, and eligibility requirements in January 2019 to include any papers published in the interim period.

2.2.2. Eligibility requirements

A single corpus of all returned literature was compiled across the searches and cleaned of any duplications prior to filtering. Entries were filtered in three stages, based on the relevance to the study aims. These stages involved assessing the paper's: (1) title; (2) abstract; and (3) full text. At each stage, papers were included or excluded depending on their match to the following inclusion criteria: (i) one of the primary aims of the literature was to assess, describe, investigate, or compare the impact of unowned free-roaming dog population management, in terms of dog population demographics, dog health and welfare, public attitude, or public health risk; (ii) the study design was observational, intervention or modelling; and (iii) was primary literature. Papers were excluded from the review if: (i) they were not a primary research source; (ii) their study design was systematic review, meta-analysis, lab intervention, or case report; or (iii) they assessed, described, or compared only owned dogs that were not free-roaming (i.e. restricted, owned dogs). This was assessed at Stage (1) (title stage) depending on whether the title included the key words (Appendix A, Table A1) indicating that the paper met the inclusion criteria. At Stages (2) (abstract) and (3) (full text), this was assessed by whether the text met the above-stated inclusion and exclusion criteria. Studies in all languages were considered, although searches were conducted with keywords in English only. There was no restriction on date of publication.

Papers that passed through all three filtering stages were included for review and are referred to as the final corpus. At Stages (1) and (2) of the filtering process, a second reviewer assessed 3% of the papers (Stage (1) = 150 of 4629 papers and Stage (2) = 30 of

923 papers) to check the level of inter-rater inclusion/exclusion agreement. Any papers that were disagreed upon were disputed and a decision reached jointly by both reviewers (details in Appendix A).

To increase the possibility of capturing all relevant papers, references from papers in the final corpus were screened using the above three-stage filtering process. All references that matched the above inclusion/exclusion criteria were included in the final corpus.

2.2.3. Information extraction

The following information was extracted from the final corpus: (i) year of publication, country of study, and its economic status (defined by The World Bank 2019 country income classification (126)); (ii) study impact category (dog health and welfare, dog demographics, public attitude, public health, or wildlife), and dog population management method (culling, sheltering, fertility control, or a combination of methods); and (iii) methods, measurements, and study reporting quality. Reporting quality was assessed based on guidelines from Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (127) and Animals in Research: Reporting *In Vivo* Experiments (ARRIVE) (128). For the final corpus, quality was assessed based on: study design, reporting of aims/hypotheses, appropriate study outcome (as defined by (49)), and definition of study population. Study populations were classified into: (i) unowned, free-roaming; (ii) owned, free-roaming; (iii) unowned, restricted; (iv) owned restricted; (v) undefined (i.e. the paper did not report which population was under investigation); or a combination of the five categories.

2.2.4. Evaluating study design and reporting quality

Where appropriate for the study design, the study and reporting quality was assessed based on the presence/absence of a power calculation, presence/absence of a sample size calculation, inclusion of a control population, accounting for inter-observer reliability, and reporting of baseline characteristics.

2.3. Results

2.3.1. Year of publishing, country of study and economic status

The systematic review resulted in an initial (pre-filtered) corpus of 4863 papers, this was reduced following the three-stage filtering process to 36 papers (Figure 1). To ensure key papers were not missed, the references of included papers were reviewed using the same inclusion/exclusion criteria. This resulted in three additional papers and a final corpus of 39 papers. The final corpus comprised 36 peer-reviewed papers and three theses (two Masters of Science and one Masters of Veterinary Medicine). The papers were published between 1977 and 2018, with 82% published between 2008 and 2018.

Most of the studies were carried out or used data from locations within a single country (87%). These were located in 15 different countries across Africa (3%), Asia (39%), Central America (3%), Europe (18%), North America (10%), and South America (15%), in countries that were high income (27%), upper-middle income (38%), lower-middle income (32%), and low income (3%). A high proportion of the studies was conducted in India (26%) (Appendix

A, Table A2). Three studies used data from multiple countries (8%) and two studies did not specify a country (5%).

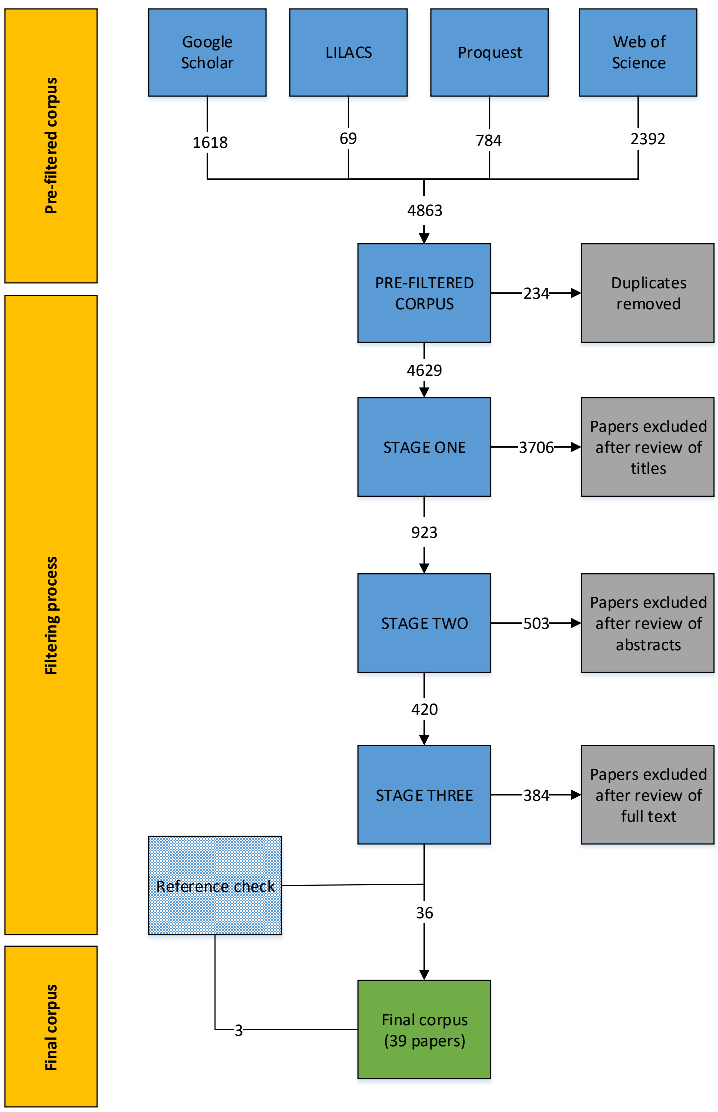

Figure 1. Number of papers included and excluded at each stage of the systematic review process. Grey boxes indicate the number excluded at each stage and the green box indicates the number of papers included in the final corpus.

2.3.2. Dog population management methods and impacts

The management methods studied in the final corpus included: fertility control through neutering and immunocontraceptives (13 papers, 33%); culling (indiscriminate culling and culling of infected dogs: (7 papers, 18%)); sheltering (2 papers, 5%); and taxation (1 paper, 3%) (Table *1*). Combinations of methods were also studied: fertility control and sheltering (9 papers, 23%); fertility control and culling (6 papers, 15%); and fertility control and movement restriction (1 paper, 3%) (Table *2*). Of the papers that involved fertility control, 79% (23 of 29 papers) controlled the fertility of both male and female dogs (Tables 3 and 4). Eight papers (21%) directly compared different methods of management: three compared fertility control and culling (8%); three compared fertility control and sheltering (8%); one compared fertility control and movement restriction (3%); and one compared different taxation methods (3%).

Table 1. Impact categories and indicators of effect used in the final corpus to evaluate the effects of management methods. Study design is indicated with either O/I indicating an observational or intervention study, or M for a modelling study. Following the indication of study design is the number of papers (denoted = n, where n is the number of papers) adopting this design to test this combination of dog population management method, indicator, and measured impact, followed by the reference details for the relevant papers.

Impact	Indicators	Fertility Control	Culling	Sheltering	Taxation	Fertility Control and Sheltering	Fertility Control and Culling	Fertility Control and Movement Restriction
Dog health and welfare	Body condition score	O/I = 3 (91,119,120)						
	Measure of dog behaviour			O/I = 1 (129)				
	Physiological stress measures					O/I = 1 (130)		

Impact	Indicators	Fertility Control	Culling	Sheltering	Taxation	Fertility Control and Sheltering	Fertility Control and Culling	Fertility Control and Movement Restriction
	Presence of injury	O/I = 1 (119)						
	Visible skin condition	O/I = 2 (91,120)						
	Dog disease prevalence (ectoparasites, viruses or bacterial infection)	O/I = 1 (119)						
	Fertility control related complications	O/I = 1 (131)						
Dog population demographics	Dog population size	O/I = 4 (117,118,132,133) M = 7 (118,134–139)	M = 3 (134,137,140)	M = 2 (136,139)	M = 1 (141)	O/I = 5 (116,122,142–144)		M = 3 (136,138,145)

Impact	Indicators	Fertility Control	Culling	Sheltering	Taxation	Fertility Control and Sheltering	Fertility Control and Culling	Fertility Control and Movement Restriction
Public attitude	Public attitude towards free-roaming dogs	O/I = 1 (146)				O/I = 1 (143)		
Public health risk	Number of human rabies cases	O/I = 2 (117,121) M = 1 (147)				O/I = 1 (144)		
	Human bite cases	O/I = 1 (148)						
	Dog rabies prevalence	M= 1 (149)	M = 3 (149–151)					
	Echinococcus granulosus prevalence in humans			O/I = 1 (34)			O/I = 1 (152)	

Impact	Indicators	Fertility Control	Culling	Sheltering	Taxation	Fertility Control and Sheltering	Fertility Control and Culling	Fertility Control and Movement Restriction
	Echinococcus granulosus prevalence in livestock			O/I = 1 (34)			O/I = 2 (152,153)	
	Echinococcus granulosus prevalence in dogs			O/I = 1 (34)			O/I = 2 (152,153)	
	Dog disease prevalence (visible skin conditions, ectoparasites, viruses or bacterial infection)					O/I = 1 (142)		
	Prevalence of visceral leishmaniasis in dogs		O/I = 2 (154,155)					

Impact	Indicators	Fertility Control	Culling	Sheltering	Taxation	Fertility Control and Sheltering	Fertility Control and Culling	Fertility Control and Movement Restriction
	Prevalence of visceral leishmaniasis in children		O/I = 1 (155)					
	Rabies R_0		M = 3 (140,156,157)					
Risk to wildlife populations	Canine distemper prevalence in wildlife populations	M = 1 (158)						

Table 2. All final corpus papers by management factors (method and intensity), study design factors, and reporting quality. Management intensity is reported in terms of coverage and length. Length is reported as years of: (i) mgmt. = management (indicating the study and management method took place at the same time) or (ii) study (indicating the study took place after management began). NA = not applicable for the study design.

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(140)	Culling	Up to 33%	Free-roaming stray, Free-roaming owned, Restricted owned	Modelling	NA	NA	NA
(150)	Culling	Various	Free-roaming stray, Free-roaming owned, Restricted owned	Modelling	NA	NA	NA

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(151)	Culling	5% and 10%	Undefined	Modelling	NA	NA	NA
(156)	Culling	Various	Free-roaming stray, Free-roaming owned, Restricted owned	Modelling	NA	NA	NA
(157)	Culling	Various	Undefined	Modelling	NA	NA	NA
(155)	Culling	C: Not reported L: first 2 years mgmt	Free-roaming stray, Free-roaming owned	Intervention	1	2 (management and control)	50% (2/4)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(154)	Culling	C: 8% L: 14 months study	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-longitudinal	1	1	20% (1/4)
(135)	Fertility control	Various (65% and above)	Free-roaming stray, Free-roaming owned, Restricted owned	Modelling and Observational-cross-sectional-single time point	NA	NA	NA
(147)	Fertility control	25 to 50%	Free-roaming stray, Free-roaming owned, Restricted owned	Modelling	NA	NA	NA

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(158)	Fertility control	Simulate a 50%, 75% and 90% reduction, but do not specify what neutering rate would achieve this	Free-roaming stray, Free-roaming owned	Modelling	NA	NA	NA
(146)	Fertility control	C: NR L: 3 years study	Free-roaming stray, Free-roaming owned, Restricted owned	Observational-cross-sectional-longitudinal	1	1	80% (4/5)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(133)	Fertility control	C: 15% of males and 31% of females L: 1.5 years mgmt	Owned (free-roaming), Owned (restricted)	Observational-cross-sectional-single time point	1	1	50% (1/2)
(131)	Fertility control	C/L: NA	Free-roaming stray, Free-roaming owned	Observational-cohort-prospective and Observational-cohort-retrospective	1	1	40% (2/5)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(148)	Fertility control	C: 65% of females L: Not reported	Free-roaming stray, Free-roaming owned	Observational-cohort-retrospective	1	1	40% (2/5)
(119)	Fertility control	C:~80% of females L: Various—17, 7, and 0 years mgmt	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-single time point	1	3 (2 CNR intensities and a control)	25% (1/4)
(118)	Fertility control	C: 62 to 87% L: 2 years mg	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-longitudinal and Modelling	6	1	20% (1/5)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(91)	Fertility control	C: Not reported L: 2 years mgmt	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-single time point	1	2 (CNR and control)	100% (3/3)
(132)	Fertility control	C: Not reported L: 12 years study	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-longitudinal	1	1	0% (0/3)
(117)	Fertility control	C: 65% of females L: 8 years mgmt	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-longitudinal and Observational-	1	1	0% (0/4)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
				cohort-retrospective			
(120)	Fertility control	C: 61% L: 2 years mgmt	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-single time point	1	2 (CNR and control)	0% (0/1)
(134)	Fertility control and culling	Various	Free-roaming stray, Free-roaming owned	Modelling	NA	NA	NA
(137)	Fertility control and culling	Various	Free-roaming stray	Modelling	NA	NA	NA
(149)	Fertility control and culling	Various	Free-roaming stray, Free-roaming owned	Modelling	NA	NA	NA

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(121)	Fertility control and culling	C: Fertility control 3% (max). Culling 10% L: 30 years study	Free-roaming stray, Free-roaming owned	Observational-cohort-retrospective	1	1	25% (1/4)
(152)	Fertility control and culling	C: Not reported L: 8 years mgmt	Free-roaming stray	Observational-cohort-retrospective	1	1	20% (1/4)
(153)	Fertility control and culling	C: Fertility control: 8%. Culling: 67% L: 4 years mgmt	Free-roaming stray	Observational-cross-sectional-longitudinal	1	1	20% (1/4)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(138)	Fertility control and movement restriction	Various	Free-roaming owned	Modelling and Observational-cross-sectional-single time point	NA	NA	NA
(136)	Fertility control and sheltering	Various	Free-roaming stray, Free-roaming owned, Restricted owned, Shelter dogs	Modelling	NA	NA	NA
(139)	Fertility control and sheltering	CNR: 20–40% more captures. Sheltering: 10% increase.	Free-roaming stray, Free-roaming owned,	Modelling	NA	NA	NA

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
			Restricted owned, Shelter dogs				
(145)	Fertility control and sheltering	Various (from 0 up to 0.2 per year)	Free-roaming stray, Free-roaming owned	Modelling	NA	NA	NA
(122)	Fertility control and sheltering	C: 88% L: 14 months study	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-longitudinal	1	2 (management and control)	67% (2/3)
(143)	Fertility control and sheltering	C/L: Not reported	Free-roaming stray, Free-roaming owned	Observational-cross-sectional-single time point	1	1	20% (1/4)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(142)	Fertility control and sheltering	C: Fertility control: 43%. Sheltered: 33% L: 9 months mgmt	Free-roaming stray, Free-roaming owned, Restricted owned	Observational-cohort-prospective and Observational-cohort-retrospective	1	1	20% (1/4)
(116)	Fertility control and sheltering	C: Not reported L: 13 years mgmt	Free-roaming stray, Free-roaming owned	Observational-cohort-retrospective	1	1	0% (0/3)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
(144)	Fertility control and sheltering	C: Fertility control: between 0.03 to 12%. Sheltering: NR L: 5 years study	Free-roaming stray, Free-roaming owned	Observational-cohort-retrospective	1	1	0% (0/2)
(130)	Fertility control and sheltering	C/L: NA	Free-roaming stray	Observational-cross-sectional-single time point	1	1	0% (0/3)
(129)	Sheltering	C/L: NA	Free-roaming stray	Observational-cross-sectional-single time point	1	2 (previously unowned	0% (0/3)

Paper	Dog Population Management Method	Management Intensity: Coverage (C) and Length (L) of Management/Study	Dog Population Type	Study Design	No. Replicates	No. Groups	Reporting Quality Indicator Score
				and Observational-cohort-retrospective		free-roaming; previously owned)	
(34)	Sheltering	C: Not reported L: 11 years mgmt	Free-roaming stray, Shelter dogs	Observational-cohort-retrospective	1	1	0% (0/4)
(141)	Taxation	NA	Free-roaming stray, Free-roaming owned, Restricted owned, Shelter dogs	Modelling	NA	NA	NA

Table 3. Results from papers in the final corpus (excluding modelling studies) of the effects of methods of dog population management on the indicators of impact and impact categories. ↑ indicates an increasing effect, ↓ a decreasing effect, and n.e. no effect; combinations of different symbols indicate where evidence is conflicting. Where p-values were reported, this is included (e.g. $p < 0.05$), NR = p-value was not reported, NS = p-value not significant. NA = not applicable for the study design. The size of effect is extracted from papers and reported in terms of the years of: (i) mgmt. = management (indicating the study and management method took place at the same time) or (ii) study (indicating the study took place after management began). Where fertility control is included in the dog population management method, (M&F) indicates fertility control was applied to both males and females, (F) indicates only female fertility was controlled. Supporting evidence is provided in references.

Impact Category	**Dog Population Management Method**	**Indicator**	**Effect**	**Country of Study**	**Management Intensity: Coverage (C) and Length (L) of Management**	**Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported**	**Sample Size**
Dog health and welfare	Fertility control	Body condition score (1–5 scale)	↑	India	C: Not reported L: 2 years mgmt	(91) (M&F) Normal body condition 1.7 (CI 1.1–2.5) times more likely in sterilised dogs (does not overlap null	888 total (439 CNR; 448 control)

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
						value, no *p*-value given). Analytical method: logistic regression models and likelihood ratio test.	
					C: ~80% of females L: Various—17, 7, and 0 years mgmt	[c] (119) (M&F) Normal body condition 13% (No CI) increase in prevalence in high management areas. (Reported significant, values not given). Analytical method: pairwise comparisons.	240 total (106 high intensity; 82 medium intensity; 101 no previous CNR)
			↓	Bangladesh	C: 61% L: 2 years mgmt	[a] (120) (M&F) Normal body condition 3% decrease in prevalence (NR).	6341

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
		Fertility control related complications	n.e.	India	C/L: NA	(131) (M&F) Incidence at: 24 h monitoring major complications 3% (2.1–3.6%); minor complications 3% (1.9–3.4%); 4-day monitoring major complications 7% (3.9–11.5%); minor complications 6% (2.8–9.6%) (NR).	2398 (2198 24 h monitoring, 200 4 day monitoring)
		Presence of injury	↓	India	C: ~80% of females L: Various—17, 7, and 0 years mgmt	[c] (119) (M&F) Decrease of 22% (No CI) in high management areas. (Reported significant, values not given).	240 total (106 high intensity; 82 medium intensity; 101 no previous CNR)

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
		Prevalence of pathogens (ectoparasites, virus and bacterial infection)	↑↓	India	C: ~80% of females L: Various—17, 7, and 0 years mgmt	[c] (119) (M&F) Canine parvovirus ↓ 6%, Canine distemper virus ↓ 9%, fleas ↓ 21%, *Ehrlichia canis* ↓32%, *Leptospira serovars* ↓28%, Infectious canine hepatitis ↓ 23%, *Brucella canis* ↑ 7% in high management areas. (Reported significant, values not given). [c] ↑ ticks > 28% (high and low fertility control p = 0.0001, high and intermediate fertility control p =	

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
						0.131) (No CIs). Analytical method: Pairwise comparisons.	
		Prevalence of visible skin conditions	↑	India	C: Not reported L: 2 years mgmt	(91) (M&F) ↑ 1.7 (CI 1.3–2.2) times more likely in sterilised dogs (*p* < 0.001). Analytical method**:** Logistic regression models and likelihood ratio test.	888 total (439 CNR; 448 control)
			↓	Bangladesh	C: 61% L: 2 years mgmt	(120) (M&F) ↓5% (NR).	6341
	Fertility control and sheltering	Physiological stress measures	↓ n.e.	Serbia	C/L: NA	(130) (F) I = immediately after transport; 24h = 24 hours after housing):	40

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
						n.e. Cortisol, Cholesterol, Triglycerides, and lymphocyte. ↓ Glucose < 0.9(mmol/l) ($p < 0.001$) I = 4.5(+/−1.0) to 24 h = 3.6(+/−1.0), ↓ Leukocyte 4(×109 cells/L) ($p < 0.01$) = 15.1(+/−5.9) to 24 h = 11.1(+/−4.8), ↓ Neutrophil 4.2(×109 cells/L) ($p < 0.001$) I = 11.8(+/−4.8) to 24 h = 7.6(+/−3.2) ↓ Leukocyte/neutrophil ratio ($p < 0.01$) I = 7.4(+/−4.2) to 24 h =	

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
						4.9(+/−2.5). Analytical method: Non-parametric Mann-Whitney U test.	
	Sheltering	Prevalence of behavioural problems	n.e.	Turkey	C/L: NA	(129) n.e. Destructive behaviour, hyper-attachment to owner, barking, aggressiveness, fearfulness, and escaping (No CI) (NS). Analytical method**:** Chi-squared.	75 total (40 previously unowned free-roaming; 35 previously owned)
Dog population demographics	Fertility control	Dog population size	↓	India	C: Not reported L: 12 years study	(132) (M&F) ↓ ~40% [b] (NR).	NA
					C: 65% of females	(117) (M&F) ↓ 28% (NR).	NA

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
					L: 8 years mgmt		
				Brazil	C: 15% of males and 31% of females L: 1.5 years mgmt	(133) (M&F) ↓12% (NR).	NA
			↓ n.e.	India	C: 62 to 87% L: 2 years mgmt	(118) (M&F) Both ↓ n.e. Decrease between 3% ($p > 0.05$) and 51% ($p < 0.05$). Analytical method: Not reported.	NA
			n.e.	Italy	C: Not reported L: 13 years mgmt	(116) (M&F) No effect (NR).	NA

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
	Fertility control and sheltering	Dog population size		Brazil	C: 88% L: 14 months study	(122) (M&F) No effect (NR). Control (area A): from 81 (66–97) to 94 (75–113). Intervention (area B): from 70 (57–84) to 81 (65–96). Analytical method: Jolly-Seber mark-recapture model.	NA
			↓	Canada	C: Fertility control: 43%. Sheltered: 32% L: 9 months mgmt	(142) (M&F) ↓ 34% ($p < 0.001$). Analytical method**:** Not reported.	NA

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
					C/L: Not reported	(143) (M&F) no quantitative data.	18
				Thailand	C: Fertility control: between 0.03 to 12%. Sheltering: NR L: 5 years study	(144) (M&F) ↓ 23% (NR).	NA
Public attitude	Fertility control	Public attitude towards perception of dog management method	n.e.	Brazil	C: NR L: 3 years study	(146) (M&F) n.e. (p = 0.774) (No CI). Analytical method: Chi-squared.	354 Pre-management; 70 post-management

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
	Fertility control and sheltering	Public attitude towards free-roaming dogs	↓	Canada	C/L: Not reported	(143) (M&F) No quantitative data.	18
Public health risk	Culling	Prevalence of visceral leishmaniasis in dogs	↓	Brazil	C: 8% L: 14 months study	(154) ↓ Between 66% and 69% (NR).	328
					C: Not reported L: first 2 years mgmt	(155) Short term: Initial decrease of ↓ 26% ($p < 0.001$). Analytical method: Chi-squared (temporal changes within areas (intervention and control), and Poisson	Intervention area: 1989–1990 = 235; 1990–1991 = 248; 1991–1992 = 70; 1992–

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
						regression for between intervention and control.	1993 = 131; and 1993 = 164. Control area = not reported.
			n.e.	Brazil	C: Not reported L: 4 years mgmt	(155) Long term: incidence not significantly different between intervention and control (p = 0.07). Analytical method: As above.	
		Prevalence of visceral leishmaniasis in children	↓	Brazil	C: Not reported. L: 4 years mgmt	(155) ↓ incidence from 12 cases/1000 inhabitants/year to 2 cases/1000 inhabitants/year (p < 0.01). Analytical method: As above.	NA

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
	Fertility control	Human bite cases	↓	India	C: 65% of females L: Not reported	[b] (148) (F) ↓ 5 bites per month (*p* < 0.001) [b]. Analytical method: Linear least squares regression.	NA
		Number of human rabies cases	↓	India	C: 65% of females. L: 10 years mgmt	(117) (M&F) ↓ 100% (NR).	NA
	Fertility control and culling	Number of human rabies cases	↓	Sri Lanka	C: Fertility control 3% (max). Culling 10% L: 30 years study	(121) (M&F) ↓ 82% (NR).	NA
		Echinococcus granulosus	n.e.	Cyprus	C: Not reported L: 8 years mgmt	(152) (F) n.e. on the number of people operated on for	NA

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
		prevalence in humans				*Echinococcus granulosus* cysts (NR).	
		Echinococcus granulosus prevalence in livestock	↓	Cyprus	C: Not reported L: 5 years mgmt	(152) (F) ↓ overall infection rate (cattle from 0.09% to 0.01%, sheep from 0.03% to 0.02%, and goats from 0.01% to 0.003%) (NR).	1,899,040 total (104,134 cattle; 885,618 sheep; and 909,288 goats)
					C: Fertility control: 8%. Culling: 67% L: 4 years mgmt	(153) (F) ↓ prevalence between 47% to 2% (depending on species and age) (NR).	Not reported
			↓	Cyprus	C: Not reported	(152) (F) ↓ 100% in dogs (NR).	2391

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
		Echinococcus granulosus prevalence in dogs			L: 6 years mgmt		
					C: Fertility control: 8%. Culling: 67% L: 4 years mgmt	(153) (F) ↓ 80% in dogs (NR).	12,213 in 1972; 3947 in 1976
	Fertility control and sheltering	Dog disease prevalence (helminths, *Isospora, Sarcocystis*, *Giardia*, *Cryptosporidiu*	n.e.	Canada	C: Fertility control: 43%. Sheltered: 33%. L: 9 month mgmt	(142) (M&F) Overall ↓ 43% ($p <$ 0.001). Analytical method: Chi-squared.	145 Pre-clinic; 95 post-clinic

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
		m, *Taenia, Echinococcus* spp, *Dirofilaria immitis, Ehrlichia canis, Borrelia burgdorferi and Anaplasma phagocytophilum*, and					

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
		Toxoplasma gondii)					
		Number of human rabies cases	↓	Thailand	C: Fertility control: between 0.03 to 12%. Sheltering: NR. L: 6 years study	(144) ↓ 15% (NR).	NA
	Sheltering	*Echinococcus granulosus* prevalence in humans	↓	Spain	C: Not reported L: 11 years mgmt	(34) ↓ 97% (NR).	NA

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Intensity: Coverage (C) and Length (L) of Management	Size of Effect and Confidence Interval (CI)/Error Estimate (EE) Where Reported	Sample Size
		Echinococcus granulosus prevalence in livestock	↓	Spain	C: Not reported L: 11 years mgmt	(34) ↓ 75% (NR).	376 in 1992; 1172 in 1999
		Echinococcus granulosus prevalence in dogs	↓	Spain	C: Not reported L: 11 years mgmt	(34) ↓ 79% (NR).	553 in 1989; 1040 in 1998

[a] Contradictory result within paper, contacted author to confirm correct results. [b] Estimated by approximating numbers from figures in paper.

[c] Alpha value for pairwise post-hoc adjusted to 0.005 to control for multiple comparisons.

Table 4. Results from only modelling papers from the final corpus of the effects of methods of dog population management on the indicators of impact and impact categories. ↑ indicates an increasing effect, ↓ a decreasing effect, and n.e. no effect; combinations of different symbols indicate where evidence is conflicting. The size of effect is extracted from papers and reported in terms of the years of modelling simulation. Supporting evidence is provided in references.

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Coverage	Size of Effect
Dog population demographics	Culling	Dog population size	↓	No specific country	Up to 33%	(140) Decreasing trend.
				North America	Various	(137) Decreasing trend.
				India	Various	(134) * ↓ 13% over 20 years.
	Fertility control	Dog population size	↓	India	62 to 87%	(118) ↓ 69% (80% neutering coverage) over 20 years.

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Coverage	Size of Effect
					Various	(134) * ↓ Between 55% and 75% over 20 years.
				Brazil	Various (65% and above)	(135) Decreasing trend.
				North America	Various	(136,137) Decreasing trend.
				Mexico	Various	(138) ↓ Between 14% and 78% (depending on neutering effort and targeting young vs. mixed age dogs) over 20 years.
				Italy	20–40% more captures.	(139) ↓ 34% over 10 years.

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Coverage	Size of Effect
			n.e.	India	62 to 87%	(118) n.e. (31% neutering coverage) over 20 years.
	Sheltering	Dog population size	n.e.	North America	Various	(136) n.e. over 30+ years
			↓ n.e.	Italy	10% increase	(139) ↓ 3% and n.e. over 10 years.
	Taxation	Dog population size	↓	No specific country	NA	(141) Decreasing trend.
	Fertility control and movement restriction	Dog population size	↓	Mexico	Various	(138) Between <18% and 73% (depending on neutering effort and

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Coverage	Size of Effect
						confinement level) over 20 years.
				Brazil	Various (from 0 up to 0.2 per year)	(145): ↓ 5% in 30 years.
				North America	Various	(136): Decreasing trend.
Public health risk	Culling	Dog rabies prevalence	↓	Parameters from multiple countries	Various	(149,150) Decreasing trend.
				Chad	5% and 10%	(151) Decreasing trend
		Rabies basic reproductive number (R0)	↓	China	Various	(156,157) Decreasing trend.
				No specific country	Up to 33%	(140) Decreasing trend

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Coverage	Size of Effect
	Fertility control	Number of human rabies cases	↓	India	25 to 50%	(147) ↓ 92% in 5 years.
		Dog rabies prevalence	↓	Multiple countries	Various	(149) Decreasing trend.
Wildlife	Fertility control	Prevalence of canine distemper in Indian foxes (*Vulpes bengalensis*)	↓	India	Simulate a 50%, 75% and 90% reduction, but do not specify what neutering rate would achieve this	(158) ↓ Between 3 fewer canine distemper spill over events per 10 years (at 50% population reduction) to 6 fewer canine distemper spill over events per 10 years (at

Impact Category	Dog Population Management Method	Indicator	Effect	Country of Study	Management Coverage	Size of Effect
						90% population reduction)

* Estimated by approximating numbers from figures in paper.

Dog population management methods were investigated in terms of the impact they have on: dog health and welfare (6 papers, 15%); dog demographics (13 papers, 33%); public attitude to free-roaming populations (3 papers, 8%); public health (16 papers, 41%); and risk to wildlife populations (1 paper, 3%) (Appendix, Table A3). To evaluate these impacts, the final corpus reported 19 different indicators of effect.

The majority of these were different indicators of dog health and welfare, and public health risk, and relatively few different indicators were used to assess dog demographics and public attitude. Considering all the reported indicators, studies used dog population size most frequently to evaluate impact (19 papers, 49%). Considering all management methods and indicators, studies most often evaluated the effect of fertility control and sheltering using dog population size as an indicator (8 papers, 21%).

2.3.3. Quality evaluation

The quality of the intervention and observational studies in the final corpus was assessed. I split the measures into two categories: those that applied to all papers (including study design, reporting of aims/hypotheses, appropriate outcome studied, and definition of study population), and those that applied to papers depending on their study design (inclusion of power calculation, sample size calculation, control population, inter-observer reliability, and reporting of baseline characteristics).

In the final corpus, 33 papers used only one study design and six papers used two different study designs within the paper (Table *2*). Papers in the final corpus used observational (i.e. observing dog population management, but not imposing the intervention themselves) (18 papers, 46%), intervention (1 paper, 3%), modelling (14 papers, 36%), a combination of observational study designs (3 papers, 8%), and a combination of observational and modelling study designs (3 papers, 8%). Of the observational study designs, seven papers used a retrospective cohort (33%), six papers used a longitudinal cross-sectional (29%), nine papers used a single time point cross-sectional approach (38%), two papers combined prospective cohort and retrospective cohort (10%), and one paper combined a single time point cross-sectional and retrospective cohort study design (5%). Papers reported various combinations of dog populations, including free-roaming owned, free-roaming unowned, restricted owned, and shelter dogs (Table *2*). Of the various combinations, 36 papers (92%) investigated both free-roaming unowned and free-roaming owned dogs. Twenty-six of these papers (72%) grouped this population as one (e.g. the free-roaming dog population) and did not distinguish between owned and unowned dogs (Appendix A, Table A3). Two papers did not define their study population (5%).

All papers in the final corpus reported their aims, with the majority aiming to understand the impact of dog population management as a primary objective and others describing methods of dog population estimation, model development, and guideline development. All papers in the final corpus used an appropriate outcome to measure the effect of dog population management (as defined by Hiby *et al.,* (2017) (49)). In the observational/intervention studies, 35% of papers did not report the management coverage and 9% did not report the length of management (Table *2*). In general, study quality was low in the observational/intervention papers. Only one study used replication (4%), only six studies investigated different groups (26%) and only four included a control population (17%). Reporting was low for both power calculations (11%) (i.e. a calculation to determine statistical power: the probability of correctly rejecting the null hypothesis) and sample size calculations (11%) (i.e. a calculation to determine the minimum sample size required to answer the study question). Where appropriate, the reporting of inter-observer reliability (71%) and baseline characteristics was high (80%). Appendix A, Table A5 outlines the results of the reporting quality indicators. Reporting quality (RQ) scores are reported in Table *2*.

2.3.4. Effects of management methods on impact categories—observational and intervention Studies

The effects of the different methods of dog population management in observational and intervention studies are summarised in Table 3.

2.3.4.1. Dog health and welfare

The impacts of fertility control alone, sheltering alone, and combined fertility control and sheltering were investigated on dog health and welfare in observational studies. No papers in the final corpus investigated the effect of culling or taxation on dog health and welfare.

Fertility control significantly increased body condition score in two of three papers. This was achieved when fertility control was implemented at an unreported coverage level over two years of management ((91) 100% RQ) and when an 80% coverage was applied to the female free-roaming dog population over both seven and 17 years of management ((119) 25% RQ). Fertility control was associated with reduced prevalence of injuries ((119) 25% RQ: 80% female coverage over seven and 17 years) and had few associated post-operative complications (between 5% and 7%, depending on the length of observation) ((131) 40% RQ). Yoak *et al.,* (2014) ((119) 25% RQ) reported that fertility control (at an unreported coverage level over two years of management) had varying effects on the prevalence of pathogens, depending on the type of pathogen. This paper compared the prevalence of various pathogens between areas where varying levels of fertility control had been applied. Whilst fertility control significantly decreased viruses and most bacteria, it significantly increased the prevalence of ectoparasites (e.g. *Rhipicephalus sanguineus*) and *Brucella canis* over the two years of management. Similarly, Totton *et al.,* (2011) ((91) 100% RQ; unreported management coverage over two years of management) found that neutered dogs were 1.7 times more likely to have a visible skin condition compared to intact dogs.

One study investigated the impact of sheltering on the post-adoptive welfare of previously free-roaming dogs. This study found no significant differences in the prevalence of behavioural problems following adoption, using the behavioural indicators “destructiveness”, “hyperattachment to owner”, “fearfulness”, “aggressiveness”, and “excessive barking” ((129) 0% RQ).

One paper in the final corpus investigated the impact of combined fertility control and sheltering on dog health and welfare. Radisavljevic *et al.,* (2017) ((130) 0% RQ) reported that neutering, transport, and housing in a new environment did not have a significant effect on physiological stress measures (Table 3).

2.3.4.2. Dog population demographics

The effects of fertility control and combined fertility control and sheltering on dog population demographics were explored through observational studies. All applied fertility control to both male and female dogs at various intensities (see Table 3) and all reported a reduction in dog population size. Totton *et al.,* (2010) ((118) 20% RQ) described different results between their study areas. These study areas had various levels of fertility control coverage. In three of their five study areas, they observed a decline in the dog population size ($p < 0.05$) (at 62%, 66%, and 67% coverage), in one they found a decreasing trend ($p > 0.05$), and in one study area they saw no effect of fertility control (87% coverage). Although different results were reported for the impact of fertility control and sheltering, one study reported a significant decrease in population size by 34% when fertility control and sheltering was applied at 43% over nine months of management ((142) 20% RQ). It is important to note that this is a particularly short period of management and these initial results may be the immediate effects of sheltering, rather than fertility control.

2.3.4.3. Public attitude

The effect of fertility control alone and fertility control and sheltering on public attitude was explored in two papers. Costa *et al.,* (2017) ((146) 80% RQ) reported no effect of fertility control on the public perception towards the effectiveness of different dog population management methods after three years of fertility control at an unspecified level of coverage. Public attitude, in this study, was quantified using a questionnaire with both open and closed questions. Boey (2017) ((143) 20% RQ) described a positive improvement of public attitude towards the presence of free-roaming dogs after fertility control and sheltering campaigns at an unspecified level of coverage and length. This was measured using qualitative data collected in interviews and discussion groups.

2.3.4.4. Public health risk

The effects of culling, fertility control, sheltering, combined fertility control and culling, and combined fertility control and sheltering on public health risk were explored in observational and intervention studies. Two papers in the final corpus investigated the effect of culling on public health risk. Both reported that culling decreased the prevalence of visceral leishmaniasis in dogs over short-term periods, but did not have a significant effect over long-term periods (at an unreported level of coverage over two years of management ((155) 50% RQ), and 8% coverage over 14 months of management ((154)

20% RQ). One study found that culling significantly decreased the prevalence of visceral leishmaniasis in children (decrease in incidence from 12 cases per 1000 people per year to 2 cases per 1000 people per year, at an unreported coverage level over four years of management) ((155); 50% RQ). Papers were in agreement that fertility control can reduce public health risk, at the investigated management intensities (see Table 3). Fertility control of 65% of females over an unspecified length of management was associated with a significant reduction in human bite cases (a decrease of five bites per month) ((148) 50% RQ). Sheltering at an unspecified level of coverage over 11 years of management was associated with a reduction in *Echinococcus granulosus* prevalence in humans, livestock, and dogs, but significance was not reported ((34) 0% RQ). The combination of fertility control and culling on public health risk was explored in three observational studies. All studies reported a reduction in *Echinococcus granulosus* prevalence in dogs and in livestock at the reported management intensities (see Table 3) but did not report significant effects. There was no effect of this management method at an unspecified level of coverage on the number of people operated on for *Echinococcus granulosus* cysts over eight years of management ((152) 20% RQ). Combined fertility control and sheltering at various management intensities was associated with a decrease in public health risk. Schurer *et al.,* (2015) ((142) 20% RQ) reported a decrease of 43% of dog parasite prevalence after nine months of population management intervention at 43% fertility control and 33% sheltering coverage.

2.3.5. Effects of management methods on impact categories—modelling studies

The effects of the different methods of dog population management in modelling studies are presented in Table *4*. The effects of methods that are directly compared within the final corpus papers are summarised in Table *5*.

Table 5. Summary of methods directly compared within papers. All papers included in the final corpus directly comparing different methods of dog population management used a modelling study design.

Methods Being Compared	Indicator	Effect		Evidence	Most Effective Method
		Fertility control	Culling		
Fertility control and culling	Dog population size	↓	↓	North America	(137) Over a shorter period (5 years), culling was a more effective strategy. Over a longer period (20 years), both methods had similar effectiveness.
				India	(134) Fertility control was more effective than culling, fertility control reduced population size by over 75%, compared to ~13% with culling over 20 years.
	Dog rabies prevalence	↓	↓	Multiple countries	(149) Culling was as effective as fertility control combined with rabies vaccination.

Methods Being Compared	Indicator	Effect		Evidence	Most Effective Method
		Fertility control	Sheltering		
Fertility control and sheltering	Dog population size	↓	↓	Multiple countries	(145) Fertility control and adoption, through sheltering, had synergistic effects. Adoption, through sheltering, was the most effective method when comparing the two.
				North America	(136) Fertility control was the most effective, although adoption, through sheltering, worked well in combination with fertility control.
		↓	↓	Italy	(139) Fertility control was the most effective, reducing dog population size by 34%, compared to only 3% in sheltering.
Fertility control and		Fertility control	Movement restriction		

Methods Being Compared	Indicator	Effect		Evidence	Most Effective Method
movement restriction	Dog population size	↓	↓	Mexico	(138) Varying size of effect relating to neutering coverage, age of dog neutering and confinement level. Fertility control of owned dogs and dog movement restriction were most effective when used together.
Different taxation methods		Taxation of dog purchases	Subsidy of dog adoption		
	Dog population size	↓	↓	No specific country	(141) Taxation of dog buyers is the most effective option at reducing the number of free-roaming dogs.

2.3.5.1. Dog population demographics

The effects of culling, fertility control, sheltering, taxation, and combined fertility control and movement restriction on dog population demographics were investigated through modelling studies. All used dog population size as an indicator of effect. Three modelling studies investigated the effect of culling on dog population demographics. All reported that culling decreased dog population size at the intensity modelled (see Table *4* for management coverage and length). Yoak *et al.*,'s (2016) (134) agent-based model simulated that culling would decrease population size by 13% over 20 years (134) at current capture rates, although the intensity required to achieve this reduction is not reported. All papers reported that fertility control reduced population size at the intensity modelled. The effect varied from a minimum decrease in population size of 14% over 20 years to 78% over 20 years, depending on the neutering coverage (138). Sheltering at the modelled intensity had little or no effect on dog population size (population decrease of 3% in 10 years (139)), or no effect (136,139)). One paper in the final corpus (141) reported that taxation of dog buyers at various intensities decreased the free-roaming dog population size. Three papers (136,138,145) explored the effect of combined movement restriction and sheltering at various modelled intensities, all reported synergistic effects but this varied from a 5% population decrease in 30 years (145) to a 73% decrease in 20 years (138).

When sheltering was directly compared to fertility control, fertility control was more effective at reducing population size (136,139). For example, Hogasen *et al.,* (2013) (139) modelled that an increase in fertility control by 20–40% per year reduced the free-roaming dog population size by 34%, compared to only a 3% reduction where sheltering was increased by 10% each year. In studies that directly compared the effects of culling to fertility control on dog population size, culling was less effective at reducing the population size. Yoak *et al.,* (2016) (134) reported that fertility control decreased population size by 75%, compared to approximately only 13% with culling when using model simulations with the same capture probability and intensity of intervention.

2.3.5.2. Public health risk

The effects of culling and fertility control on public health risk were investigated in modelling studies. All papers reported that, at various modelled intensities, culling decreased dog rabies prevalence (decreasing trend (149–151)) and rabies basic reproductive number (R_0) (decreasing trend (140,156,157)). Fertility control at the modelled intensities also decreased public health risk. Fitzpatrick *et al.,* (2016) (147) reported a reduction in the number of human rabies cases, estimating a 92% decrease in five years of model simulation when an intervention coverage between 25% and 50% was modelled. Carroll *et al.,* (2010) (149) reported that fertility control decreased the prevalence of dog rabies. The modelled intensity of fertility control required to eradicate rabies varied from maintaining 100% coverage for one month to maintaining 25% coverage for over two years. Carroll *et al.,* (2010) (149) directly compared culling to fertility control and reported culling to be just as effective at reducing dog rabies prevalence at the modelled intensities. However, when combined with rabies vaccination, fertility control was more effective than culling at eradicating dog rabies (149).

2.3.5.3. Wildlife

One modelling study investigated the effect of fertility control on disease risk to wild animal populations. Using an agent-based model, Belsare *et al.,* (2015) (158) reported that fertility control (at unspecified intensities) reduced the risk to the Indian fox (*Vulpes bengalensis*) population, using the number of canine distemper spill over events as an indicator.

2.4. Discussion

2.4.1. Limitations in assessing dog population management

This systematic review synthesises research papers investigating different dog population management methods. I determined: (1) where and when the impact of dog population management has been described in the published literature; (2) what methods were assessed and at what intensity (coverage and length of management); and (3) what effects were reported. Furthermore, I evaluated the reporting quality of the studies. Papers in the final corpus suggest that most dog population management methods were associated with some effect on the impact of interest, and mostly in a favourable direction (such as decreasing public health risk or dog population size). The interpretation of these results and assessment of the effectiveness of dog population management methods is limited due to the following reasons:

1. Few studies used a study design that would allow causation to be determined (such as intervention or certain observational studies), and many lacked an appropriate number of treatment and control groups (Appendix A, Table A5) and replication (Table 3). This makes it challenging to distinguish between changes to a population that are caused by the management method, to incidental changes caused by other factors (e.g. reduction in population numbers over a few years caused by environmental or human related factors in the study area).
2. Multiple indicators are used to assess the impact of dog population management (Table *1*). It is difficult to compare the effect of the same population management

method across different studies, and even more challenging to compare different methods across studies. This makes it difficult to carry out a formal synthesis of results, such as a meta-analysis, to report the combined evidence. For example, different papers reporting on the evaluation of different management methods did not use the same measurement of dog health and welfare. In this example, it does not make substantive sense to compare whether an increase in normal body condition scores of 13% (with fertility control) indicates a greater impact on dog health and welfare compared to a decrease in leukocyte counts by 4 (×109 cell/L) (when fertility control and sheltering are combined). This therefore makes it difficult to directly compare effects between methods.

3. Studies often investigated combinations of population management methods, such as fertility control and sheltering, and fertility control and culling. It is difficult to assess the impact of dog population management when methods are not used in isolation. Even where studies investigated one method alone, it is unclear whether other methods of dog population management were in place, such as sheltering or taxation. Culling might also be under-represented, as the method is often not reported due to lack of public acceptance (e.g. ad-hoc poisoning and drowning).

4. To effectively review the results of dog population management intervention, it is important to not only consider what method was applied, but also how the method was implemented. This means in practice that information about the intensity of management and associated costs (logistics, training, and facilities) are required in order to fully appreciate and contextualise the results. Any management method has the potential to be effective if the intensity is large enough. For example, moving 100% of the dog population into shelters every week would be much more effective than to only 15% of the population once a year. It is therefore important to consider: (i) management coverage; (ii) length of management; and (iii) cost of management

when assessing the effectiveness of different methods. Many papers in the final corpus did not provide information about the coverage of management and some did not report the length of management (Table *2*). Information about the cost of management was rarely provided, apart from where included as a parameter in modelling studies.

2.4.2. Investigated methods and reported effects of dog population management

The results of this systematic review highlight the scale and increasing interest in dog population management, which has been studied globally with an increase in the rate of publications in the last decade (Appendix A, Figure A1). In particular, fertility control was often investigated. This aligns with increasing interest over recent years in the use of fertility control to manage animal populations in general (159). Although interpretation of results from the final corpus is limited, some tentative conclusions can still be drawn about the impact of the different management methods.

Overall, papers reported that fertility control had positive effects on dog health and welfare, including improved body condition score and reduced presence of injuries and some pathogens. However, this method increased skin conditions and prevalence of ectoparasites. The positive effects on body condition and presence of injuries could be explained by the lack of sex hormones caused by fertility control. This results in a reduced desire to seek out mates, as well as reduced sexual competition, which can cause weight gain (160,161) and decrease aggression between individuals, respectively (162). Additionally, as fertility control methods (such as CNR) are often combined with vaccination and antiparasitic treatment, an improved health condition may be reflected in an improvement in body condition (91). The negative effects of fertility control on the prevalence of skin conditions could relate to the specific protocols carried out by the different population management programs, such as the conditions the dogs are kept in pre- and post-surgery and the medical treatment provided (such as antiparasitics). It is therefore important that future groups carrying out dog population management through fertility control ensure they take measures to reduce pathogen transmission in clinical facilities.

The impact of different management methods on dog population demographics was measured solely through dog population size, allowing some level of comparison between papers. The comparison is still limited, as these effects were measured across different time scales, applied at different rates (e.g. neutering coverages), and to different populations of dogs (e.g. free-roaming owned and unowned or free-roaming unowned). For example, in the observational studies, the impact of fertility control varied from decreases in population size of 12% in 1.5 years to decreases in size of 40% over 12 years. Although all methods decreased population size, fertility control had the greatest effect in both observational studies (117,118,132,133) and modelling studies (118,134–136,138,139). Fertility control decreases dog population size by preventing births, therefore allowing a reduction of numbers as natural deaths occur. This is in contrast with culling and sheltering, which reduce the population size through the removal of individuals, either through death or the moving of dogs into a shelter population. When fertility control was combined with other methods, such as movement restriction and sheltering, synergistic effects were reported (138). By increasing the rate of fertility control and restriction status of dogs, this would both reduce the opportunities for reproduction and therefore potentially reduce the birth rate even greater than if fertility control had been used alone. Culling, by increasing the death rate of a population, may cause a rapid reduction in population numbers (134,137). The culling method has been criticised as ineffective at reducing populations over longer periods of time (137). This was supported by modelling studies that directly compared fertility control and culling. These papers found that, although culling resulted in an initial decrease in dog population size (e.g. a five-year period (137)), fertility control was either more (134) or equally (137) effective at reducing the population size over longer periods of time (e.g. a 20-year period). This may be because individuals removed through culling are replaced by new individuals through compensatory breeding or migration from other locations (163), rendering the method less effective in the longer term. It is also important to note that there were no empirical studies investigating the impact of culling on population size, all were modelling studies, and therefore have limitations in the inferences that can be made to real dog populations.

Multiple different measures were reported to assess effects on public health risk, again making it difficult to compare methods directly. Culling had decreasing effects on the various indicators of public health risk in both observational (154,155) and modelling studies (140,149–151,156,157). This contradicts previous literature suggesting that culling is ineffective at controlling disease in free-roaming dogs (164,165). For the measurement “prevalence of visceral leishmaniasis”, culling only decreased prevalence over shorter study periods of up to two years (e.g. up to 69% over 14 months (154)), and had no effect over longer periods (155). This is potentially due to other mammalian disease reservoirs that would allow continued transmission of *Leishmania infantum* to the remaining dog population (155) or by the number of free-roaming dogs recovering after culling, through immigration or compensatory breeding mechanisms (163). In addition, culling decreased both dog rabies prevalence (149,150) and the basic reproductive number of rabies (140,156,157) in modelling studies. When disease control through vaccination was included in the analysis, all papers in the final corpus reported that culling was not as effective as vaccination alone (140,151,156,157) or combined vaccination and fertility control (149). The prevalence of *Echinococcus granulosus* in humans, livestock, and dogs decreased where culling was combined with fertility control (152,153). The two studies reported either large decline (153) in dog prevalence or complete eradication (152). Neither study used experimental design or statistical analysis that would allow inference to the association between the management methods and the effect. All papers in the final corpus agreed that fertility control decreased the public health risk indicators (148,149,166). The reduction in human bite cases can be linked to a reduction in sex hormones, which can in turn reduce the occurrence of aggression and dog bites (167). The impact of sterilisation on owned dog aggression has long been debated within the literature, some studies finding a reduction in aggressive behaviour and others finding no effect, or increased aggression (see McKenzie (2010) (168) for review). In terms of free-roaming dogs, Garde *et al.,*'s (2016) (169) behavioural observations in free-roaming dogs found no decrease in aggressive behaviour towards conspecifics or humans. The reduction in human bite cases reported in the findings of this systematic review may instead be due to an overall reduction in the free-roaming dog population size or a reduction in the number of puppies, therefore reducing protective behaviour of adult dogs (148).

2.4.3. Study quality and recommendations for future work

Good quality reporting of research methods and results is vitally important in understanding the validity and reliability of research findings. Additionally, research conclusions should be supported by appropriate study design and statistical modelling approaches. To improve reporting quality and study design, I suggest the following simple refinements for studies investigating the effectiveness of these dog population management approaches:

1. Increase reporting quality

Reporting guidelines are available for a number of biological areas (see (127,128,170–172)). In general, recommendations include reporting specific details about the experimental design, study subjects, statistical analyses, and modelling approaches. To increase reporting quality in studies investigating the impact of dog population management, I recommend reporting the following:

Power and sample size calculations

The reporting of power calculations (11%) and sample size calculations (11%) was low across the published papers. By not reporting this information, the value of the findings and recommendations resulting from the research are limited (128). Power and sample size calculations should be clearly reported to increase reporting quality, replicability, and confidence in results.

Defined target dog population under investigation using clear common terminology

I suggest grouping dogs into: (i) unowned, free-roaming; (ii) owned, free-roaming; (iii) unowned, restricted; and (iv) owned restricted. Reporting which target dog population is under investigation would allow the effects of dog population management to be compared between different studies and between studies in different countries. This is particularly important where the definition of dog ownership might differ, for example in areas where there are community dogs that are loosely owned.

Management intensity and cost

Papers in the final corpus often did not explicitly state the length, coverage, and cost of the applied management method. As described above, to assess management effectiveness, it is important to report the length and coverage of management (e.g. the number of dogs neutered as a percentage of the total population). Reporting management coverage requires knowledge of the dog population size and this can be achieved through methods such as mark-recapture (see (173) for review of dog population estimation methods). Conducting population estimation requires time, manpower, and expertise in study design and analysis. Dog population management is often carried out by charities and government agencies (Appendix A, Table A2) and these organisations may lack the financial and logistical power, as well as the expertise to conduct such ecological methods. This might partly explain the lack of reporting of management coverage. It is also important to consider and report the population management history in the study area, as previous management may impact the effectiveness of successive management. This information may also be difficult to access but should be reported if available.

2. Improve experimental and statistical modelling approaches

Experimental approaches

Where possible, researchers should consider their experimental approach and use an intervention (e.g. randomised control trials) or observational (e.g. cohort studies) study design that allows cause and effect to be determined, therefore allowing assessment of the true impact of dog population management. Where appropriate for the study design (i.e. intervention and analytical observational studies), appropriate numbers of groups and replication should be included, such as multiple treatment and control groups. This ensures that any effects reported are caused by the dog population management method and not by other causes (e.g. differences in population numbers between years due to differing mortality rates because of weather or other events).

Statistical modelling approaches

Due to practical, logistical, and financial constraints, studies that are observational (including cohort, cross-sectional, and case-control studies) are often the only feasible options for assessing dog population management. These studies may result in datasets that include large variability due to biological processes, sampling methods, and context (e.g. the specific country the study was conducted). Statistical modelling approaches can be used to deal with the limitations in inferring causal relationships using observational data. These include controlling for variables in statistical models or matching of additional variables. I recommend using approaches such as directed acyclic graphs (174,175) to help to identify when controlling for variables in the statistical analysis is appropriate, and what variables to control for (see (176) for primer on creating acyclic graphs, dealing with measurement error, and statistically controlling for variables). For example, in a study investigating the impact of population management on dog health, it would be appropriate to control for age of dogs, as young dogs have a different probability of developing certain health conditions than older dogs. If age were not controlled for in these analyses, the causal relationship between population management and dog health might not be observed. Additionally, process based modelling approaches have been developed to incorporate the underlying processes in the statistical analysis (177). These modelling approaches incorporate both the sampling and biological processes that create the patterns observed in the data (e.g. hidden process models (178)), leading to better interpretation of complex causal relationships, where context creates differing outcomes. An example of datasets where hidden process models could be used includes data collected about dog population size through mark–recapture methods or citizen science (178–180). This would therefore incorporate the processes involved in observing dogs (sampling process—e.g. detection probability) and the biological processes involved in the dogs being in the sampling area (biological process—e.g. the probability of migration, birth, or death). It is worth noting that these approaches require statistical and modelling knowledge that may be challenging for the organisations involved in dog population management to acquire/access.

2.5. Conclusions

This systematic review found that dog population management is conducted in many countries globally (48,49), carried out by different groups (e.g. researchers and animal welfare or government agencies), applying different methods to different populations types (restricted and unrestricted) and using different indicators to monitor the impact of the intervention. It is therefore difficult to synthesise the evidence base and assess the true impact of dog population management techniques (10,49), despite the quantity of work being conducted. Very few of the reviewed studies allowed robust conclusions to be drawn. I recommend that future studies: (i) increase reporting quality; (ii) clearly define target populations; and (iii) increase the use of study design and modelling approaches that allow causality to be determined, in order that cross-study data synthesis and learning can be conducted for a stronger evidence base to support interventions.

Chapter 3. Public attitudes towards free-roaming dogs and dog ownership practices

3.1. Introduction

Human behaviour can shape the success of a population management programme. This includes actions of local communities, the teams involved in dog population management and the governments imposing management strategies. Indeed, the World Organisation for Animal Health (OIE) has identified that understanding public attitudes is important for developing effective dog population control (98). This chapter addresses the OIE's question, assessing how the behaviour and outlook of local communities may influence the efficacy of dog population management, by gauging attitudes towards the presence of free-roaming dogs and of dog ownership practices.

An assessment of the impact of dog population management strategies must consider the extent to which owned dogs contribute to the free-roaming dog population. Unrestricted owned dogs (free-roaming owned) and abandoned dogs have been identified as sources that may increase the free-roaming dog population (98). Owned dogs can contribute to an overabundance of free-roaming dogs: (i) directly, if they are unrestricted and part of the free-roaming dog population, regardless of whether they are intact or neutered; and (ii) indirectly by increasing unowned free-roaming dog numbers if intact and owned free-roaming dogs reproduce with intact and unowned free-roaming dogs. Dog ownership practices that allow owned dogs to roam and do not prevent reproduction can hinder efforts to control free-roaming dog populations. Encouraging responsible ownership practices is therefore an important part of dog population management.

Responsible ownership is included as an objective in the OIE stray dog population control guidelines (98). The OIE defines responsible ownership as: "*When a person takes on the ownership of a dog, there should be an immediate acceptance of responsibility for the dog, and for any offspring it may produce, for the duration of its life or until a subsequent owner is found*" (98). Responsible dog ownership involves: (i) controlling reproduction through restricting the contact of intact owned dogs or through neutering; (ii) preventing risks to the health of humans, wildlife, livestock and other companion animals; (iii) disease control; (iv) relinquishing dogs responsibly if an owner can no longer house their dogs (i.e. owners should not abandon dogs to the street, but relinquishment to a shelter instead); and, where required by law, (v) registration and identification of dogs, meaning that if dogs are lost, they can be reconnected with their owners (98). Responsible dog ownership may be encouraged through legislation and education programmes.

Public attitudes can also play an important role in determining the success of dog population management. In order for interventions to be successful, there must be public support for both the management method and aims (e.g. reducing the number of free-roaming dogs). Different communities may have different attitudes towards free-roaming dogs and management methods due to culture, religion, and the specific risks to humans, wildlife, livestock and companion animals in the area. Organisations involved in dog population management should consider these factors to ensure interventions are effective. For example, free-roaming dog populations can be an important part of a community, providing protection to people and livestock (9). Where management methods aim to reduce free-roaming dog numbers, there may still be demand for dogs in a community. Reduction in numbers could result in increased movement of dogs from neighbouring communities, which has important implications for disease control (181–

183). Interventions should gauge the level of acceptance of free-roaming dogs in the area (i.e. determine whether the public prefer to have fewer free-roaming dogs in the community) and work towards a goal that benefits the community.

Prior to the commencement of dog population management intervention, local dog ownership practices and public attitudes to free-roaming dogs should be assessed, including: (i) determining ownership practices (e.g. measuring the number of free-roaming owned dogs, prevalence of neutering, and movement of dogs from owned to unowned populations through abandonment); (ii) assessing the support for management methods and aims; and (iii) identifying risk factors for dog ownership practices and attitudes. This information can inform interventions so that education campaigns can target groups who are at-risk of irresponsible dog ownership behaviours (146,184), as well as provide a baseline for evaluating the impact of interventions on human behaviour and attitudes (146).

Questionnaire surveys are frequently used to gain insight into public attitudes, opinions, behaviours, and the demographic and sociological factors associated with these. In terms of dog population management, different attitudes, opinions and behaviours about and towards dogs have been associated with responder gender (124,184–187), age (184,185,188), education (124,146,185), and previous life experiences (e.g. experience of keeping dogs in childhood) (189).

Questionnaires aiming to describe dog ownership, public attitudes and knowledge have been conducted in many countries around the world, but few published studies have been carried out in European countries (e.g. Australia (190), The Bahamas (124,184,191), Bhutan (192), Brazil (135,146,193), Bolivia (194), Cameroon (195), Ethiopia (196), Guatemala (197,198), Italy (125,199), India (200,201), Japan (202,203), Kenya (204), Mexico (205,206), Nepal (202,207), New Zealand (185), Nigeria (208), Samoa (209,210), Taiwan (189), Tanzania (211), Uganda (212), the United Kingdom (187,203), and the United States of America (213)). The aim of this study was to use a questionnaire survey to investigate public attitudes towards the management of free-roaming dogs and determine dog ownership practices in three countries where dog population management is conducted - in Bulgaria, Italy and Ukraine. By targeting three different countries, I hoped to investigate attitudes and practices in culturally distinct areas. The three study countries all have free-roaming dog populations and ongoing efforts to control the free-roaming dog population, including sheltering and CNR. In Bulgaria and Italy, the killing of dogs for the purpose of population management is prohibited (104,105), but does occur in Ukraine (123). The objectives of this study were to:

(i) Determine public attitudes towards the presence of free-roaming dogs.

(ii) Determine local ownership practices, including whether owned dogs were free-roaming, neutered, the level of dog abandonment, and the reasons for dog abandonment.

(iii) Compare the above factors with local demographic parameters (including age, gender, education level, and religious beliefs) and previous experience to determine demographic risk factors for ownership practices and attitudes towards free-roaming dogs.

3.2. Methods

3.2.1. Study design

This was a cross-sectional study, with target populations of Bulgaria, Italy, and Ukraine. The study populations were residents who use social media. Subjects were recruited through social media using an online questionnaire (Online Surveys (214)) that was open between the 8th of March 2019 and the 21st of December 2019, in languages Bulgarian, Italian, Ukrainian, and Russian. The social media outlets used to distribute the questionnaire included Facebook (215) and Twitter (216). Facebook advertising was used to increase the visibility of the questionnaire to the study population and increase the number of respondents. Facebook advertising targeted Facebook users who: (i) were recorded in their online profile as living in Bulgaria, Italy, or Ukraine; and (ii) were over the age of 18. The Facebook adverts invited participants to provide their opinion on free-roaming dogs and dog ownership practices (see appendix for English translation of adverts). Sample sizes were calculated for the three study areas, using Equation *1*. A sample size of 385 respondents per study country was necessary to provide estimates with a 5% error margin and 95% confidence interval. The questionnaires were open to all residents of Italy, Bulgaria, and Ukraine, excluding subjects under the age of 18 (filtered in the first page of the online questionnaire).

Equation 1. Sample size calculation

$$Sample\ size = \frac{\frac{z^2 \times p(1-p)}{e^2}}{1+(\frac{z^2 \times p(1-p)}{e^2 N})}$$

Where N = population size, e = margin of error, z = z-score, p = population proportion.

3.2.2. Ethics

Prior to completing the questionnaire, all participants were asked to consent to their responses being collected, stored and analysed in an anonymised form for the purpose of reports and publication. No directly identifiable information was collected; all data obtained remains anonymous. Participants were able to withdraw from the questionnaire prior to completion, but as the data was collected anonymously, participants could not withdraw after the questionnaire was submitted. This questionnaire was approved by the University of Leeds Ethical Committee (reference BIOSCI 17-003).

3.2.3. Questionnaire design

The questionnaire was developed in English and translated into Bulgarian, Italian, Ukrainian, and Russian by colleagues at the Istituto Zooprofilattico Sperimentale dell’Abruzzo e del Molise “Giuseppe Corporale” (IZSAM) (Italian) and VIER PFOTEN International (Bulgarian, Ukrainian, Russian). The questionnaire was tested prior to being distributed online to determine the time taken for completion and to identify any ambiguous questions. This was done for the Bulgarian questionnaire with colleagues at VIER PFOTEN International, in Italian with colleagues at the IZSAM and in English with colleagues at the University of Leeds. All questionnaire testing was completed with different people who did not take part in the original translation.

The questionnaire comprised closed questions regarding the subjects’ attitudes and practices towards dog ownership and free-roaming dog population control. Likert-type scales were used to estimate the level of agreement with specific questions. The questionnaire consisted of three sections: (1) socio-demographic information of the respondent; (2) ownership practices; and (3) attitudes towards the presence of free-roaming dogs and the management of the free-roaming dog population. A copy of the questionnaire in English can be found in Appendix B.

3.2.4. Data processing and analyses

Questionnaire responses were downloaded from Online Surveys (214) into a Microsoft Excel spreadsheet. As all questions were closed, there were limited answer options. This allowed simple translation, using Google Translate, back into English for analyses. Descriptive analyses of the demographics, ownership practices and attitudes of the respondents (numbers and percentages) were conducted in Microsoft Excel.

Bernoulli logistic regression models were used to test the effect of demographic parameters and respondent experience on the response variables: (i) *Neutering status*; and (ii) respondents' answers to the question *"Do you think an increase in dogs on the street should be prevented?"*. Ordinal probit models were used to test the effect of demographic parameters and respondent experience on: (i) *Roaming status*; (ii) *Do not like the presence of stray dogs around my home or work*; and (iii) respondents' answers to question "*Would you prefer to see: no stray dogs, fewer stray dogs, do not mind stray dogs, more stray dogs*" . Ordinal variables are categorical variables with a natural order, for example Likert-type scales (217). Ordinal variables are assumed to have an underlying continuous latent variable that cannot be measured directly (e.g. the attitude of a respondent). This underlying latent variable is therefore split into discrete options that can be measured (e.g. *Strongly agree* or *Agree*). The intervals between these discrete options may not be equal (i.e. not equidistant), an assumption required by metric models (218), and responses to ordinal questions may have non-normal distributions. Ordinal predictor variables can be problematic if analysed metrically, leading to Type I (false positive) and Type II (false negative) errors (219). Ordinal models deal with issues in potential non-equidistant responses and non-normal distributions.

All predictor and response variables are described in Table *6*. This thesis takes a Bayesian statistical approach throughout, as Bayesian approaches allow the uncertainty of parameter values to be quantified, are valid for all sample sizes, and are beneficial when dealing with missing data (see Dozario 2016 for discussion (220)).

3.2.4.1. Effect of parameters on dog ownership practices

Model 1 tested the effects of demographic parameters and respondent experience on neutering of owned dogs using a Bayesian Bernoulli logistic regression model. The response variable was *neutering status* with fixed effects of *gender*, *age*, *education status*, *religious belief*, *dog ownership for practical reasons* and *country* (Table *6*).

Model 2 tested the effects of demographic parameters and respondent experience on the roaming status of owned dogs using a Bayesian ordinal probit model. The response variable was *roaming status* and fixed effects were the same as for Model 1.

3.2.4.2. Effect of parameters on public attitudes

Model 3 tested the effects of demographic parameters and respondent experience on agreement to the statement *I do not like the presence of stray dogs around my home or work* using a Bayesian ordinal probit model. The response variable was *Do not like the presence of stray dogs around my home or work* and fixed effects were *dog ownership*, *gender*, *age*, *education status*, *children in household*, *threatened by dogs on street*, *been attacked by dogs on street*, *respondent or family members have been bitten by dogs on the street in last 12 months,* and *country* (Model 3).

Model 4 tested the effects of demographic parameters and respondent experience on the question *Do you think an increase in dogs on the street should be prevented?* using a Bayesian Bernoulli logistic regression model. The response variable was *Prevent street dog increase* with fixed effects the same as in Model 3.

Model 5 tested the effects of demographic parameters and respondent experience on response to the question *Would you prefer to see: no stray dogs, fewer stray dogs, do not mind stray dogs, more stray dogs* using a Bayesian ordinal probit model. The response variable was *Prefer to see dogs* with fixed effects the same as in Model 3.

To fit the statistical models using a Bayesian analysis framework, the package "**brms**" version 2.12.0 (221) was used in R version 3.6.1 (222). All models were run with four chains, each with 2000 iterations (1000 used for warmup and 1000 for sampling). Thinning was set to one. The total number of post-warmup samples was 4000. Where a response was missing (i.e. a respondent did not answer a question), the response was omitted from the statistical analysis (see Appendix B, Table B7 for number of *No response* per variable). All predictor variables were centred around the mean to allow interpretation of results (i.e. the mean was subtracted from the predictor variable from every value to centre the intercept).

Collinearity in the predictor variables was checked using the "**vif**" function in R package "**car**" (223) and values lower than three were considered not collinear. Model parameters were summarised by the mean and 95% credible intervals (CI; also known as Bayesian confidence intervals or highest density intervals; the 2.5 and 97.5 percentiles of the posterior distribution). A significant effect was determined if the 95% credible intervals of the posterior distribution did not contain zero on the log odds or probit scale. Probabilities were converted from the logit scale to the probability scale by $\exp(x) \big/ 1 + (\exp(x))$, and are converted to odds using $\exp(x)$, where χ is the posterior value on the logit scale.

Table 6. Response and predictor variables included in the statistical analyses, their description, type and levels.

Variables	Variable type	Description	Type	Levels
Age	Predictor	Self-reported age of respondent	Ordinal, but analysed as continuous	*18-24, 25-34, 35-44, 45-54, 55-64, 65-74 and 75 and above*
Children in household	Predictor	Self-reported whether respondent lives in a house with children	Categorical	*Children in household, no children in household*
Country	Predictor	Country from which the respondent answered the questionnaire	Categorical	*Bulgaria, Italy, Ukraine*
Dog ownership	Predictor	Self-reported ownership of dog	Categorical	*Dog owner, non-dog owner*
Education status	Predictor	Self-reported level of education	Ordinal, but analysed as continuous	*No education, primary, secondary, tertiary*
Gender	Predictor	Gender to which the respondent identified	Categorical	*Male*, *Female*, NA (including option *Other*)

Variables	Variable type	Description	Type	Levels
Neutering status	Response	Self-reported neutered status of owned dogs (i.e. reproduction prevented through surgical neutering)	Categorical	*Neutered, not neutered*
Reason for dog ownership practical	Predictor	Self-reported reason for dog ownership as practical	Categorical	*Practical, not practical*
Religious belief	Predictor	Self-reported religious beliefs	Categorical	*Religious, non-religious*
Threatened by dogs on the street	Predictor	Respondents level of agreement with *I feel physically threatened by dogs on the street*	Ordinal, but analysed as continuous	*Strongly disagree, disagree, neither agree nor disagree, agree, strongly agree*
Been attacked by dogs on the street	Predictor	Response to question *Have you ever been attacked by dogs in the street*?	Categorical	*Been attacked, not been attacked*

Variables	Variable type	Description	Type	Levels
Respondent or family members have been bitten by dogs on the street in last 12 months	Predictor	Response to question *Have you or your family members been bitten in the last 12 months?*	Categorical	*Been bitten, not been bitten*
Roaming status	Response	Response to roaming status of owned dogs	Ordinal, underlying this ordinal scale is a continuous latent roaming scale that cannot be measured directly	*Never, Sometimes, Always*
Do not like the presence of	Response	Respondent level of agreement with *I do not like the presence of*	Ordinal, underlying this ordinal scale is a	*Strongly disagree, disagree, neither agree nor disagree, agree, strongly agree*

Variables	Variable type	Description	Type	Levels
stray dogs around my home or work		*stray dogs around my home or work*	continuous latent agreement scale	
Prevent street dog increase	Response	Response to question *Do you think an increase in dogs on the street should be prevented?*	Categorical	*Yes, No*
Prefer to see dogs	Response	Response to question *Would you prefer to see: no stray dogs, fewer stray dogs, do not mind stray dogs, more stray dogs*	Ordinal, underlying this ordinal scale is a continuous latent preference scale	*No stray dogs, fewer stray dogs, do not mind stray dogs, more stray dogs*

3.3. Results

3.3.1. Descriptive analyses

3.3.1.1. Demographics

Respondent demographic information is summarised in Figure 2 with all data provided in Appendix B, Table B4. The numbers of respondents were: 5,434 in Bulgaria; 3,468 in Italy; and 19,323 in Ukraine. Respondents were from multiple regions within Bulgaria, Italy and Ukraine (see appendix B Tables B1 to B3). A broad range of ages between 18 and 64 were represented in all three study countries. A higher proportion of the respondents were female (over 83% in all three study countries). In Bulgaria and Ukraine, over half of the respondents considered themselves to be religious. In Italy, 42.0% of respondents considered themselves to be religious. In Bulgaria 36%, Italy 43% and Ukraine 57% of respondents lived in households with children.

3.3.1.2. Ownership practices

Ownership practices are summarised by Figure *3* and Figure 4. The main reason for dog ownership in all three study countries was for pleasure and company (Figure *3*). In Italy, a higher percentage of respondents acquired their dog from a dog shelter (38.1%), compared to in Bulgaria (9.7%) and Ukraine (9.9%). In Bulgaria and Ukraine, more respondents found their dog on the street (Bulgaria 35.5% and Ukraine 34.6%) or received their dog from friends/family (Bulgaria 32.6% and Ukraine 27.9%). More respondents in Italy answered that they prevent their dog from breeding through neutering (65.4%), compared to 40.4% in Bulgaria and 35.4% in Ukraine. When asked the reason why respondents did not prevent breeding, 37.6% of respondents in Bulgaria, 34.6% in Italy, and 13.7% in Ukraine answered: “A dog should reproduce at least once”.

When respondents were asked if they allowed their dog to roam outside unsupervised, 59.0% in Bulgaria, 92.1% in Italy and 79.4% in Ukraine responded *Never*, and 29.5% in Bulgaria, 6.3% in Italy and 16.3% in Ukraine responded *Sometimes*.

Most respondents in all study countries responded that they had never given up a dog (Figure 4). Those respondents who had given up a dog mostly answered that this was because of an *Animal behavioural problem* (Bulgaria 27.3%, Italy 36.5% and Ukraine 23.8%), or *Other* reason (Bulgaria 39.4%, Italy 57.5% and Ukraine 45.3%).

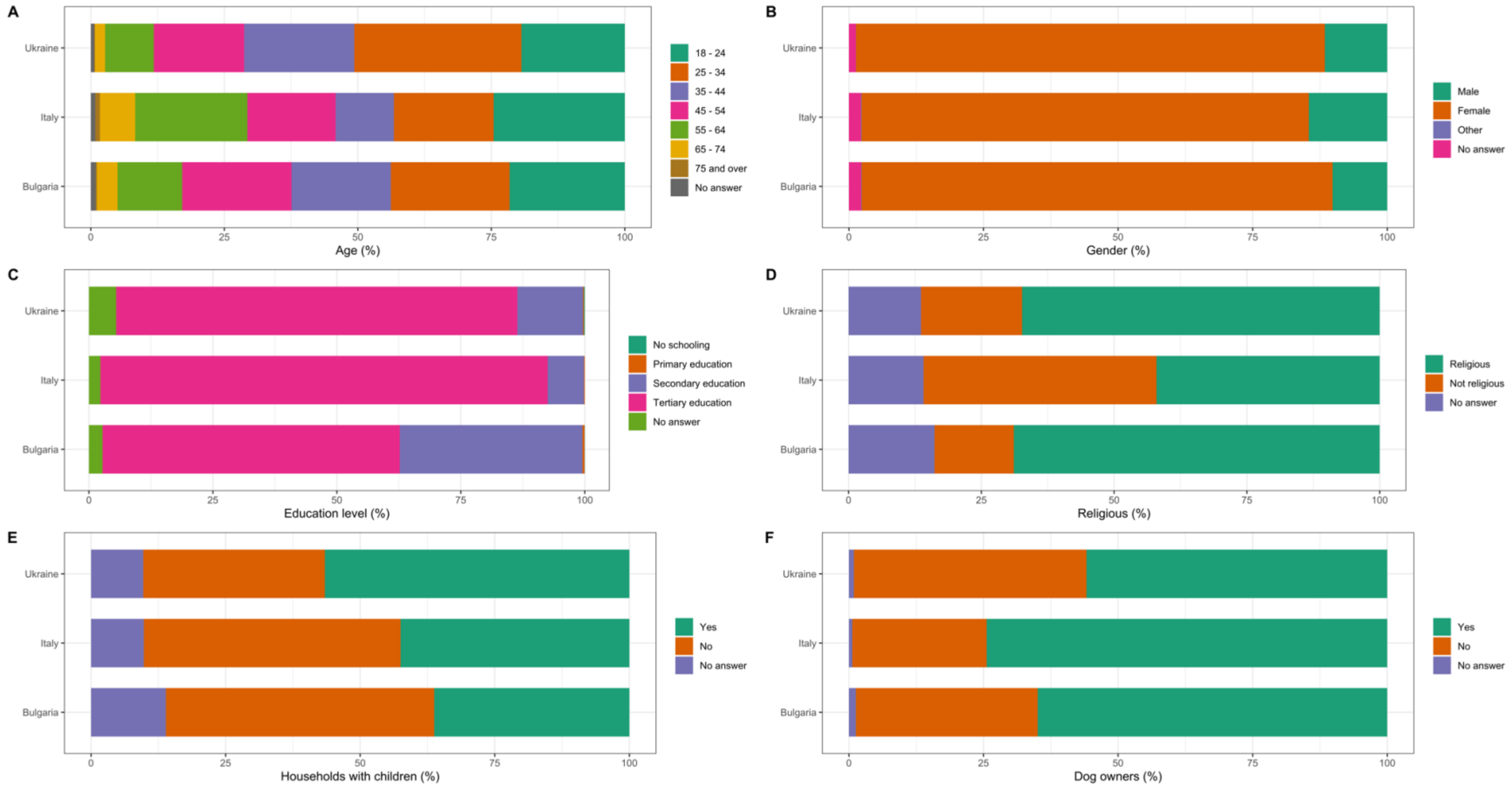

Figure 2. Demographic information for respondents in Bulgaria (n=5434), Italy (n=3468) and Ukraine (n=19323). Figures represent the percentage of respondents who answered each of the answer options regarding (A) age, (B) gender, (C) education level, (D) religious beliefs, (E) children in household, and (F) dog owners.

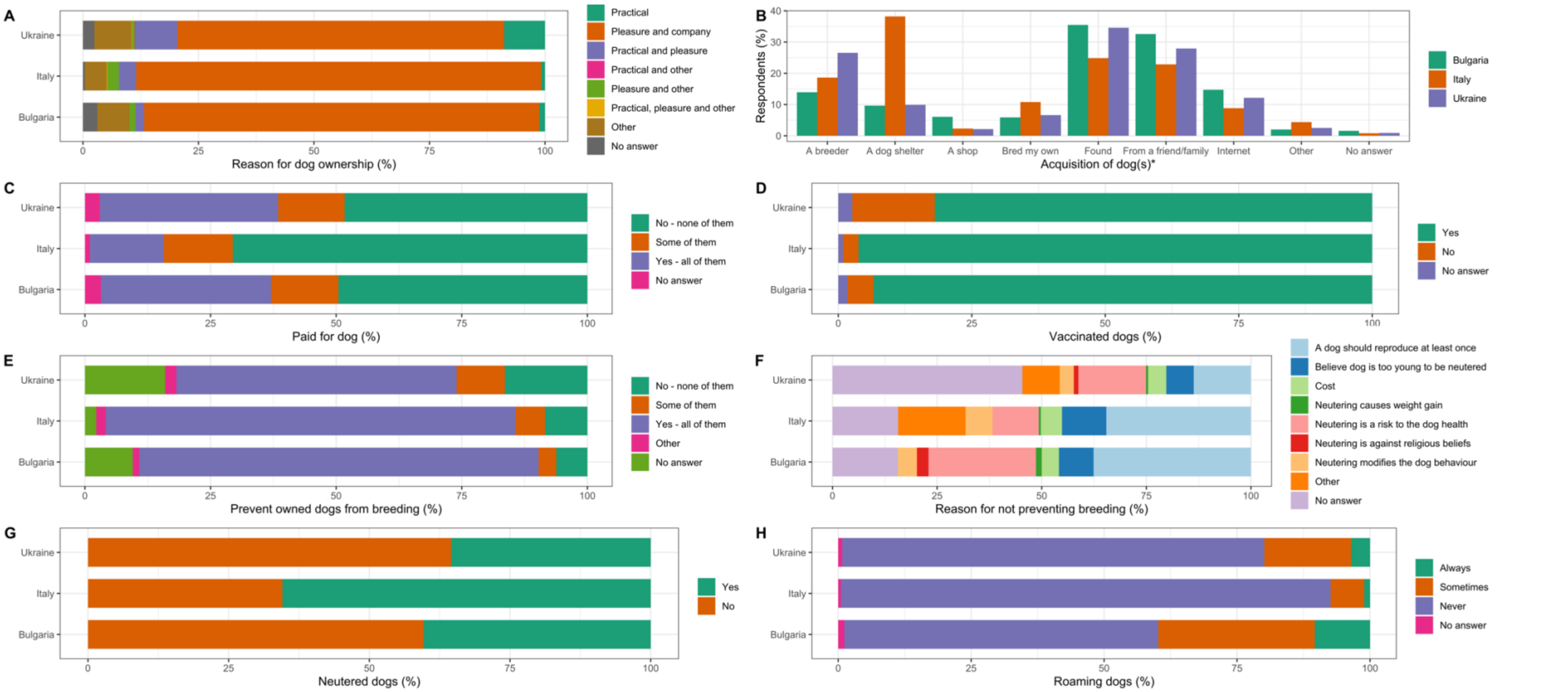

Figure 3. Ownership practices of respondents in Bulgaria (n=5434), Italy (n=3468) and Ukraine (n=19323). Figures represent the percentage of respondents who answered each of the answer options regarding (A) reason for dog ownership, (B) acquisition of dog, (C) payment of dog, (D) vaccination status of dog, (E) breeding prevention, (F) reasons for not preventing breeding, (G) neutered status, and (H) roaming status. * *Multi answer question: Percentage of respondents who selected each answer option (i.e. 100% would indicate that all respondents chose this option).*

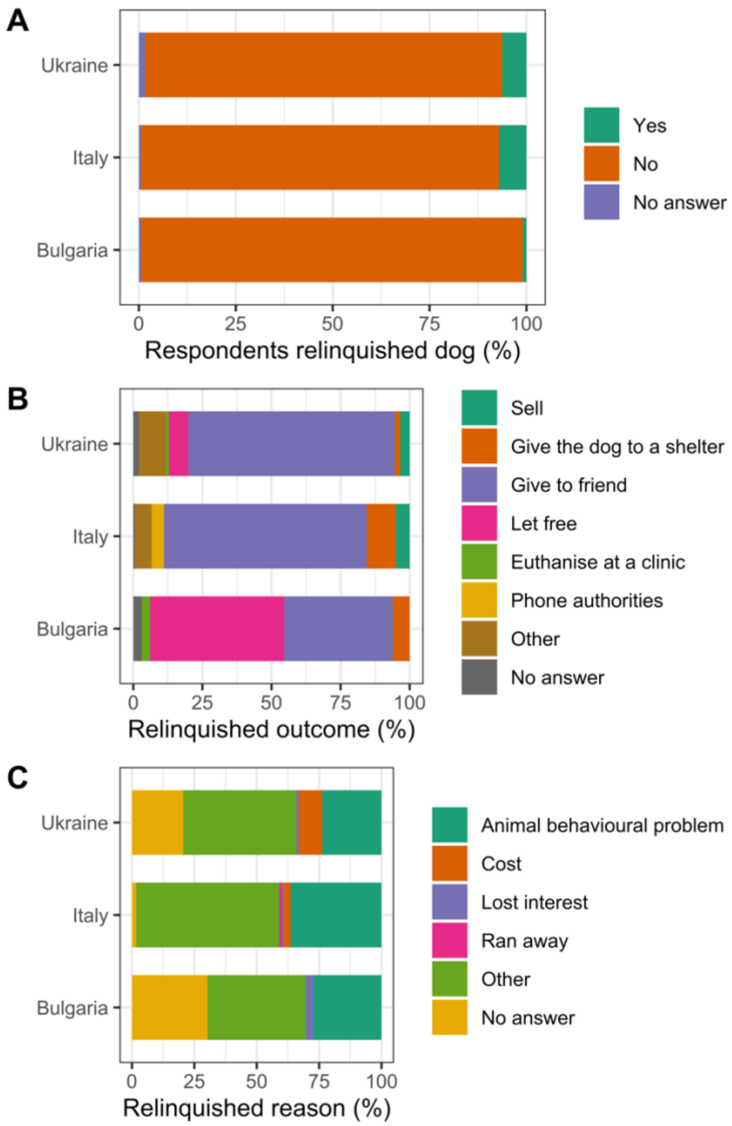

Figure 4. Ownership practices in Bulgaria (n=5434), Italy (n=3468), and Ukraine (n=19323) representing the percentage of respondents who answered each of the options regarding dog relinquishment. This includes: (A) whether respondents had relinquished a dog, (B) the outcome of the dog, (C) reason for relinquishment. All were multi answer questions: figures present percentages of respondents who selected each answer option (i.e. 100% would indicate that all respondents chose this option).

3.3.1.3. Attitudes

Responses to questions regarding attitudes towards free roaming dogs are summarised in Figure 4 and Figure *6* with all data provided in the Appendix B, Table B6. In Bulgaria and Ukraine, high percentages of respondents had seen a free-roaming dog on the day they filled in the questionnaire (73.3% and 77.3% respectively), compared to only 15.4% of respondents in Italy (Figure *5*; see Appendix B, Table B6 for detailed results). A higher percentage of respondents in Bulgaria (21.6%) and Ukraine (26.5%) had been attacked by dogs ever in their lifetime, compared to few (4.2%) in Italy. Higher percentages of respondents in Bulgaria answered that they provided care to free-roaming dogs by giving food (90.6%), water (71.0%), and shelter (34.8%), compared to Italy (53.7% food, 44.2% water, 19.0% shelter) and Ukraine (67.5% food, 29.6% water and 9.7% shelter) (Appendix B, Table B6).

When respondents were asked their level of agreement with the statement "*I do not like stray dogs being present in the streets around my home or work*", responses were varied across the full range of options between strongly disagree and strongly agree in Bulgaria and Ukraine (varying between 14 and 25% for all answer options) (Figure *5*). Most respondents in Italy disagreed with this statement (35.8%). In all three study countries, most respondents disagreed (Bulgaria 20.8%, Italy 19.3% and Ukraine 25.3%) and strongly disagreed (Bulgaria 42.2%, Italy 56.4% and Ukraine 31.6%) with the statement "*I feel physically threatened by stray dogs*".

Respondents answered most often that the municipality government and volunteer organisations should be responsible for managing the free-roaming dog population (Figure *6*; Appendix B, Table B6). Respondents most often answered that they would like to see *no* and *fewer* free-roaming dogs. Respondents who answered that they would like to see *no* or *fewer* free-roaming dogs answered that this should be achieved through sheltering, CNR, and controlling the breeding of owned dogs. Few answered that the free-roaming dog population should be reduced through culling (Bulgaria 1.7%, Italy 1.6% and Ukraine 6.3%).

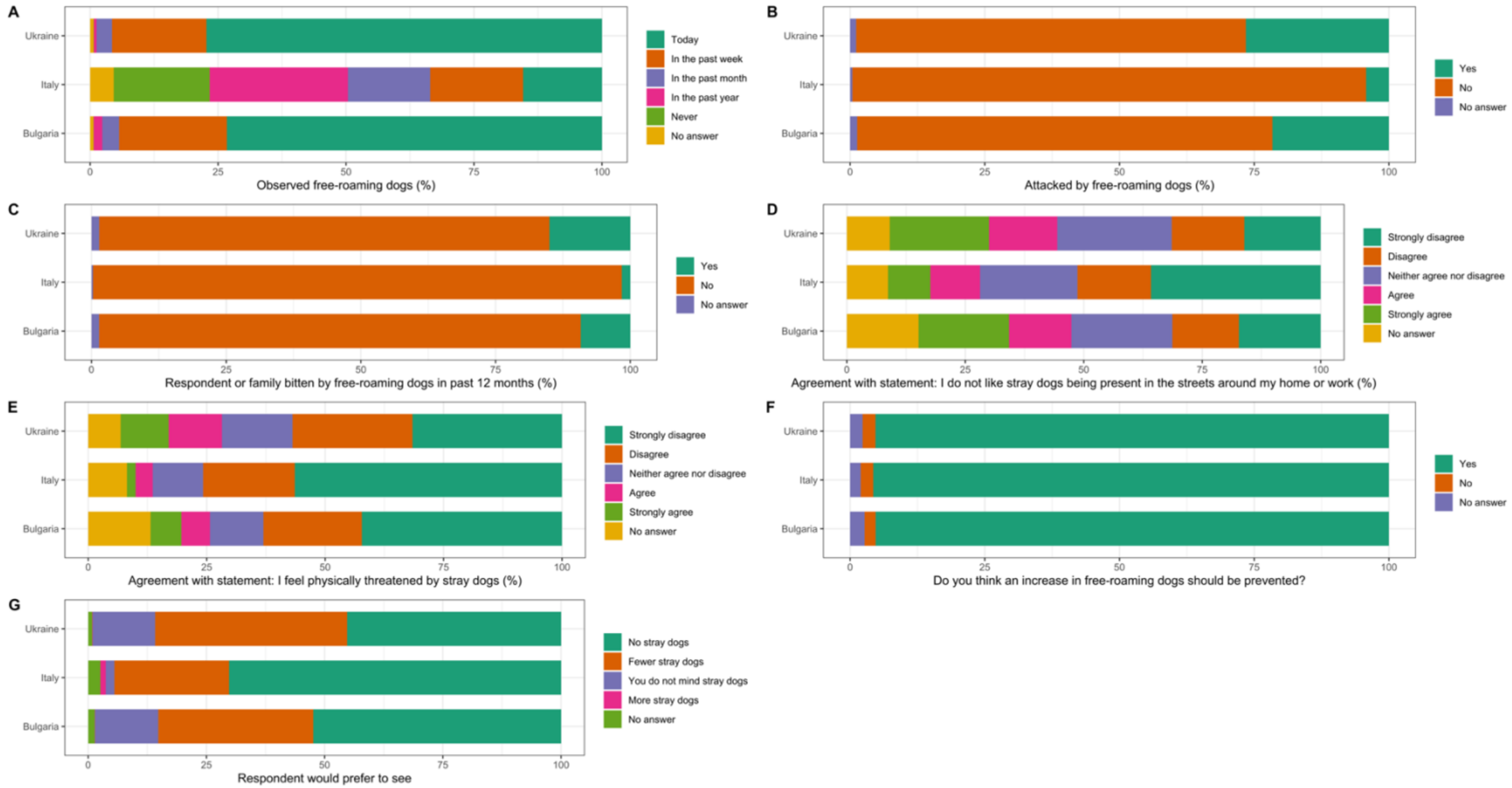

Figure 5. Attitudes of respondents towards free-roaming dogs in Bulgaria (n=5434), Italy (n=3468) and Ukraine (n=19323). Figure represents the percentage of respondents who answered each of the answer options regarding (A) observation of free-roaming dogs, (B) respondent experience previous attack by free-roaming dogs, (C) respondents or family experience bite by free-roaming dogs in past 12 months, (D) agreement with

statement “*I do not like stray dogs being present around my home or work*”, (E) agreement with statement “*I feel physically threatened by stray dogs*”, (F) preventing an increase in free-roaming dogs, and (G) preference to observing free-roaming dogs.

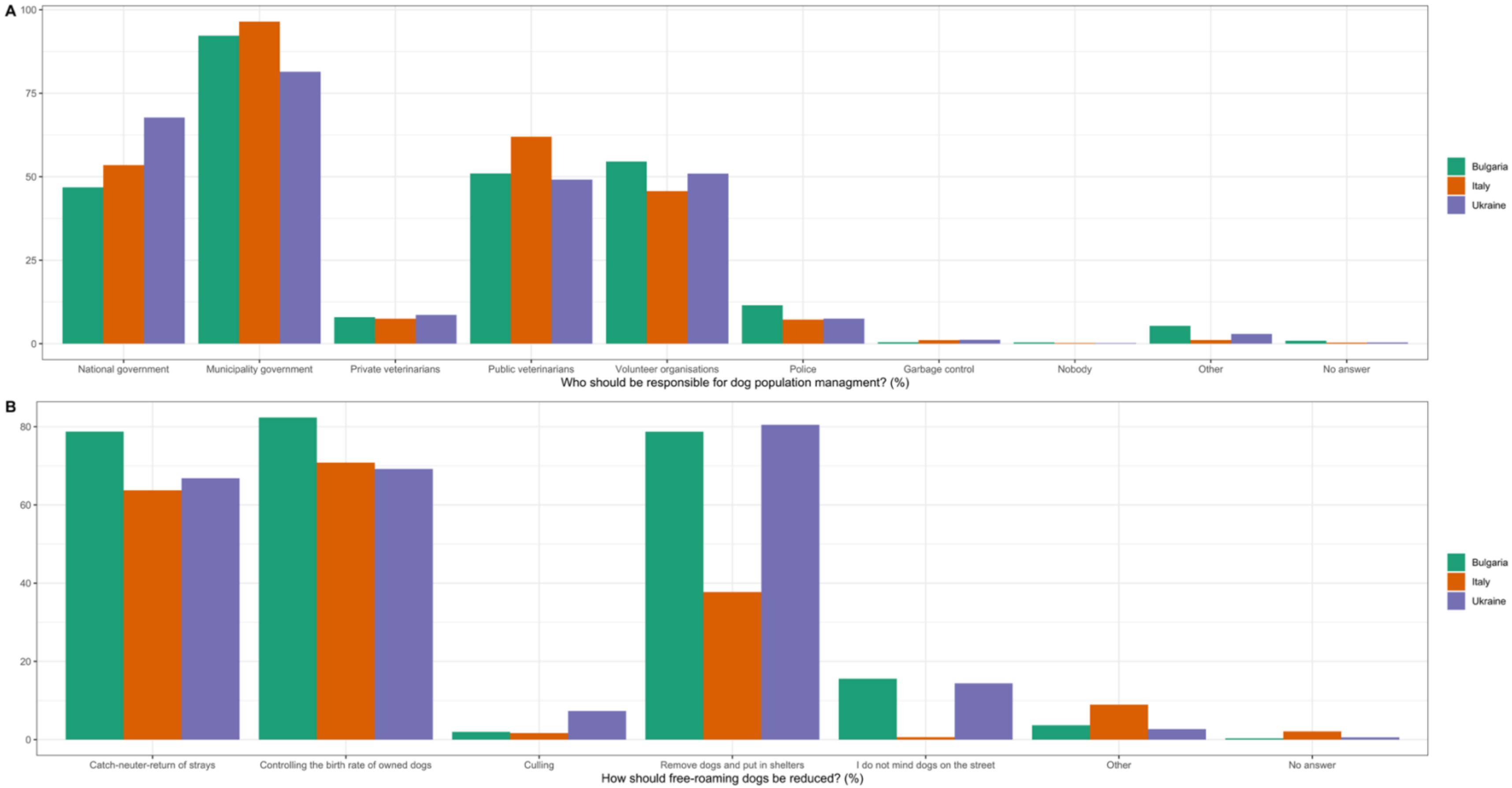

Figure 6. Attitudes of respondents in Bulgaria (n=5434), Italy (n=3468) and Ukraine (n=19323) representing the percentage of respondents who answered each of the answer options regarding dog population management. Answer to questions: (A) who should be responsible?; and (B) how should free-roaming dogs be reduced?. These were multi answer questions: Percentage of respondents who selected each answer option (i.e. 100% would indicate that all respondents chose this option).

3.3.2. Statistical analyses

All models converged (for all parameters Rhat = 1.00 and effective sample size >1000, see Appendix B). There was no collinearity in the predictor variables (all values less than three). All raw model results are presented in the Appendix B Tables B8 to B12. Estimates for mean and 95% CI's for probabilities are reported for each model and presented in Table *7*. Odd ratios (OR) are reported for predictor variables in the Bernoulli logistic regression models (Models 1 and 4).

3.3.2.1. Model 1: Effect of demographic parameters on neutering status of owned dogs

The posterior mean values, standard deviations and 95% credible intervals (95% CI, the 2.5% and 97.5% percentiles of the posterior distribution) for the raw results of Model 1 are presented in the Appendix B, Table B8. *Gender*, *age*, e*ducation level*, *reason for dog ownership practical*, *religious beliefs* and *country* had significant effects on *neutering status* (Appendix B, Table B8). Probabilities of neutering are presented in Table *7*. Male respondents had a lower probability of neutering, compared to females (OR 1.47; 95% CI 1.28-1.64). Holding religious beliefs (OR 0.66, 95% CI 0.61 to 0.72) and owning dogs for practical reasons (i.e. guarding or hunting, compared to for pleasure and company; OR 0.49, 95% CI 0.43 to 0.54) were both negatively associated with neutering. Respondent age (OR 1.15; 95% CI 1.12-1.18) and education level (OR 1.29; 95% CI 1.17-1.41) were both positively associated with neutering (i.e. the older and more educated a participant, the more likely they were to neuter). Respondents from Italy had a higher probability of neutering compared to Bulgaria (OR 2.32; 95% CI 2.05-2.62) and Ukraine (OR 2.73; 95% CI 2.44-3.01). Respondents from Ukraine had a lower probability of neutering compared to Bulgaria (OR 0.37; 95% CI 0.33-0.40).

3.3.2.2. Model 2: Effect of demographic parameters on roaming

The posterior mean values, standard deviations and 95% credible intervals for the raw results of Model 2 are presented in the Appendix B, Table B9. *Gender*, *age*, *education level*, *reason for dog ownership practical*, *religious beliefs* and *country* had significant effects on *roaming status* (Appendix B, Table B9). Probabilities of answering *Never* allow dog to roam for predictor variables are presented in Table *7*. Females had a higher probability of answering that they *Never* allowed their dog to roam. Both respondents who held religious beliefs, and respondents who owned dogs for practical reasons were less likely to answer *Never*. Age of respondent was positively correlated with answering *Never* (i.e. older respondents were less likely to allow their dog to roam; *Figure 7*). Increasing the education level of the owner was positively associated with answering *Never* (i.e. respondents with higher levels of education were less likely to allow their dog to roam; *Figure 7*). Respondents from Italy had the highest probability of answering *Never*, respondents in Bulgaria had the lowest probability of answering *Never*.

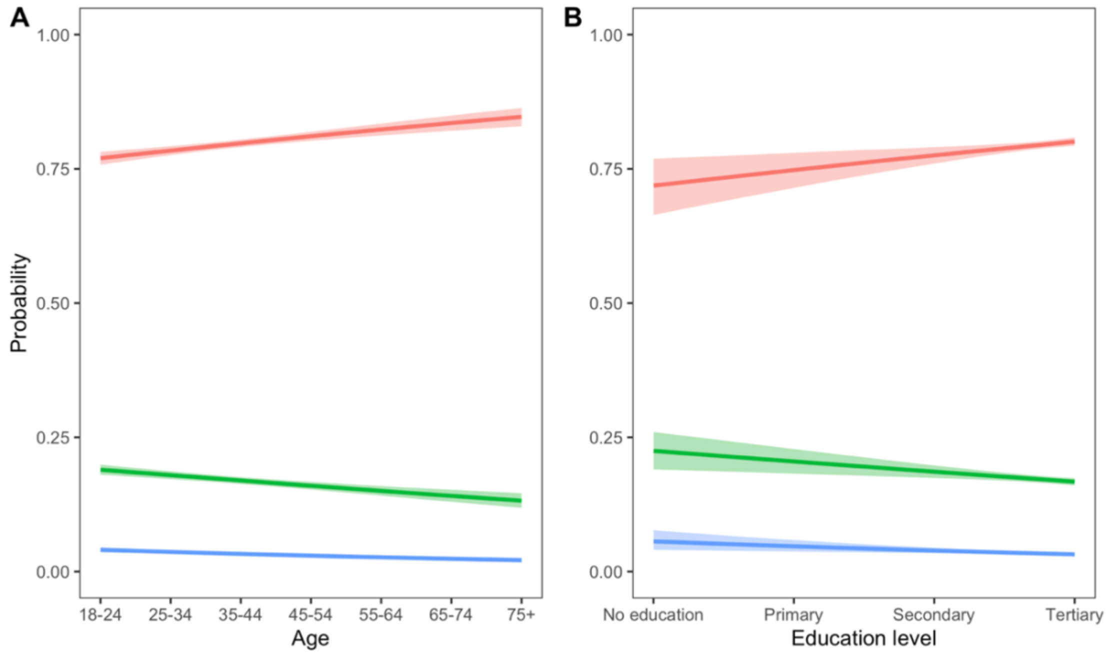

Figure 7. The effect of predictor variables (A) age and (B) education level on the probability of answering that dog(s) are allowed to roam: *Never* (red), *Sometimes* (green) and *Always* (blue).

3.3.2.3. Model 3: Effect of demographic parameters and respondent experience on “Do not like stray presence around home or work”

The posterior mean values, posterior standard deviations and 95% credible intervals for the raw results of Model 3 are presented in the Appendix B, Table B10. Predictor variables *gender*, *age*, *reason for dog ownership practical*, *threatened by dogs on the street*, *been attacked by dogs on the street, respondent or family members have been bitten by dogs on the street in last 12 months*, and *country* had significant effects on agreement with the statement *I do not like the presence of stray dogs around my home or work.* Probabilities for answering *Strongly agree* for predictor variables are presented in Table *7*. Female respondents had a decreased probability of agreeing with the statement. Respondents who answered *Yes* to the question *Have you ever been attacked by dogs on the street?* had an increased probability of agreeing with the statement. Respondents who answered *Yes* to the question *Have you or your family members been bitten in the last 12 months?* had an increased probability of agreeing with the statement. Respondent age was positively associated with agreement to the statement (i.e. older respondents were more likely to agree; Figure *8*). Agreement with the statement *I feel physically threatened by dogs on the street* was positively associated with agreement with the statement *I do not like the presence of stray dogs around my home or work* (i.e. respondents who felt threatened were more likely to agree with the statement that they did not like the presence of dogs around their home or work; Figure *8*). Respondents from Italy had the lowest probability of answering *Strongly* agree, and respondents from Bulgaria had the highest probability of answering *Strongly* agree.

There was no evidence of an effect of: *dog ownership*, *education level*, and *children in household* on agreement with the statement *I do not like stray dogs present around my home or work* (Appendix B, Table B10).

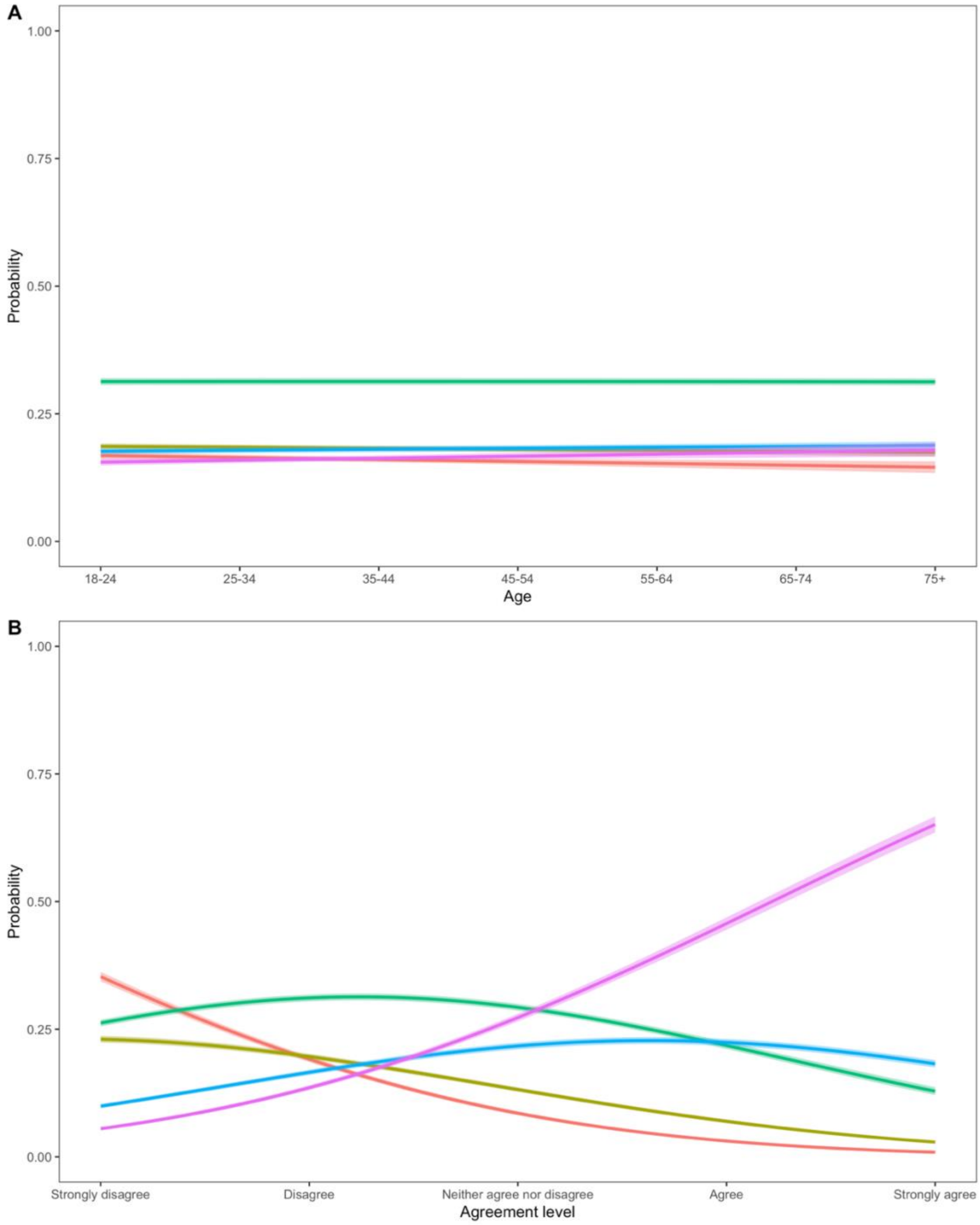

Figure 8. Effect of predictor variables (A) age; and (B) agreement with the statement *I feel physically threatened by dogs;* on probability of answering *Strongly disagree* (red), *Disagree* (yellow), *Neither agree nor disagree* (green), *Agree* (blue), and *Strongly agree* (purple) to the statement *I do not like stray dogs present around my home or work*.

3.3.2.4. Model 4: Effect of demographic parameters and respondent experience on believing an increase in stray dogs should be prevented.

The posterior mean values, posterior standard deviations and 95% credible intervals for the raw results of Model 4 are presented in the Appendix B, Table B11. There were significant effects of *gender*, *age*, *education level*, *threatened by dogs on the street*, and *country* on answering *Yes* to the question *Do you think an increase in dogs on the street should be prevented?.* Female respondents had a higher probability of answering *Yes* (OR 2.14; 95% CI 1.67-2.65). There was a positive association between respondents' agreement with the statement "*I feel physically threatened by dogs on the street*" (OR 1.53; 95% CI 1.37-1.68); age (OR 1.11; 95% CI 1.03-1.19); and education (OR 1.54; 95% CI 1.24-1.83) and answering *Yes*. There was a small but significant effect of country on respondents answering *Yes"*. The probability of answering *Yes* was higher in Bulgaria than in Italy (OR 1.28; 95% CI 0.88-1.74). The probability of answering *Yes* was lower in Ukraine than in Italy (OR 0.86; 95% CI 0.63-1.10).

There was no evidence of an effect of *dog ownership*, *children in household*, *been attacked by dogs on the street,* or *respondent or family members have been bitten by dogs on the street in last 12 months* (Appendix B, Table B11).

3.3.2.5. Model 5: Effects of demographic parameters and respondent experience on the question "Would you prefer to see: no stray dogs, fewer stray dogs, do not mind stray dogs, more stray dogs"

The posterior mean values, posterior standard deviations and 95% credible intervals for the raw results of Model 5 are presented in the Appendix B, Table B12. *Dog ownership*, *gender*, *age*, *threatened by dogs on the street*, *been attacked by dogs on the street,* *respondent or family members have been bitten by dogs on the street in last 12 months*, and *country* had significant effects on response to this question regarding preference for observing stray dogs. Probabilities for answering *No stray dogs* for predictor variables are presented in Table *7*. Male respondents had a lower probability of answering *No stray dogs* (Table *7*). Dog owners had a higher probability of answering *No stray dogs*. Respondents who answered *Yes* to the question "*Have you ever been attacked by dogs on the street?*", or *Yes* to the question "*Have you or your family members been bitten in the last 12 months*", or had children in their household had a higher probability of answering *No stray dogs*. Agreement with the statement "*I feel physically threatened by dogs on the street*" was positively correlated with answering *No stray dogs* (i.e. respondents who feel threatened by dogs on the street are more likely to answer *No stray dogs;* Figure *9*). Respondent age was positively correlated with answering *No stray dogs* (i.e. older respondents had an increased probability of preferring to see *No stray dogs;* Figure *9*). Respondents in Italy had the highest probability of answering *No stray dogs*, and respondents in Ukraine had the lowest probability of answering *No stray dogs*.

There was no evidence of an effect of *children in household* and *education level* on the probability of preference of observing stray dogs (see Appendix B, Table B12).

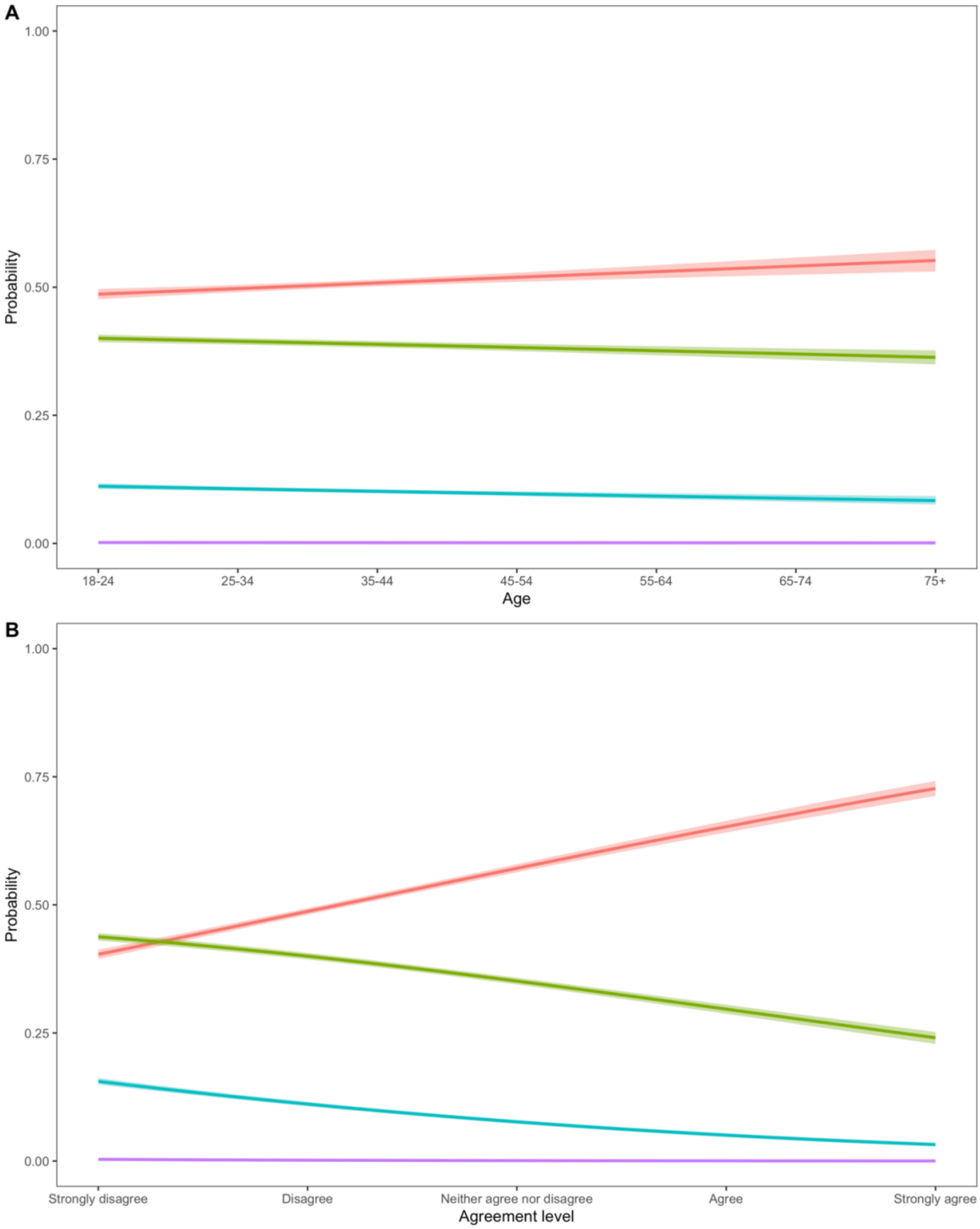

Figure 9. Effect of predictor variables (A) age; and (B) agreement with the statement *I feel physically threatened by dogs;* on probability of answering *No stray dogs* (red), *Fewer stray dogs* (green), *I don't mind stray dogs* (blue), and *More stray dogs* (purple).

Table 7. Effect of predictor variables on statistical models on the probability scale. Significant results are highlighted in bold.

Predictor variable		Model 1	Model 2	Model 3	Model 4	Model 5
		Probability of neutering (95% CI)	Probability of answering *Never* allow dog to roam (95% CI)	Probability of answering *Strongly agree* (95% CI)	Probability of answering *Yes* to the question "*Should an increase in stray dogs be prevented*" (95% CI)	Probability of answering *No stray dogs* (95% CI)
Gender	Male	**0.38 (0.35 to 0.41)**	**0.74 (0.71 to 0.76)**	**0.17 (0.16 to 0.18)**	**0.97 (0.96 to 0.97)**	**0.53 (0.51 to 0.55)**
	Female	**0.48 (0.47 to 0.49)**	**0.81 (0.80 to 0.82)**	**0.15 (0.14 to 0.15)**	**0.98 (0.98 to 0.99)**	**0.60 (0.59 to 0.61)**
Religious belief	Religious	**0.44 (0.43 to 0.45)**	**0.79 (0.78 to 0.80)**	-	-	-

Predictor variable		Model 1	Model 2	Model 3	Model 4	Model 5
	Non-religious	**0.54 (0.52 to 0.56)**	**0.83 (0.82 to 0.85)**	-	-	-
Reason for dog ownership	Practical	**0.31 (0.28 to 0.33)**	**0.71 (0.69 to 0.74)**	-	-	-
	Non-practical	**0.48 (0.47 to 0.49)**	**0.81 (0.80 to 0.82)**	-	-	-
Been attacked by dogs on the street	Attacked	-	-	**0.16 (0.15 to 0.17)**	0.98 (0.98-0.99)	**0.61 (0.59 to 0.62)**
	Not attacked	-	-	**0.15 (0.14 to 0.15)**	0.98 (0.98-0.99)	**0.59 (0.58 to 0.59)**
Respondent or family members have been bitten by dogs on the	Bitten	-	-	**0.19 (0.18 to 0.21)**	0.98 (0.98-0.99)	**0.65 (0.63 to 0.67)**
	Not bitten	-	-	**0.15 (0.14 to 0.15)**	0.98 (0.98-0.99)	**0.58 (0.57 to 0.59)**

Predictor variable		Model 1	Model 2	Model 3	Model 4	Model 5
street in last 12 months						
Dog ownership	Dog owner	-	-	0.15 (0.15-0.16)	0.98 (0.98-0.99)	**0.59 (0.59 to 0.60)**
	Not dog owner	-	-	0.15 (0.14-0.16)	0.98 0.98-0.99)	**0.56 (0.55 to 0.57)**
Children in household	Children in household	-	-	0.15 (0.15-0.16)	0.98 (0.98-0.99)	**0.585 (0.58 to 0.60)**
	No children in household	-	-	0.15 (0.14-0.15)	0.98 (0.98-0.99)	**0.593 (0.57 to 0.59)**
Age	18-24	**0.40 (0.39 to 0.42)**	**0.78 (0.76 to 0.79)**	**0.14 (0.14 to 0.15)**	**0.980 (0.977 to 0.984)**	**0.57 (0.56 to 0.58)**
	25-34	**0.44 (0.43 to 0.45)**	**0.79 (0.78 to 0.80)**	**0.15 (0.14 to 0.15)**	**0.982 (0.980 to 0.985)**	**0.58 (0.57 to 0.59)**
	35-44	**0.47 (0.46 to 0.48)**	**0.80 (0.80 to 0.81)**	**0.15 (0.15 to 0.16)**	**0.984 (0.982 to 0.986)**	**0.59 (0.58 to 0.60)**

Predictor variable		Model 1	Model 2	Model 3	Model 4	Model 5
	45-54	**0.51 (0.49 to 0.52)**	**0.82 (0.81 to 0.83)**	**0.16 (0.15 to 0.16)**	**0.985 (0.983 to 0.988)**	**0.60 (0.59 to 0.61)**
	55-64	**0.54 (0.52 to 0.56)**	**0.83 (0.82 to 0.84)**	**0.16 (0.15 to 0.17)**	**0.987 (0.984 to 0.989)**	**0.61 (0.60 to 0.63)**
	65-74	**0.57 (0.55 to 0.59)**	**0.84 (0.83 to 0.86)**	**0.16 (0.15 to 0.17)**	**0.988 (0.985 to 0.991)**	**0.62 (0.61 to 0.64)**
	75+	**0.61 (0.58 to 0.63)**	**0.85 (0.84 to 0.87)**	**0.17 (0.15 to 0.18)**	**0.989 (0.985 to 0.993)**	**0.63 (0.61 to 0.65)**
Education level	No education	**0.30 (0.24 to 0.35)**	**0.73 (0.67 to 0.78)**	0.14 (0.12-0.16)	**0.95 (0.92 to 0.97)**	0.55 (0.51-0.60)
	Primary	**0.35 (0.32 to 0.39)**	**0.75 (0.72 to 0.79)**	0.14 (0.13-0.16)	**0.96 (0.95 to 0.98)**	0.57 (0.54-0.60)
	Secondary	**0.41 (0.39 to 0.43)**	**0.78 (0.77 to 0.80)**	0.15 (0.14-0.16)	**0.98 (0.97 to 0.98)**	0.58 (0.56-0.60)

Predictor variable		Model 1	Model 2	Model 3	Model 4	Model 5
	Tertiary	**0.48 (0.47 to 0.49)**	**0.81 (0.80 to 0.82)**	0.15 (0.15-0.16)	**0.98 (0.98 to 0.99)**	0.60 (0.58-0.60)
Threatened by dogs on the street	Strongly disagree	-	-	**0.05 (0.047 to 0.054)**	**0.973 (0.969 to 0.977)**	**0.49 (0.48 to 0.50)**
	Disagree	-	-	**0.13 (0.12 to 0.13)**	**0.982 (0.980 to 0.984)**	**0.57 (0.56 to 0.58)**
	Neutral	-	-	**0.26 (0.25 t0 0.27)**	**0.988 (0.986 to 0.990)**	**0.65 (0.64 to 0.66)**
	Agree	-	-	**0.44 (0.43 to 0.45)**	**0.992 (0.990 to 0.994)**	**0.73 (0.72 to 0.74)**
	Strongly agree	-	-	**0.64 (0.62 to 0.65)**	**0.995 (0.993 to 0.997)**	**0.79 (0.78 to 0.81)**
Country	Bulgaria	**0.41 (0.39 to 0.43)**	**0.61 (0.59 to 0.62)**	**0.20 (0.18 to 0.21)**	**0.987 (0.983 to 0.990)**	**0.55 (0.53 to 0.56)**

Predictor variable		Model 1	Model 2	Model 3	Model 4	Model 5
	Italy	**0.62 (0.60 to 0.64)**	**0.92 (0.91 to 0.93**	**0.10 (0.10 to 0.11)**	**0.983 (0.979 to 0.987)**	**0.76 (0.74 to 0.77)**
	Ukraine	**0.37 (0.36 to 0.38)**	**0.81 (0.81 to 0.82)**	**0.17 (0.16 to 0.17)**	**0.980 ()0.978 to 0.982**	**0.45 0.44 to 0.46)**

3.4. Discussion

This study quantified dog ownership practices and investigated public attitudes towards the management of free-roaming dogs in Bulgaria, Italy, and Ukraine. Risk factors for neutering, roaming and tolerance of free-roaming dog presence have been identified by comparing attitudes and dog ownership practices to demographic factors. This study found evidence for significant effects of gender, religious beliefs, age, education level, reason for dog ownership, previous experience with free-roaming dogs, and country of residence on ownership practices and attitudes (Table *7*).

3.4.1. Ownership practices

Responsible ownership is an important component of dog population management. In order to effectively target dog population management interventions, it is important to understand the level of dog ownership, level of care for owned dogs (e.g. feeding and vaccination) and prevalence of abandonment, neutering and roaming practices.

In all three study countries, the numbers of respondents who answered that they owned dogs were high (Figure 2), but within the range reported in other studies. In these previous studies, the reported percentages of dog-owning households varies greatly depending on geographic area, for example, percentages for 14 countries have been reported as between 13-88% (125,191,210–213,224,225,193,195,196,198,204–206,208). The differences in percentages between and within geographic areas may be due to urban/rural study areas (196,225), cultural differences, and the methods used to obtain these estimates. The results of this study may not necessarily reflect the true level of ownership—dog owners may have been more motivated to complete the survey—but these results indicate that dogs are popular pets in Bulgaria, Italy, and Ukraine.

There were differences in dog-acquiring behaviour between the countries. More respondents in Italy acquired their dogs from a shelter, compared to acquiring from friends or by finding a dog in the street in Bulgaria and Ukraine (Figure *3*). The differences in dog acquiring behaviour could be due to a lack of public awareness of local shelters, or perceived differences in shelter quality between the study countries. However, there is currently little research to substantiate these explanations and more work on public awareness is needed. In all study countries, many participants had adopted a dog directly from the street (Figure *3*), potentially reflecting the prevalence of free-roaming dogs in the study countries. Fewer participants in Italy paid for their dog (Figure *3*). Previous studies have suggested that dogs who are received for little cost are at increased risk of relinquishment (226). However, the number of respondents who answered that they had given up a dog was low across the study countries (Figure 4). These numbers are likely an underestimate, given the taboo around relinquishing dogs. A study by Hsu, Severinghaus and Serpell (2003) (189) found similar estimates, where 5.3% of respondents answered that they had given up a dog, however, far more respondents answered that they knew someone who had given up a dog (31.9%). This indicates that respondents may underreport relinquishment of owned dogs.

Responsible dog ownership requires that an owner provides care for a dog until they are transferred to another owner (98). Most respondents who had relinquished a dog in Italy and Ukraine reported they had given their dog to a friend (Figure 4), complying with responsible ownership. In Bulgaria, a higher percentage of respondents answered they had "*Let free*" their dog (Figure 4). Letting a dog free to the street is not considered responsible ownership and directly increases the free-roaming dog population. Previous studies have found that respondents prefer to let a dog free to the street as it offers the dog an opportunity to live, unrestricted, outside of a shelter and offers the possibility to find another owner through adoption from the street (189). Further research is required to understand why respondents in Bulgaria chose to let a dog free, instead of giving to a shelter or to another owner.

Across all countries, the level of vaccination was high, although lower in Ukraine (Figure *3*). Previous studies have found a relationship between the vaccination of owned dogs and income level (212). Ukraine has a lower income level (lower-middle income) compared to Bulgaria (upper-middle income) and Italy (high income) (126), which could partly explain the lower levels of vaccination.

Preventing the production of unwanted puppies is an important part of responsible ownership (98). Most respondents answered that they prevented their dogs from reproducing (Figure *3*); 50.8% respondents in Bulgaria, 65.3% in Italy, and 35.3% in Ukraine answered that they did so through neutering (Figure *3*). Neutering of owned dogs can prevent unwanted offspring and, if owned dogs are free-roaming, can help to prevent unowned dogs from reproducing. When respondents were asked why they did not neuter their dog, the most common answer (if one was provided) across all countries was that a dog should reproduce at least once (Figure *3*). Few respondents answered that it was for cost reasons. This contrasts with previous findings in Taiwan by Hsu, Severinghaus and Serpell (2003) (189) and Brazil by Baquero *et al.,* (2018) (135), where respondents cite cost and “too much trouble” as primary reasons for not neutering. As cost, in this study, was not found to be a primary reason that owners did not neuter their dogs, this suggests that in Bulgaria, Italy, and Ukraine, whilst low-cost or free neutering interventions may be important (213), interventions should also address owner attitudes towards reproduction, in order for interventions to have a greater impact.

This study found evidence for significant associations between country, gender, religious belief, reason for ownership, age and education level and the probability of neutering (Appendix B, Table B9). These results reflect those reported in other studies (124,146,184–187). For example, a study by Fielding (2007) in New Providence, The Bahamas (124) also found that respondents with higher levels of education were more likely to have neutered their dog. Similarly, Costa *et al.,* (2015) (146) found that respondents with higher levels of education were more likely to answer that neutering was the best way to control the overabundance of stray animals in Brazil. Respondents with higher levels of education may have a higher level of awareness of responsible ownership and the benefits of neutering, in addition to potentially having a higher income and ability to pay for neutering. Fielding, Samuels & Mather (2002) (184) also found a significant effect of owner age on neutering probability, suggesting that younger owners may have a greater desire to breed from their dog, compared to older owners. Associations between religious beliefs and neutering probability have been reported in previous studies (187,227,228). A possible explanation for this association may lie partly in the fact that the practice of neutering may be against some religious beliefs or doctrine (for example, Buddhism (229)). However, few respondents in this questionnaire answered that they were against neutering as this was against their religious beliefs (Appendix B, Table B5). Further investigation is required into the association between religious beliefs and neutering practices in the focal countries.

In this study, respondents who owned dogs for practical reasons (such as hunting or guarding) had a lower probability of neutering their dog (Table 7). This may be because of the mistaken belief that neutering will cause negative behavioural changes that would impact the dogs' working ability (124,125). As a higher proportion of the respondents in Ukraine owned dogs for practical reasons (Bulgaria 1.2%, Italy 0.8%, Ukraine 8.9%), this may contribute to the lower probability of Ukrainian respondents answering that they prevent their dog from reproducing through neutering.

Owned dogs that are free-roaming contribute to the free-roaming population directly by increasing the population size. Owned free-roaming dogs therefore contribute to the issues, such as the risks to public health (120,230) and wildlife (41,42,75–77,79,80). Efforts encouraging responsible ownership may help reduce the number of dogs roaming, and may therefore help to reduce the impacts of the free-roaming dogs on public health and wildlife (98). This study found evidence for significant effects of gender, religious beliefs, reason for dog ownership, age, education, and country, on the probability of allowing owned dogs to roam (Appendix B, Table B9). It is clear from these results that interventions should be targeted using these demographic risk factors to prevent roaming behaviour, and particularly in countries where higher percentages of owned dogs are free-roaming, such as Bulgaria and Ukraine.

The majority of respondents (59-92%) across all three countries answered that they never allowed their dogs to roam (see Appendix B, Table B5). These results are higher than those reported in the Bahamas 57% (191), Bhutan 50% (192), Cameroon 37.7% (195), Guatemala 25.7% (198), urban households in Haiti 54% (231), Kenya 19% (204), Mexico 44.9% (205), Ethiopia 15.7% (196), Tanzania 22% (211), Uganda 21.7% (212), but lower than those reported in semi-urban households in Haiti 62% (231) and Taiwan 79% (189). There was a significant effect of study country on roaming probability (Appendix B, Table B9), with respondents in Bulgaria more likely to allow their dogs to roam, compared to Italy and Ukraine. The significant effect of country may reflect differences in dog ownership behaviour and culture. Although not investigated in this study, Hsu, Severinghaus and Serpell (2003) (189) found that if, as children, respondents had dogs that were free-roaming, they were more likely, as adults, to allow their dogs to roam. Hsu, Severinghaus and Serpell (2003) (189) relate this effect to urbanisation – respondents may have lived, as children, in more rural areas where roaming behaviour was more common, and now live in urban areas but continue to allow their dogs to roam. It would be interesting to investigate these effects in other study locations.

3.4.2. Attitudes towards free-roaming dogs

In Bulgaria and Ukraine, almost no respondents answered that they had never seen a free-roaming dog, compared to 18.7% of respondents in Italy (Figure *5*). These results may indicate that the populations of free-roaming dogs are larger in Bulgaria and Ukraine. Within Italy, there are differences in dog population management: some regions permit CNR and the presence of "community dogs" (free-roaming dogs owned by the municipality), whilst other regions only permit dog population management through sheltering. Respondents living in regions that do not permit community dogs, or in regions where free-roaming dog populations are smaller, may therefore be expected to observe fewer free-roaming dogs. Higher percentages of respondents in Bulgaria and Ukraine answered that they felt threatened by free-roaming dogs, and that they or a member of their family had been bitten in the last 12 months (Figure *5*). These results may also indicate a greater free-roaming dog population size and related problems in Bulgaria and Ukraine.

A large proportion of respondents across all countries answered that they provided care for free-roaming dogs (Appendix B, Table B6). For example, 90.6% in Bulgaria, 53.7% in Italy, and 67.5% of respondents in Ukraine answered that they provided food for free-roaming dogs. For Bulgaria and Ukraine, these numbers are similar to those reported by Costa *et al.,* (2015) in Brazil, where 61.9% of respondents reported that they or their neighbours fed stray animals, and Massei *et al.,* (2017) (207) in Nepal, where 47% of respondents provided food and care for free-roaming dogs. In a previous study by Slater *et al.,* (2008) (199) in central Italy, only 5% of respondents reported that they provided care for free-roaming dogs. This is much lower than the numbers reported in this study, where 71.5% of Italian respondents answered that they provided care for free-roaming dogs. This may be explained by the potential bias in the recruitment process of this study, respondents who provide care for free-roaming dogs may also have been more motivated to complete the questionnaire. Data was collected by Slater *et al.,* (2008) using an anonymous telephone survey and had a high response rate (74%). Providing care for free-roaming dogs is controversial. Providing food may alleviate welfare issues associated with lack of nutrition in the free-roaming dog population (15,91,92), but also provides a direct source of food and, therefore, increases the carrying capacity for the free-roaming dog population.

Most respondents across all study countries felt that the municipality government and volunteer organisations should be responsible for managing free roaming dog populations, and mostly by methods such as sheltering, CNR and by controlling the breeding of owned dogs (Figure *6*). These results are similar to those found in previous studies (199,209,225). For example, a study by Ortega-Pacheco *et al.,* (2007) (225) in Yucatan, Mexico found that 52.8% of interviewed households supported the neutering of dogs for dog population management, and felt that the government and society were responsible for dog population management. The results in this study suggest there is support for dog population management through sheltering, CNR, and restricted breeding of owned dogs. Few respondents answered that culling should be used to control the free-roaming dog population (Figure *6*). These results are similar to those found by Beckman *et al.,* (2014) (209), but are much lower than results by Costa *et al.,* (2017) (146), where culling was supported by 26.8% of respondents.

As public attitudes can play an important role in determining the success of dog population management, it is important that organisations involved in dog population management gauge the level of support for reducing free-roaming dogs in the area. Across all three countries, most respondents answered that they would prefer to see fewer or no stray dogs, and that an increase in stray dogs should be prevented (Figure *5*). With regards to Italy, these responses correspond with previously reported attitudes in the Teramo province in the Abruzzo region of Italy (199). Demographic risk factors relating to public tolerance for the presence of free-roaming dogs were explored through the statistical analyses. This study found significant effects of gender, age, previous negative experience with free-roaming dogs and country on respondents' tolerance to free-roaming dog presence. These results can be used to help predict the level of tolerance of free-roaming dogs in a community.

3.4.3. Implications for future interventions

The results of this study suggest that the public in the three study countries would prefer a reduction in free-roaming dog numbers, and for this to be achieved through sheltering, CNR and responsible ownership. There is therefore support for the management interventions that are taking place in these study countries. Targeted interventions that can influence the behaviour of those less likely to practice responsible ownership may help to improve responsible ownership and reduce free-roaming dog numbers. For example, as there was evidence for significant effects of gender and age on roaming and neutering, interventions could be adapted to target men and younger people on responsible ownership practices.

Questionnaires are important tools for evaluating the impact of interventions on human attitudes and behaviour. This includes monitoring public attitudes and behaviour (such as responsible ownership) to determine whether education campaigns are having a significant effect. There have been numerous studies on public attitudes towards free-roaming dogs and dog ownership practices, but few repeated surveys to assess the effectiveness of dog population control on human attitudes and behaviour (143,146), as highlighted by the systematic review in Chapter Two. The results from this present study can be used to target interventions to those who are less likely to practice responsible ownership and the results can also be used as a baseline for monitoring the effect of dog population management interventions on dog ownership behaviours and public attitudes in Bulgaria, Italy and Ukraine.

3.4.4. Limitations of questionnaire research methods

There are limitations in using questionnaires to determine public attitudes and behaviours. The self-selection process involved in the recruitment for questionnaires can result in a biased sample of the target population, as certain members of the public may be more motivated to complete the survey, for example dog owners, or those with strong views about the subject. In this survey, as with other similarly themed surveys (199), a high percentage of the respondents were female. As responses from male members of the public were lacking, the survey results may not necessarily reflect that of the wider study population. A similarly high percentage of respondents reported to have or be in tertiary education. This is likely not representative of the wider populations. The questionnaire was also primarily advertised through social media; therefore, members of the public who do not have access to social media could have been missed. Although this is a possible limitation, social media provides opportunities to recruit a large and diverse range of participants (see (232,233) for review) and given the large sample sizes achieved in this study, the results provide a good indication of ownership practices, public attitudes, and risk factors for behaviours.

3.5. Conclusions

When planning dog population management intervention, it is important to understand how human behaviour may impact the success of an intervention. In terms of dog population management, this involves understanding how public behaviour, such as dog ownership practices, may influence intervention success, and gauging the level of public support for management intervention. This study found evidence for significant effects of demographic factors on ownership practices and public attitudes. These results can be used to inform future dog population management interventions in these countries. Interventions should consider also carrying out periodic questionnaire surveys to evaluate changes in public attitudes towards responsible ownership and the free-roaming dog population.

Chapter 4. Mark-recapture of free-roaming dog populations in Italy and Ukraine using Pollock's robust design

4.1. Introduction

Dog population management is conducted by different groups, such as government agencies, animal welfare organisations and researchers (48), often with the aim to reduce numbers of free-roaming dogs, as outlined by the results of Chapter Two (Systematic review). Free-roaming dog population size is an important indicator of the effectiveness of dog population management. Reducing population size and stabilising population turnover can lead to reductions in risks to public health (149,165), conservation of wildlife (43), and dog welfare (9,46,91).

Organisations involved in dog population management often use simple count methods (i.e. census surveys) to provide an indicator of population size (173,234). Population size can be estimated if counts include all individuals in the area (i.e. a complete census), or if methods account for imperfect detection of individuals (i.e. detection probability: the probability that if a dog is in the study area, it will be detected during the survey). Simple counts that do not include all individuals cannot provide a population estimate. Instead, simple counts can provide an indicator of population size, such as the number of dogs per length of street survey (e.g. dogs per km^2), and these can be used to track relative population trends (i.e. whether the population is increasing or decreasing) (234). This requires that detection probability and population size are uncorrelated (i.e. that detection probability does not change with changes in population size), otherwise trends may be difficult to detect.

In addition to estimating dog population size, those involved in dog population management may be interested in estimating the processes that change population size, such as the rates of recruitment into and removal from a population. Several studies have estimated rates of recruitment, removal, births, mortality, migration and dispersal for free-roaming owned and unowned dog populations (26,36,118,122,165,204,235–238). These studies mostly use household questionnaires and/or direct observation of dog populations to attain estimates. Household questionnaires take advantage of the loose ownership status of free-roaming dogs and allow monitoring of individual dogs over several years through repeated surveys of households (36,165,204,235–237). While these methods may be applicable for populations where free-roaming dogs are mostly owned, they may miss or unequally sample the part of the population that is unowned or unclaimed by dog owners. Some studies suggest that most free-roaming dogs are in some way owned (32,36,239–241). These studies have been mostly conducted in Asia and Africa, so it is unclear if this applies to all dog populations. Studies have also estimated rates of recruitment and removal through direct observations of the free-roaming dog population by using methods incorporating focal animals or censuses (26,238). Studies estimating these demographic processes have been conducted in parts of Asia (26,36,118,238), Africa (36,165,204,235,237) and South America (122,236). There is a lack of data on recruitment and removal rates for free-roaming dog populations in Europe.

Estimating the size of animal populations and the processes in which they change is a long-established research area, and multiple methods exist (97). Ultimately, methods aim to determine the underlying biological and sampling processes taking place during observations of animals to allow parameters, such as population size, to be estimated. For example, if detection probability was 1, population size could be accurately determined by simply counting all animals in a given area (i.e. censuses). In reality, detection probability is often less than 1. To provide an estimate of population size, the detection probability needs to calculated, for example using distance-sampling or mark-recapture methods with repeated observations of individuals (242). Dog population size has often been estimated using closed mark-recapture methods, such as Lincoln-Petersen and Beck methods (see Belo *et al.,* 2015 (173) for review). Closed mark-recapture methods involve only one sampling occasion where surveys are conducted over consecutive days, or a short period of time that allows for the assumption of geographic and demographic closure (i.e. no births, deaths or migration). The Lincoln-Petersen method involves only two days of surveys; dogs are marked on the first day and the proportion of dogs counted on the second day that are marked is used to determine detection probability and estimate population size (243). Beck's method is similar to that of Lincoln-Petersen, but extended to include more than two days of surveys (Figure 10; i.e. surveyors return to recapture dogs over several days of surveys within a time period that is determined short enough to allow the assumptions of geographic and demographic closure) (244).

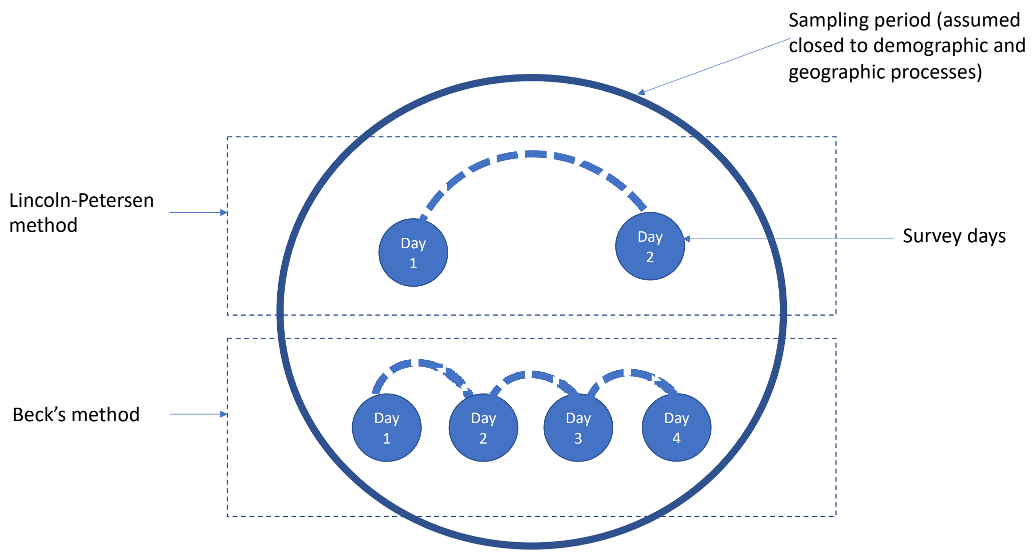

Figure 10. Example of the Lincoln-Petersen and Beck's method of mark-recapture. Both methods occur during one sampling period and assume that the population is closed to demographic and geographic processes. The Lincoln-Petersen method has only two consecutive days of surveys, whilst the Beck method has more than two (in this example, four) days of consecutive surveys.

Closed mark-recapture methods allow the estimation of population size and detection probability (245). These methods are advantageous as they can allow for individual heterogeneity in detection probability (i.e. differences in detection probability between individuals) and differences in detection probability after first capture (i.e. changes in individual detection probability due to the marking process), leading to less biased parameter estimates (245). These methods can be repeated, and results can be compared to determine whether the population is increasing or decreasing. Closed mark-recapture methods assume that during the sampling period the population is closed geographically (i.e. no migration) and demographically (i.e. no births or deaths). They do not allow the estimation of parameters that describe how the population is changing through recruitment (i.e. births, immigration, and abandonment of dogs) and removal (i.e. deaths, emigration, and adoption of dogs). To reduce population size, population management methods aim to alter rates of recruitment or removal in a population. For example, increasing removal of individuals through culling or sheltering, and decreasing recruitment by reducing births. Assessing the effectiveness of different management methods requires an understanding of how the population is changing through the relative rates of recruitment and removal.

Open mark-recapture methods account for the demographic and geographic processes occurring in the population, allowing rates of recruitment and removal to be estimated. Mark-recapture methods that allow for an open population include Jolly-Seber (246,247), Cormack-Jolly-Seber (246–248), and Pollock's robust design (249). Few studies investigating dog population dynamics have used open mark-recapture methods (173). Belo *et al.,* (2017) (122) is the first to report dog demographic parameter estimates through the Jolly-Seber mark-recapture approach. Jolly-Seber mark-recapture methods primarily focus on the estimation of time-specific recruitment rate, removal rate, and population size (246,247). The Cormack-Jolly-Seber approach is a refinement of the Jolly-Seber method and primarily focuses on the estimation of removal rate over the open sampling period (246–248). Both Jolly-Seber and Cormack-Jolly-Seber methods require the assumptions of homogeneous survival and detection probabilities between individuals, which can lead to biases in estimated values (250).

The Pollock's robust design method is advantageous over other methods as it incorporates both open and closed mark-recapture study design and analyses (249,251). By incorporating both methods, this allows for the demographic processes of recruitment and removal to be estimated (as in open models), and also deals with individual heterogeneity in detection probability (as in closed models) and survival probability (249,251). This allows more robust estimation of the parameters: (i) detection probability; (ii) population size – the total number of individuals in the study site at each primary period; (iii) recruitment rate – the probability of an individual entering the population at each primary period; and (iv) removal rate – the probability of an individual leaving the study site between primary sampling periods, or conversely, (v) survival probability – the probability of an individual remaining in the study site between primary sampling periods (251). By incorporating both closed and open mark-recapture methods, the robust design is a nested sampling design incorporating sampling occasions over two temporal scales, involving widely spaced primary sampling periods (t), where the population is assumed open to the influences of recruitment and removal, and narrowly spaced secondary sampling periods (s), where the population is assumed closed to the influences of recruitment and removal. Whilst the Pollock's robust design mark-recapture has been applied to a number of other animal populations (252–254), it has not previously been applied to free-roaming dogs.

The aim of this study was to determine the size, dynamics and health status of free-roaming dog populations in two locations, Pescara, Italy and Lviv, Ukraine. By studying sites in two different countries, I hoped to capture factors of dog population demographics and health in locations with different environments and cultures. In Lviv, as different study sites had varying levels of population management intensity, I also aimed to investigate whether there were changes in population dynamics between study sites where different dog population management had been applied.

The aim was met through four objectives:

(1) Determine: (i) population size; (ii) conditional entry probability (derived from recruitment probability); (iii) apparent survival probability; and (iv) detection probability in free-roaming dog populations in study sites within Pescara Province, Italy and Lviv city, Ukraine.

(2) Investigate whether there were differences in detection probability: (i) for different average survey temperatures; (ii) for surveys where markets were observed during the surveys; (iii) for surveys with recorded rainfall; (iv) for weekend versus weekday surveys; (v) for male versus female dogs; (vi) for different study sites within each study region; and (vii) for different primary sampling periods.

(3) Investigate whether there were differences in apparent survival probability for: (i) male versus female dogs; (ii) different study sites within each study region; and (iii) different primary sampling periods.

(4) Determine: (i) percentage of population vaccinated; (ii) body condition score; (iii) percentage of population with visible skin conditions; and (iv) percentage of population with obvious injury in the free-roaming dog populations in study sites within each study region.

4.2. Methods

4.2.1. Study regions and study sites

This study was carried out in two countries, Italy and Ukraine. Within each country, one study region was selected: the Pescara province in Italy, and the Lviv region of Ukraine. Pescara is located in southern Italy in the Abruzzo region and has an oceanic climate (255). The province has a total area of 1,230km^2 and a population size of 318,909 (256). Population density is 123 people per km^2 (257). Lviv is located in the west of Ukraine and has a temperate continental climate (255). The region covers 21,833km^2 and the population size is 2,522,021 (258). The population density is 115 people per km^2 across the region. Study regions were selected where networks were established to facilitate data collection, including sites where there was existing historical information on dog population management. In Pescara, this network was the Veterinary Services – Pescara Province Local Health Unit, an organisation involved in dog population management. In Lviv, these networks were VIER PFOTEN International, the Lviv local Communal Enterprise, and Animal-id.info. Both VIER PFOTEN International and the Lviv local Communal Enterprise have been involved in dog population management in Lviv.

Both study regions had ongoing dog population management through a combination of CNR and sheltering. Within both study regions, data was available for 42 areas (e.g. towns and villages) within the province of Pescara and all districts within the city of Lviv. Four of the available areas in each study region were selected to have similar: (i) number of inhabitants in each town/suburb; and (ii) profiles in terms of size, structure (e.g. residential/industrial) and household numbers (assessed visually prior to fieldwork).

In Pescara, a study site refers to a town/village in the rural Pescara province. Population density in the study sites in Pescara varied between 127 and 193 people per km^2. Distances between study sites varied between 4.65km and 12.40km in Pescara. Study sites in Pescara were also selected to have similar dog population management: similar numbers of dogs had been caught, neutered and released within the study sites between 2015 and 2019 (Table *8*). Records of dog population management in Pescara were accessed from the Veterinary Services - Pescara Province Local Health Unit.

In Lviv, a study site refers to a section of Lviv city. Lviv city is an urban environment with a population size of 717,803 and a population density of 3,982 people per km^2. Distances between study sites varied between 1.00km and 6.80km in Lviv. All study sites were approximately $2km^2$. In Lviv, as the level of dog population management differed throughout the city, I aimed to assess whether there were differences between sites with varying management intensity by selecting two study sites where dogs had been caught, neutered and released (sites one and two) and two study sites where no dogs had been caught, neutered and released (sites three and four) (Table *8*). Records of dog population management in Lviv were accessed from the local Communal Enterprise in Lviv.

The study sites remain anonymous as a condition of data sharing with the local networks. Prior to the fieldwork commencing, pilot trips to the study sites were conducted to check the suitability of the selected study sites for: (i) accessibility (i.e. no private land such as industrial areas where access is prohibited); and (ii) the presence of free-roaming dogs. Data collected during the pilot trip was not included in the analysis. As population size estimates were not available for study sites prior to the study, the coverage of dog population management (i.e. percentage of the population neutered) in both locations was unknown. As population size estimates were calculated in this study, the management coverage was back-calculated.

Table 8. Numbers of dogs caught, neutered and released to study sites in Pescara, Italy and Lviv, Ukraine between 2014 and 2019. Sources: Veterinary Services – Pescara Province Local Health Unit for Pescara; and local Communal Enterprise for Lviv.

		Number of dogs released to study site						
	Study site	**2014**	**2015**	**2016**	**2017**	**2018**	**2019 (Jan-Jul)**	**Total**
Pescara	One	5	11	7	13	4	4	44
	Two	4	8	6	10	6	3	37
	Three	3	8	6	3	4	10	34
	Four	14	10	22	4	9	5	64
Lviv	One	0	0	69	105	89	7	270
	Two	0	0	34	58	51	20	163
	Three	0	0	0	0	0	0	0
	Four	0	0	1	0	0	0	1

4.2.2. Data collection

Data was collected in each study site every three months between April 2018 and July 2019 (Figure 11), excluding in January 2019, where data collection did not occur due to the logistical challenges associated with the extremely low temperatures in both study regions. The time between the third and fourth primary sampling period was six months. Within each of the primary sampling periods, data was collected over three consecutive days (secondary sampling periods) in each study site. This occurred for each study site in order (from study site one to four) in Italy and then in Ukraine.

Data was collected using a street survey approach between approximately 7am and 9am (see Appendix C, Table C1). Two field workers (Lauren Smith plus one assistant) travelled together on foot along predesigned routes and recorded information on every visible free-roaming dog. Survey routes were designed to maximise street coverage across the study site and avoid enclosed areas as a safety measure to reduce the risk of dog attack. Roads without a pavement were excluded as a traffic safety measure. The street surveys followed the same route across both the secondary and primary sampling days. Although this did not occur during this study, surveys were to be terminated for any days that may show abnormal free-roaming dog numbers, for example due to unusual weather (e.g. extremely high or low temperature or prolonged heavy rain).

Dogs were classified as free-roaming if they were: (i) not within an enclosed private property (e.g. the front yard of a house); (ii) not on a lead; and (iii) not associated with a person (i.e. not on a lead but under the watch and responsibility of a person). The following information was recorded: GPS location; sex (male/female/unknown); age (juvenile: less than one year; adult: over one year); size (large: over 65cm in height; medium: 45 to 65cm; or small: less than 45cm); neutering status (ear tag presence/absence and colour – Ukraine only); collar (presence/absence); visibly pregnant (females only); lactation status (females only); visible skin condition (presence/absence); visible injury (presence/absence); and body condition score (emaciated; underweight; normal; overweight; or obese). Body condition scores were not recorded for visibly pregnant or lactating females, or for juveniles, as the body condition scoring system is unsuitable for these individuals.

All dog characteristics were estimated visually. Sex was determined by direct observation of reproductive organs. Age was estimated by body size, allometry (i.e. head size and leg length proportional to body size) and behaviour (17,259,260). For example, juveniles were distinguished by a larger head relative to body size and by juvenile-like movement and behaviour. Visible pregnancy was determined by the presence of an enlarged abdomen and mammary glands. Lactating females were identified by enlarged mammary glands. The presence of skin conditions were determined by visible hair loss and/or dermatitis. The presence of visible injuries were recorded for dogs with visible lesions (e.g. wounds) or observed lameness. Body condition scores were based on visible body fat coverage, following International Companion Animal Management guidelines (261).

All information was logged on the Animal-id.info app. To reduce inter-observer variation, field assistants undertook training prior to fieldwork on how to score the body condition of dogs. Field workers photographed every observed dog using a Nikon D3400 camera for photograph identification of individuals. Photographs were taken of both sides of the dog's body, its legs, head and tail. At every survey, the following information about the local conditions were recorded: temperature at the beginning and end of the survey, as reported by weather.com; rain (yes/no); and whether a local market was taking place at the time of the survey (yes/no, depending on fieldworkers observations during the survey).

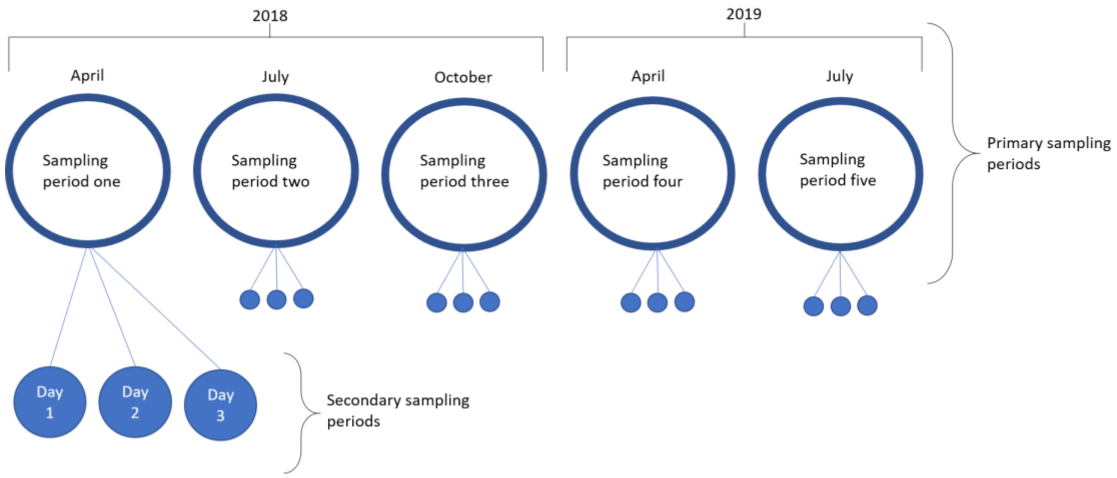

Figure 11. Study design consisting of five primary sampling periods conducted at three-month intervals between April 2018 and July 2019 (excluding January 2019) and three consecutive days of secondary sampling periods within each primary sampling period. During primary sampling periods the study populations in the study sites were assumed to be open to influences of recruitment and removal and during secondary sampling periods the study populations were assumed closed to these influences.

4.2.3. Mark-recapture analysis

4.2.3.1. Capture histories and individual identification

Data on individual dogs and their capture histories were recorded in a Microsoft Excel spreadsheet. Individual capture histories were based on prior observations of the individual dogs in street surveys. Each individual dog was identified and determined to be either a new individual (first capture) or resight (recapture). Dogs were identified through photographs using distinctive markings on the body, legs, head and tail. Each individual was given a unique code (e.g. IT001 or UA001) and their capture history (γ) was determined by observations during the primary and secondary sampling periods (1 = observed, 0 = not observed). Each individual was given a distinctiveness rating between one and three (1 = very distinct, with unique colouring/marking; 2 = moderately distinct, with some identifiable colouring/marking; 3 = indistinct, mono-coloured with minimal markings). Figure 12 provides examples of distinctiveness ratings for individuals identified across primary sampling periods. All individuals were included in the mark-recapture analysis, regardless of their distinctiveness rating. Observations of dogs where photograph quality was extremely poor were not included in the mark-recapture analysis. Photograph quality describes the focus, contrast of individuals with the background, and the size of the individual in relation to the photograph frame.

Figure 12. Examples of distinctiveness ratings of dogs identified across primary sampling periods: A1-3 of distinctiveness 1 (distinct with unique markings); B1-3 of distinctiveness 2 (moderately distinct, with some identifiable colouring/markings); and C1-3 of distinctiveness 3 (indistinct, mono-coloured, minimal markings).

4.2.3.2. Model description

It is challenging to estimate demographic parameters using mark-recapture data because several ecological processes can lead to the mark-recapture histories that are observed. For example, individuals may be present in the population, but not detected during surveys, meaning their presence or absence is not an accurate estimate of whether an individual is contributing to the population processes. To deal with these challenges, a hierarchical Bayesian hidden Markov model of Pollock's closed robust design was used to analyse the mark-recapture histories for both Pescara and Lviv. Hidden Markov models deal with these challenges as they allow the underlying latent states of dogs (e.g. their presence or absence in the population) to be estimated depending on observations during the mark-recapture surveys (i.e. their capture histories).

Pollock's robust study design

A nested study design was used, comprising *t* primary sampling periods and *s* secondary sampling periods where an individual was able to be observed. Each study site had a population of dogs that underwent the processes of recruitment (individuals entering the population through births and immigration) and removal (individuals leaving the population through death and emigration) between *t* primary sampling periods. Between the *s* secondary sampling periods the population was assumed closed to the processes of recruitment and removal. As described above, there were five *t* primary sampling periods, each with three *s* secondary sampling periods (Figure 11).

Hidden process model

Hidden Markov models allow estimation of the underlying latent states of each individual dependent on their capture histories. Each dog's latent state was determined by a state transition matrix (Table 9) and an emission matrix (Table *10*). At each primary sampling period *t*, the model estimated each individual dog's probability of being in one of the following three latent states, conditional on their capture history (i.e. their true states cannot be measured directly): *not-yet-entered; dead;* or *alive.* The *not-yet-entered* state describes those individuals who are yet to enter the study population (these individuals are part of the augmented dataset, *m*). The *dead* state describes those individuals who are no longer part of the study population (i.e. removed from the population through mortality, adoption to the owned dog population, or emigration), and the *alive* state denotes individuals who are part of the study population. Only individuals in state *alive* are available to be observed. An individual could transition between latent states across primary sampling periods (t to t^{+1}). No state transitions occurred between secondary sampling periods. Transitions between the latent states from primary period t to t^{+1} were dictated by each dog's state at *t*. Table 9 (state transition matrix) outlines the probability of an individual transitioning between states (*not-yet-entered*, *dead*, or *alive*) at primary period (t), given their state at the previous primary sampling period (t^{-1}). Table *10* (emission matrix) describes a dog's probability of being observed or unobserved at any secondary sampling period *s* was conditional on their current state in primary period *t*.

Table 9. State transition matrix: the probability of an individual transitioning to a state at primary period (*t*), given their state at the previous primary sampling period (t^{-1}) (reading from row to column).

	Not yet entered	*Dead*	*Alive*
Not yet entered	1-ψ	0	ψ
Dead	0	1	0
Alive	0	1-φ	φ

Table 10. Emission matrix: probability of a dog being observed during a secondary sampling period (*s*), given current state in primary sampling period (*t*) (reading from row to column).

	Unobserved	*Observed*
Not yet entered	1	0
Dead	1	0
Alive	1- $\delta_{t,s}$	$\delta_{t,s}$

Parameter-expansion and data augmentation

As described by Royle and Dozario (2008) (262) and Kery and Schaub (2011) (263), full capture histories were modelled through parameter-expansion and data augmentation. Parameter-expansion and data augmentation simply involved adding a list of all-zero capture histories to the data to account for individuals that were never observed over the duration of the mark-recapture study. This allowed the states of both the individuals that were observed and those that were unobserved throughout the study (i.e. those that had very low detection probabilities) to be modelled, allowing better inferences to be made about the true population (262–264).

Specifically, parameter expanded data-augmentation deals with the computational challenges of variable dimension space when modelling full-capture histories and random effects for individual dogs (263–266). In this study, a set of *pseudo-individuals* with all-zero (*unobserved*) capture histories were included in the list of capture histories for each of the study sites. The augmented dataset (*m*) totalled 150 individuals at each primary period in Pescara and 300 individuals at each primary period in Lviv. The augmented dataset (*m*) included the observed number of individuals (*n*) plus a number of *pseudo-individuals*, and the estimated number of individuals (*N*) lies between *n* and *m*. The *pseudo-individuals* did not affect the estimates of detection probability (δ), apparent survival (φ) or population size (*N*) but allowed more accurate estimation of the parameters using simpler computation. To test that the dataset included enough *pseudo-individuals*, the posterior distributions of *N* were plotted to ensure the distribution was not truncated to the right (Appendix C Figure C1 to C5). The uncaptured *pseudo-individuals* made up the population of individuals that were available for recruitment into the study population and allowed modelling of individual random effects for dogs that were missed throughout all secondary sampling periods.

Recruitment probabilities

To estimate the probability of recruitment, the model estimated the probability of an individual dog transitioning from the *not yet entered* state at t^{-1} to *alive* at *t* primary sampling period. In practice, this was a nuisance parameter because birth and immigration were confounded and, because of data augmentation, it was in fact a ‘removal entry probability’ that described the probability of a member of the augmented data set entering at time *t*. Removal entry probabilities are mathematic constructs required by the model, but with no biological meaning (see (262,263,265) for a full discussion). Instead, Royle and Dozario (2008) (262) and Kery and Schaub (2011) (263) were followed by deriving the conditional 'entry probability' for each time point *t*. This provided the fraction of the true population ('super-population'; total number of dogs that had ever been in the study site across all primary periods) of individuals entering the study site at time *t*, given they had not entered at a previous time point. The entry probability must sum to one across all primary sampling periods and individuals were assumed to be in the *not yet entered* state prior to the first primary period. This means the entry probability calculated for the first primary period was less interpretable; instead, entry probabilities after the first primary period were reported. I also estimated a per capita entry probability (*f*), as described by Kery and Schaub (2011) (263). Per capita entry probability describes the fraction of new recruits at primary period *t* per individual dog alive and in the study site at primary period *t*. This was calculated by Equation 2. Population growth (l_t) was calculated by dividing the estimated population size at period *t* (N_t) by the estimated population size at primary period N_{t-1} (Equation 3). Table *11* outlines the parameters calculated for each study site.

Equation 2. Per capita entry probability.

$$f_t = \frac{E_t \times W}{N_t}$$

Equation 3. Population growth

$$\lambda_t = \frac{N_t}{N_{t-1}}$$

Table 11. Description of parameters calculated for each study site in study regions.

Parameter	**Description**
$Z^{(m \times t)}$	Matrix of the possible latent states (*not-yet-entered; alive; dead*) for each individual (including *pseudo-individuals*) at each *t* primary sampling period.
n	Total number of dogs individually identified throughout the duration of the study.
N_t	Total number of dogs alive and available for observation during primary sampling period *t*.
m	Total number of dogs, including observed and unobserved *pseudo-individuals*.
$\gamma^{(m \times t \times s)}$	Array of capture histories for all individually identified dogs and the parameter expanded data augmented *pseudo-individuals*.
$\gamma^{(i \times t \times s)}$	Array of capture histories for all individuals *observed* in *s* secondary sampling periods throughout *t* primary sampling periods.
W	Superpopulation: Total number of dogs that have ever been in the study site across all primary sampling periods.
φ_{ti}	Apparent survival of individual dog between *t* and t^{+1} primary sampling period.
δ_{ti}	Probability of observing a dog, given it is alive, in secondary sampling period *s* within primary sampling period *t*.
ψ_{ti}	Probability of recruitment – an individual dog transitioning from *not yet entered* at t^{-1} to *alive* at *t* primary sampling period. As described, this is a nuisance parameter that is required to describe the model.

Parameter	Description
E_{ti}	Proportion of superpopulation entering at each primary period *t*, given they have not already entered.
f_t	Per capita entry probability: the fraction of new recruits at primary period *t* per individual dog alive and in the study site at primary period *t*.
λ	Population growth (Equation 3).
M_t	Matrix of time intervals between each primary sampling period.
M_d	Matrix of distances between study sites.

Model running

All model parameters had 'weakly informative' prior distributions and all individuals started in the *not-yet-entered* state. The model was written in Stan (267) and run in R version 3.6.1 (222) using the "**Rstan"** package (268) with four Markov chain Monte Carlo (MCMC) chains of 2,500 iterations of warmup and 2,500 iterations for sampling, giving 10,000 posterior samples for inference. The Stan model used the forward algorithm to marginalise out the latent, discrete states for each individual. Convergence was assessed by inspecting the Rhat values (values less than 1.05 suggest convergence) and effective sample sizes (values over 1000 suggest good precision of the tails of distribution).

Data from study sites in Pescara and Lviv were run in the same model, but parameter estimates were not informed by capture histories between countries (i.e. parameter estimates for study sites in Pescara were not informed by those estimated for study sites in Lviv). Random intercepts were included for *apparent survival, recruitment*, and *detection* to describe intra-country variation across study sites and primary periods, and intra-site variation across dogs. Spatial correlations (correlations in parameter estimates given the distances between study sites) and temporal correlations (correlations in parameter estimates given the time differences between primary sampling periods) were captured by using Gaussian process prior distributions on the sites and primary periods random intercepts (squared exponential and periodic kernel functions, respectively). Partial pooling was used for all within country random effects.

Parameter estimates were converted from the log odds scale to the probability scale using the inverse logit function: $logit^{(-1)(x)} = {}^{\exp\,(x)}\!\big/_{1\,+\,(\exp(x))}$, and converted to odds using $\exp\,(x)$, where χ is the posterior value on the logit scale. Parameter estimates were summarised by calculating the mean and 95% credible intervals of the posterior distribution (CIs; also known as highest density intervals or Bayesian confidence intervals; the 2.5 and 97.5 percentiles of the posterior distribution).

Predictor variables

The effects of the following predictor variables were tested on detection probability: average temperature (average of recorded temperature at beginning and end of survey); market event (yes/no); rain (yes/no); weekday/weekend; and sex (male/female), study site and primary period. The effect of sex (male/female), study site, and primary period was tested on apparent survival probability. Individuals of unknown sex (including pseudo-individuals) were dealt with through marginalisation: the model used a weighted average of effects across males and females to compute those of unknown sex's probability of detection and apparent survival. A significant effect was determined if the 95% CIs did not include zero on the log odds scale.

Model comparison

It is common in frequentist mark-recapture modelling to run several models, stratified by temporal and population subgroup parameter estimates (leading to an enormous number of possible models, see (269) for discussion) and to use model-averaging to provide parameter results. Studies suggest the use of Hierarchical Bayesian mark-recapture models with random-effects yield similar parameter estimates to model-averaging of frequentist mark-recapture models (using Akaike Information Criterion, AICc weights) (264,269,270). As all parameters in the model are of theoretical relevance and as there were no specific biological hypotheses, no explicit model comparison was run. Parameters in the model experienced both shrinkage effects (for the random effects describing differences between individuals, time points and study sites), and weakly informative priors were used to exclude large effects.

4.3. Results

In total, five primary sampling periods were completed in both Pescara and Lviv. Fifteen secondary sampling periods were completed in study sites in Pescara, and 14 secondary sampling periods were completed in Lviv between April 2018 and July 2019. No surveys were terminated due to conditions that may have shown abnormal free-roaming dog numbers. One survey (one secondary sampling period) did not occur due to fieldworker illness in study site one in Lviv during primary sampling period three (details of how this missing data was dealt with in the model are in Appendix C).

4.3.1. Dog demographic parameters

4.3.1.1. Pescara, Italy

A total of 53 dogs were individually identified in Pescara. Of these dogs, 14 (26%) had a distinctiveness score of one (very distinct, with unique colouring/marking), 33 (62%) of two (moderately distinct, with some identifiable colouring/marking), and 6 (11%) of three (indistinct, mono-coloured with minimal markings). No individuals were observed in more than one study site (i.e. there was no evidence for movement between study sites). Of the total number of identified dogs, 14 were female (26%), 27 were male (51%), and 12 (23%) were of unknown sex. Fifty-two (98%) dogs were adults and one (2%) was a juvenile. Six adult dogs (11%) were classified as large, 14 (26%) as medium, and 32 (60%) as small. No visibly pregnant females were observed in any study site over the primary sampling periods. One lactating female (7% of the females) was observed in Pescara in study site three on the third primary sampling period (October 2018).

The average monthly probability of a dog remaining alive and in the study population was 0.93 (95% CI: 0.81-1.00) (Table *12*). The average apparent survival probability between an average primary sampling period (3 to 6 months) was 0.71 (95% CI: 0.42 to 0.95). The average probability of a dog being observed in a single survey (detection probability) was 0.27 (95% CI: 0.05-0.54) (Table *12*). Appendix C, Table C4 outlines the apparent survival probability and detection probability per primary period and study site. Standard deviations for the effect of individual dogs on survival and detection are presented in the Appendix C, Table C6. Entry probability in Italy (the average fraction of dogs entering the study areas during the study periods) varied between 0.05 (95% CI: 0.00-0.14) and 0.14 (95% CI: 0.00-0.27) (Table 13). Entry probability was highest in Pescara in primary period two and lowest in primary period four (Table 13). The population size estimates in Pescara varied across primary sampling periods between:

12 and 15 in study site one; 12 and 18 in study site two; 15 and 22 in study site three; and 11 and 13 in study site four (Table 13, Figure 13). Study sites in Italy had an average of 7 dogs km^{-2} (95% CI: 2-14 dogs km^{-2}) across sites and primary periods. The superpopulation size (the total number of dogs estimated alive and in the study site across all primary sampling periods) was estimated to be: (i) study site one: 21 dogs (95% CI: 10-32), (ii) study site two: 25 dogs (95% CI: 9-45), (iii) study site three: 30 dogs (95% CI:16-50), and (iv) study site four: 19 dogs (95% CI: 4-36). The derived per capita entry probability varied between 0.09 (95% CI: 0.00-0.22) and 0.20 (95% CI: 0.00-0.38) across primary periods and study sites (Table 13). Population growth in Pescara varied between a minimum of 0.86 and a maximum of 1.00 per primary sampling period (Figure 15).

There was no evidence for a significant effect of weekend, market event, rain, temperature, sex, study site or primary period on detection probability in Pescara (Table 14, Table 15**,** and Table *16*). There was also no evidence for a significant effect of sex, study site or primary period on apparent survival probability in Pescara (Table 14, Table 15**,** and Table *16*). The average temperatures during the surveys in Pescara varied between 7 ^{o}C and 25.5 ^{o}C.

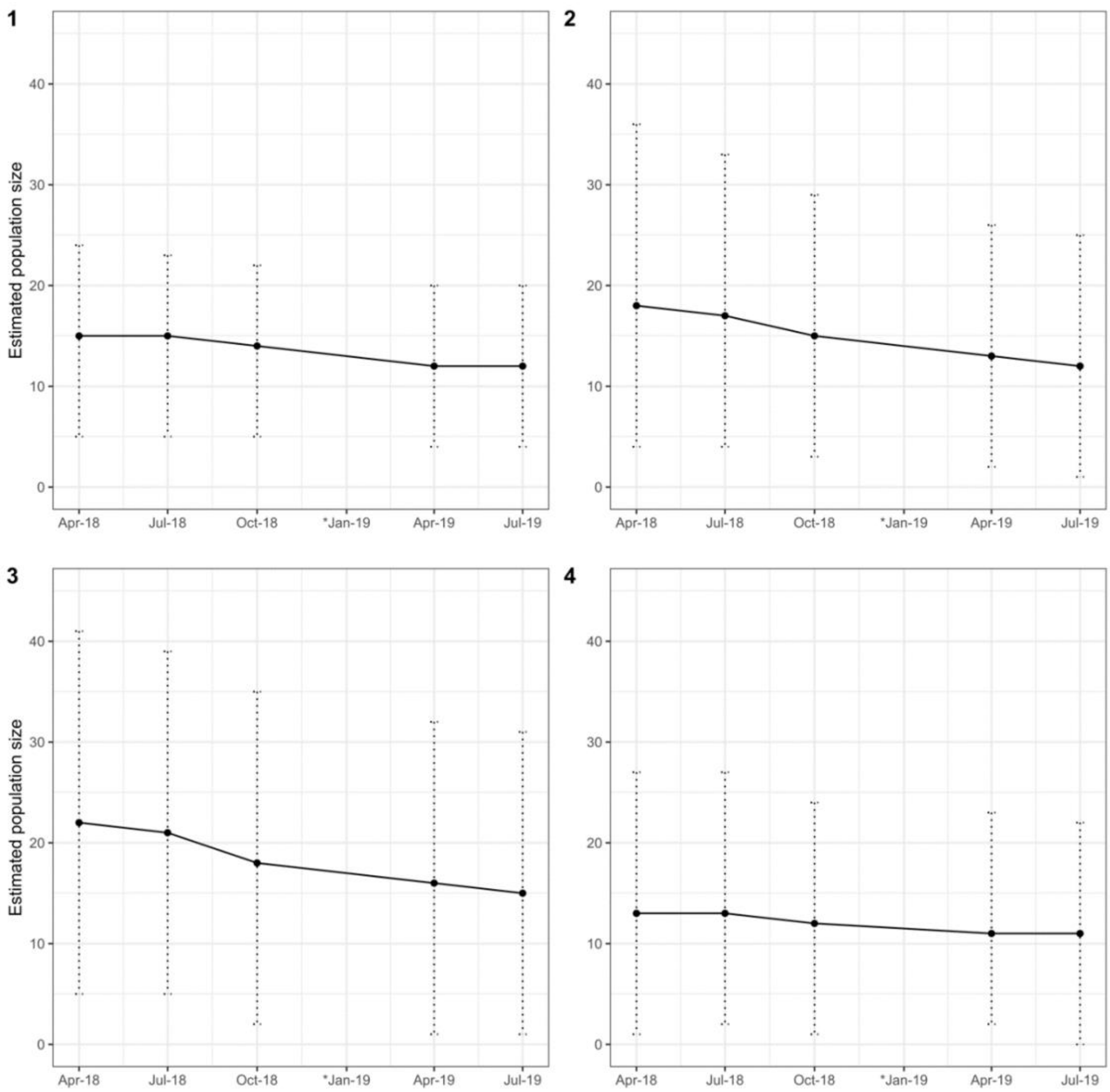

Figure 13. Estimated population size for each study site (1 to 4) in Pescara, Italy across the primary sampling periods between April 2018 and July 2019. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). *No surveys conducted in January 2019.

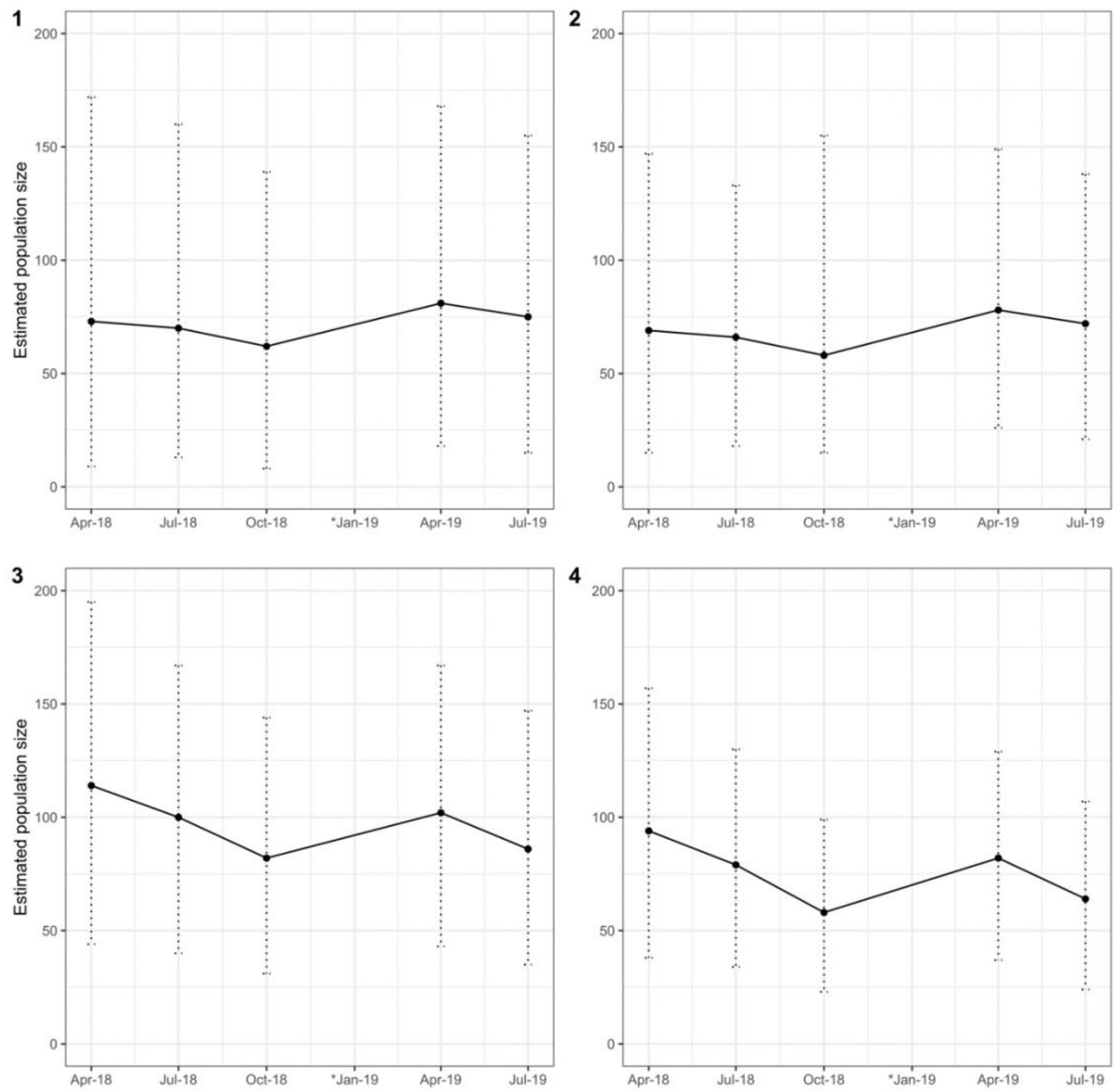

Figure 14. Estimated population size for each study site (1 to 4) in Lviv, Ukraine across the primary sampling periods between April 2018 and July 2019. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). *No surveys conducted in January 2019.

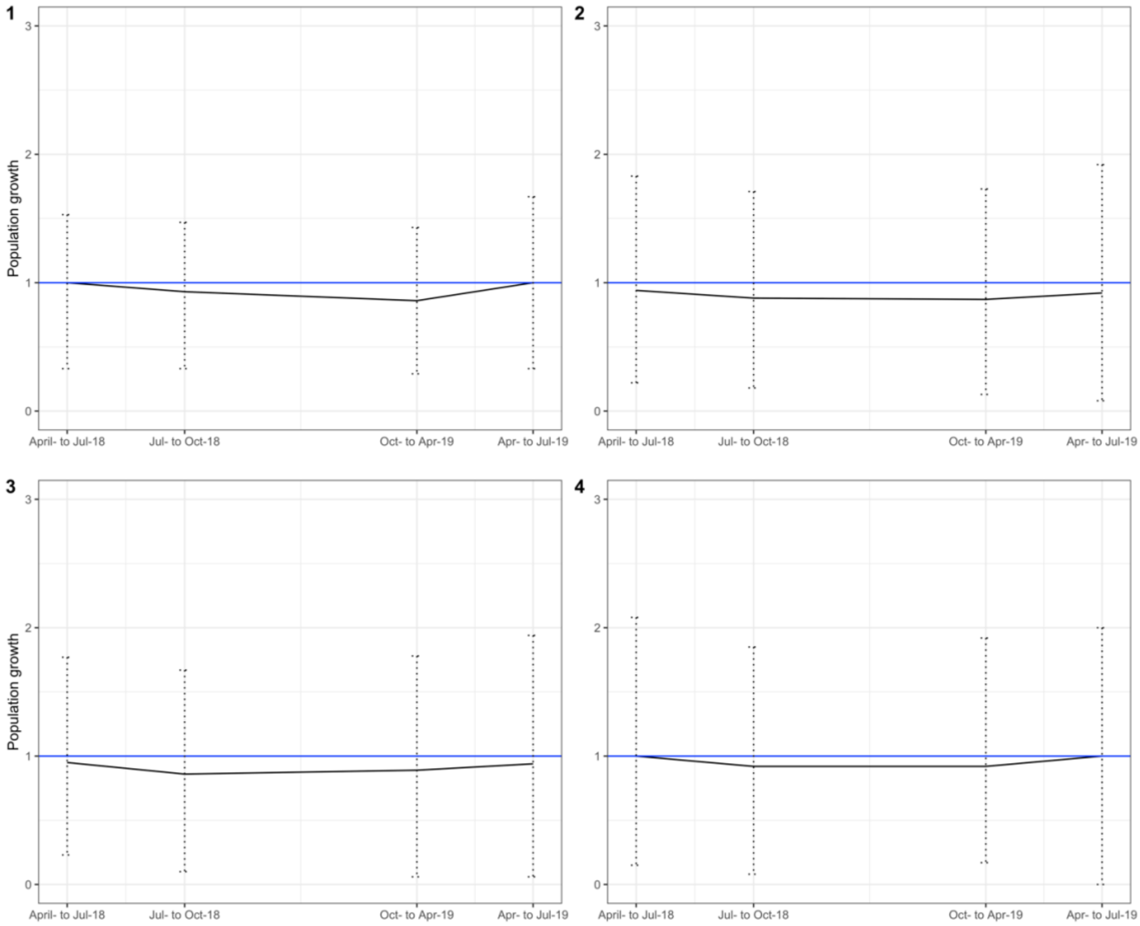

Figure 15. Population growth rates between primary sampling periods in study sites 1 to 4 for study regions Pescara, Italy. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). *Note uneven spacing as no surveys conducted in January 2019.

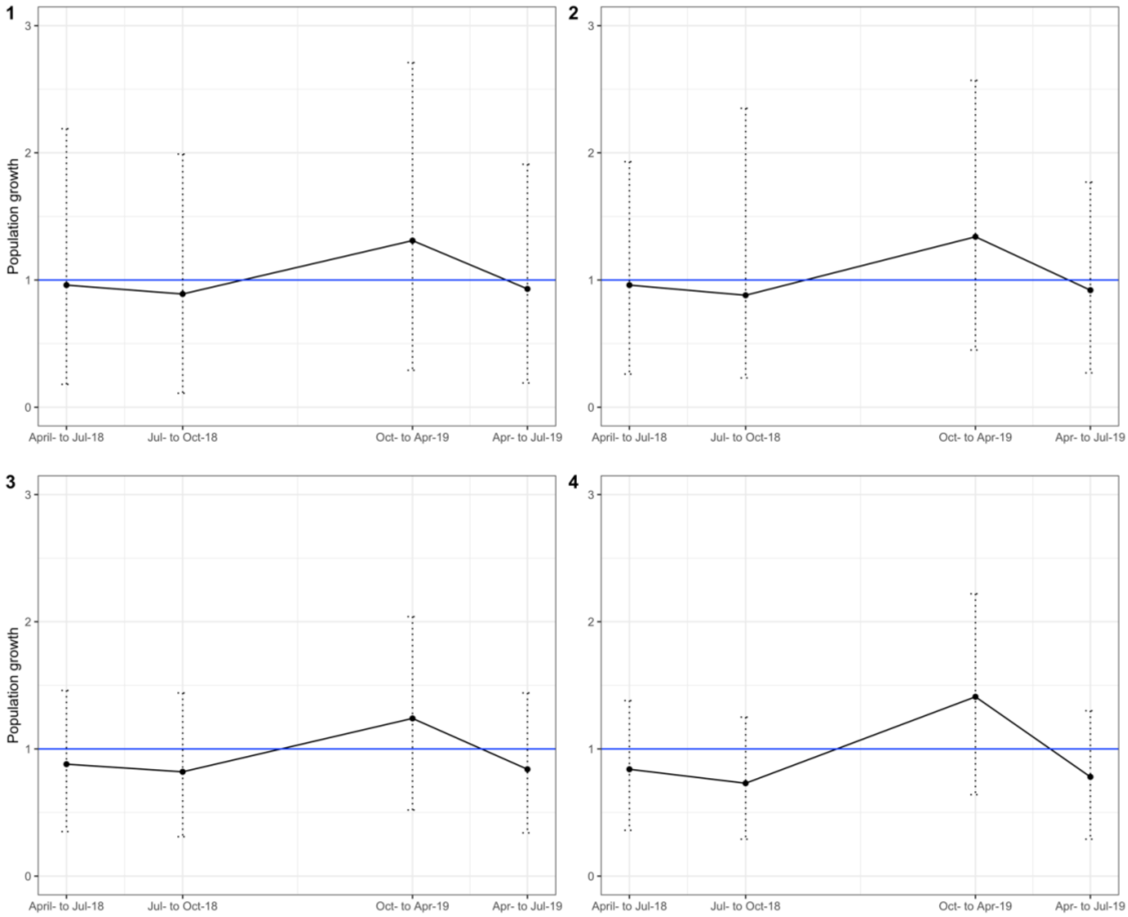

Figure 16. Population growth rates between primary sampling periods in study sites 1 to 4 for study regions Lviv, Ukraine. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI). * Note uneven spacing as no surveys conducted in January 2019.

Table 12. Average monthly probability of a dog remaining alive and in the study site (apparent survival probability) and average probability of observing a dog and 95% credible intervals (CI), for the average dog across all study sites and primary periods between April 2018 and July 2019 in study regions Pescara, Italy and Lviv, Ukraine.

		Country	**Mean**	**2.5% CI**	**97.5% CI**
φ	Average monthly apparent survival probability, across all dogs	Pescara	0.93	0.81	1.00
		Lviv	0.93	0.84	0.99
δ	Average probability of observing a dog, across all dogs and primary periods	Pescara	0.27	0.05	0.54
		Lviv	0.18	0.02	0.40

Table 13. Estimated population size, entry probability, per capita entry probability, and the 2.5 and 97.5 percentiles of the posterior distribution (95% CI) across study sites and primary periods (PP) for Pescara, Italy and Lviv, Ukraine. Entry probabilities and per capita entry probabilities for the first primary period are not included, due to lack of interpretability in the primary period one parameter estimate.

		Estimated population size						**Entry Probability**						**Per capita entry probability**					
		Pescara			**Lviv**			**Pescara**			**Lviv**			**Pescara**			**Lviv**		
	PP	**Mean**	**2.5% CI**	**97.5 %CI**	**Mean**	**2.5% CI**	**97.5 % CI**	**Mean**	**2.5% CI**	**97.5 % CI**	**Mean**	**2.5% CI**	**97.5 % CI**	**Mean**	**2.5% CI**	**97.5 % CI**	**Mean**	**2.5% CI**	**97.5 % CI**
Site 1	1	15	5	24	73	9	172												
	2	15	5	23	70	13	160	0.14	0.00	0.27	0.10	0.00	0.21	0.20	0.00	0.38	0.18	0.00	0.33
	3	14	5	22	62	8	139	0.10	0.00	0.21	0.06	0.00	0.14	0.15	0.00	0.31	0.12	0.00	0.26
	4	12	4	20	81	18	168	0.07	0.00	0.15	0.22	0.10	0.36	0.12	0.00	0.24	0.33	0.18	0.55
	5	12	4	20	75	15	155	0.08	0.00	0.17	0.10	0.00	0.20	0.14	0.00	0.27	0.16	0.00	0.33
Site	1	18	4	36	69	15	147												

		Estimated population size						Entry Probability						Per capita entry probability					
		Pescara			Lviv			Pescara			Lviv			Pescara			Lviv		
	PP	Mean	2.5% CI	97.5 %CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI
	2	17	4	33	66	18	133	0.13	0.00	0.27	0.10	0.00	0.20	0.19	0.00	0.37	0.18	0.00	0.34
	3	15	3	29	58	15	155	0.10	0.00	0.21	0.06	0.00	0.13	0.17	0.00	0.33	0.13	0.00	0.19
	4	13	2	26	78	26	149	0.06	0.00	0.15	0.23	0.12	0.35	0.12	0.00	0.26	0.36	0.19	0.54
	5	12	1	25	72	21	138	0.07	0.00	0.16	0.11	0.01	0.21	0.15	0.00	0.29	0.18	0.02	0.35
Site 3	1	22	5	41	114	44	195												
	2	21	5	39	100	40	167	0.13	0.01	0.26	0.11	0.01	0.22	0.19	0.03	0.33	0.20	0.02	0.36
	3	18	2	35	82	31	144	0.09	0.00	0.19	0.07	0.00	0.14	0.15	0.00	0.27	0.15	0.00	0.27
	4	16	1	32	102	43	167	0.05	0.00	0.14	0.19	0.09	0.29	0.09	0.00	0.22	0.33	0.20	0.48

		Estimated population size						Entry Probability						Per capita entry probability					
		Pescara			Lviv			Pescara			Lviv			Pescara			Lviv		
	PP	Mean	2.5% CI	97.5 %CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI	Mean	2.5% CI	97.5 % CI
	5	15	1	31	86	35	147	0.06	0.00	0.16	0.08	0.01	0.16	0.12	0.00	0.26	0.17	0.03	0.30
Site 4	1	13	1	27	94	38	157												
	2	13	2	27	79	34	130	0.13	0.00	0.27	0.10	0.00	0.21	0.19	0.00	0.36	0.21	0.00	0.39
	3	12	1	24	58	23	99	0.10	0.00	0.21	0.06	0.00	0.13	0.16	0.00	0.32	0.17	0.00	0.32
	4	11	2	23	82	37	129	0.06	0.00	0.16	0.21	0.11	0.33	0.10	0.00	0.25	0.42	0.26	0.62
	5	11	0	22	64	24	107	0.08	0.00	0.18	0.09	0.01	0.18	0.14	0.00	0.29	0.23	0.04	0.41

Table 14. Effects of predictor variables on detection and apparent survival as odds ratios in Pescara, Italy and Lviv, Ukraine. Significant results are highlighted in bold.

	Detection						Apparent survival					
	Pescara			Lviv			Pescara			Lviv		
	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI
Weekend vs. weekday	1.16	0.64	1.74	**0.74**	**0.53**	**0.96**						
Market day vs. no market	0.75	0.24	1.36	**2.58**	**1.28**	**4.14**						
Rain vs. dry	0.79	0.31	1.34	0.73	0.47	1.00						
Temperature	0.98	0.88	1.08	0.98	0.92	1.04						
Female vs. male	0.63	0.22	1.15	0.82	0.37	1.32	1.29	0.08	3.43	**0.25**	**0.03**	**0.59**

Table 15. Comparison of mean apparent survival and detection as odds ratios between different study sites in Pescara, Italy and Lviv, Ukraine.

		Pescara			Lviv		
Average probability	Study sites	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI
Apparent survival (φ)	1 and 2	2.19	0.01	6.50	2.11	0.02	6.52
	1 and 3	2.62	0.01	7.97	3.41	0.06	10.76
	1 and 4	1.44	0.01	4.06	5.69	0.12	17.36
	2 and 3	2.08	0.00	6.79	2.56	0.07	6.98
	2 and 4	1.31	0.00	3.95	4.20	0.33	11.21
	3 and 4	1.54	0.00	4.77	2.08	0.23	4.89
Detection (δ)	1 and 2	6.68	0.18	20.69	0.87	0.01	2.76
	1 and 3	9.26	0.55	21.59	0.92	0.01	2.88
	1 and 4	4.57	0.14	14.13	0.48	0.01	1.47
	2 and 3	2.72	0.05	8.40	1.65	0.03	4.94
	2 and 4	1.30	0.01	4.38	0.84	0.01	2.34
	3 and 4	0.65	0.03	2.05	0.71	0.05	1.85

Table 16. Comparison of mean apparent survival and detection as odds ratios between different intervals between primary periods in Pescara, Italy and Lviv, Ukraine.

		Pescara			Lviv		
Average probability	Primary period	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI
Apparent survival (φ)	2 to 3	4.06	0.01	11.64	2.56	0.14	6.82
	2 to 4	3.75	0.01	11.50	0.80	0.01	2.11
	2 to 5	3.12	0.00	8.37	3.05	0.07	8.38
	3 to 4	1.88	0.00	5.51	0.42	0.00	1.19
	3 to 5	1.33	0.00	4.16	1.54	0.09	4.00
	4 to 5	1.49	0.00	4.36	7.81	0.16	24.16
Detection (δ)	1 to 2	1.70	0.31	3.71	0.65	0.29	1.07
	1 to 3	1.29	0.46	2.37	0.59	0.19	1.10
	1 to 4	1.59	0.47	3.09	0.80	0.31	1.39
	1 to 5	1.10	0.20	2.40	0.87	0.31	1.56
	2 to 3	0.93	0.21	1.89	0.96	0.28	1.79
	2 to 4	1.26	0.11	3.13	1.31	0.53	2.28
	2 to 5	0.71	0.23	1.34	1.38	0.66	2.27
	3 to 4	1.33	0.41	2.50	1.45	0.80	2.26
	3 to 5	0.89	0.20	1.76	1.66	0.50	3.19

		Pescara			Lviv		
Average probability	Primary period	Mean	2.5% CI	97.5% CI	Mean	2.5% CI	97.5% CI
	4 to 5	0.79	0.09	1.78	1.14	0.45	1.96

4.3.1.2. Lviv, Ukraine

A total of 182 dogs were individually identified. Twenty-six (14%) dogs had a distinctiveness score of one, 124 (68%) of two, and 31 (17%) of three. One dog (1%) was not able to be identified through the photographs due to poor photograph quality and was excluded from the mark-recapture analysis. As with individuals in study sites in Pescara, no dogs were identified in more than one study site, despite the smaller distances between sites in Lviv.

Of the total number of identified dogs, 40 were female (22%), 94 were male (52%), and 48 (26%) were unknown. Across all observed dogs, 173 (95%) were adults and nine (5%) were juveniles. As the study sites had different management in Lviv, the demographic and health measures between sites with different management could be compared. Juveniles were observed in one of the two sites with direct management – study site two (5 of 35 dogs, 14%) – and in both of the sites with no direct management – three (2 of 56 dogs, 4%), and four (2 of 64 dogs, 3%). Of the adult dogs recorded, 45 (25%) were large, 92 (51%) were medium, and 36 (20%) were small. Based on the presence of ear tags, study site one had the highest percentage of dogs neutered and vaccinated (52%) across the four sites, though also had the smallest number of dogs observed. Dogs in study sites three (29%) and four (17%) were observed with ear tags, even though no/few dogs were recorded to have been caught, neutered and released to these sites (Table *8*). This potentially indicates historical dog population management in the area (i.e. CNR conducted by other organisations) or movement of dogs throughout the city, either by dogs migrating between neighbouring communities or by owners of free-roaming owned dogs moving households. No pregnant females were observed in any study site during any of the primary sampling periods. Only two females were observed lactating, both were in study site two (direct management site) at sampling period three (October 2018).

Table 17. Number and percentages of neutered and vaccinated dogs observed in each study site in Lviv, Ukraine. Neuter and vaccination status indicated by presence of ear-tag.

Study site	Number of identified dogs	Number neutered & vaccinated	Females neutered & vaccinated	Males neutered & vaccinated	Unknown sex neutered & vaccinated
1	27	14 (52%)	7 (26%)	6 (22%)	1 (4%)
2	35	10 (29%)	4 (11%)	4 (11%)	1 (3%)
3	56	16 (29%)	6 (11%)	6 (11%)	4 (7%)
4	64	11 (17%)	2 (3%)	6 (9%)	3 (5%)

The average monthly apparent survival probability was 0.93 (95% CI: 0.84-0.99) (Table *12*). The apparent survival probability between an average primary sampling period (3 to 6 months) was 0.73 (95% CI: 0.45 to 0.95). The average probability of a dog being detected in a secondary sampling period was 0.18 (95% CI: 0.02-0.40) (Table *12*). Appendix C, Table C5 outlines the apparent survival probability and detection probability per primary period and study site. Entry probability in Lviv varied between 0.06 (95% CI: 0.00-0.14) and 0.23 (95% CI: 0.12-0.35) (Table 13). Across all study sites, entry probability in Lviv was highest in primary period four and lowest in primary period three. The population size estimates in Lviv varied across primary sampling periods between: 62 (95% CI: 8-139) and 81 (95% CI: 18-168) in study site one; 58 (95% CI: 15-155) and 78 (95% CI: 26-149) in study site two; 82 (95% CI: 31-144) and 114 (95% CI: 44-195) in study site three; and 58 (95% CI: 23-99) and 94 (95% CI: 38-157) in study site four (Table 13, Figure 14). Study sites in Lviv had an average of 40 dogs km^{-2} (95% CI: 13-73 dogs km^{-2}) across sites and primary periods. The superpopulation size was estimated as: (i) study site one, 123 dogs (95% CI: 32-255); (ii) study site two, 121 dogs (95% CI: 41-229); (iii) study site three, 178 dogs (95% CI: 96-274); and (iv) study site four, 163 dogs (95% CI: 87-242). The derived per capita entry probability varied between 0.12 (95% CI: 0.00-0.24) and 0.42 (95% CI: 0.26-0.62) across primary periods and study sites. Population growth in Lviv varied between a minimum of 0.73 and a maximum of 1.41 per primary sampling period (Figure 16). Population growth was highest in April 2019: entry probability (Table 13) and apparent survival probability (Appendix C, Table C5) were both high for this primary period.

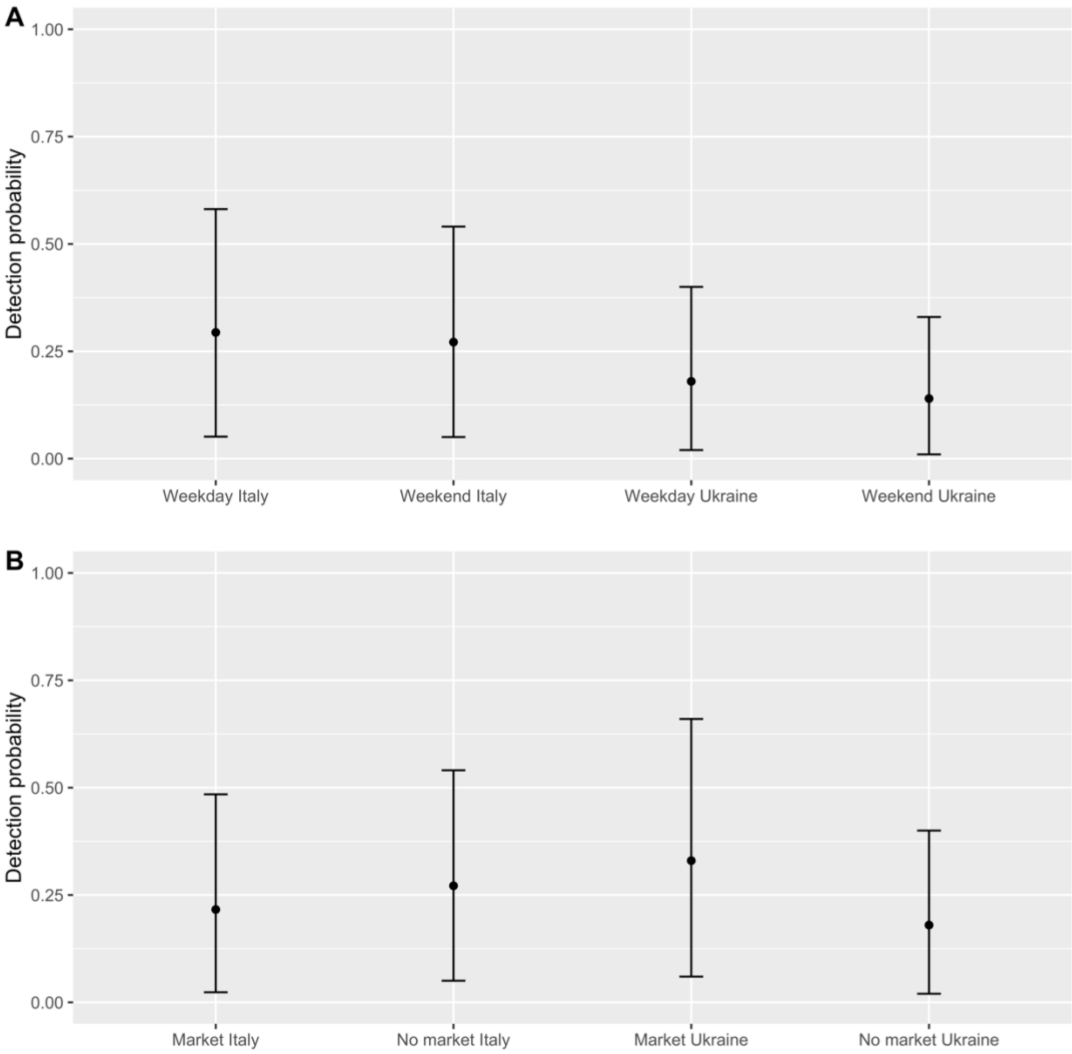

Figure 17. The effects of (A) weekend/weekday and (B) market/no market on detection probability of dogs in Pescara, Italy and Lviv, Ukraine. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI).

There was no evidence for significant effects of rain, temperature or sex on detection (Table *14*). Temperatures varied between 0.5 ^{o}C and 21 ^{o}C across study sites and secondary sampling periods in Lviv. When converted to the probability scale, surveys conducted at the weekend, compared to the weekday, had a 0.04 (95%CI: 0.00-0.09) lower probability of detecting a dog (Table 14). There was also a significant effect of market event on detection (Table 14). On the probability scale, surveys conducted on days with a market event had a 0.15 (95% CI: 0.02-0.29) higher probability of detecting a dog (Figure 17). Sex had a significant effect on apparent survival (Table 14). When comparing across the average primary period (3-6 months), females had a higher apparent survival probability than males by 0.33 (95%CI: 0.06-0.59): average male apparent survival probability was 0.40 (95%CI: 0.04-0.76) compared to 0.73 (95%CI: 0.45-0.95) in females (Figure 18). There was no evidence for significant effects of study site or primary period on probability of apparent survival and detection in Lviv (Table 15 and Table 16).

4.2.1.3. Between country comparison

There was no evidence for significant effects of country on the detection (odds ratio 3.36, 95% CI 0.04 to 10.60) or apparent survival parameters (odds ratio 1.57, 95% CI 0.01 to 5.13).

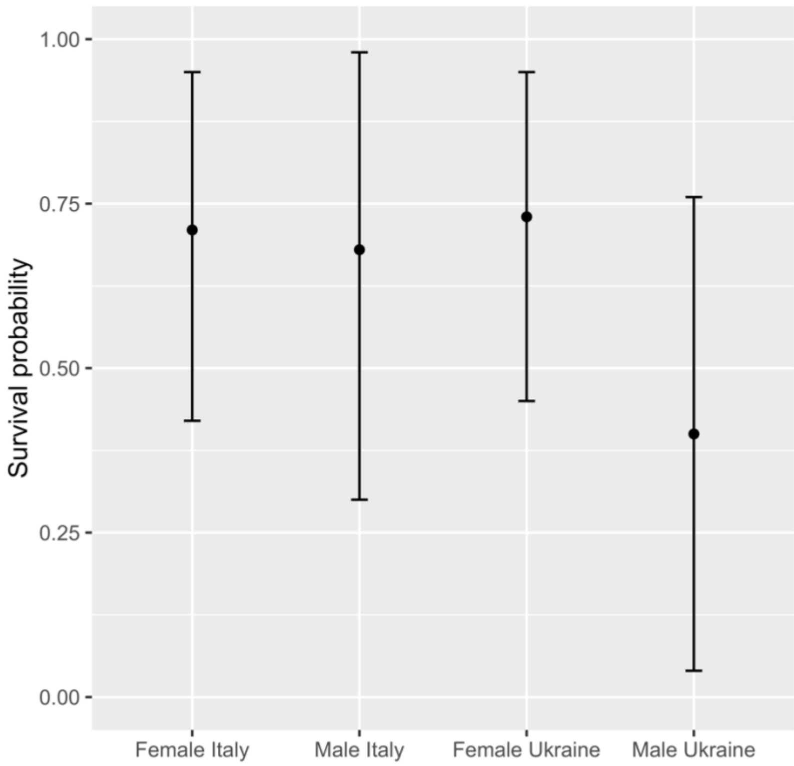

Figure 18. Effect of sex of dog on apparent survival probability (probability of remaining alive and onsite between primary sampling periods) in Pescara, Italy and Lviv, Ukraine. Error bars show the 2.5 and 97.5 percentiles of the posterior distribution (95% CI).

4.3.2. Health status parameters

4.3.2.1. Pescara, Italy

The highest prevalence of skin conditions was observed in primary sampling period three (October 2018), where four of the 19 (21%) observed dogs were recorded with skin conditions. All other primary sampling periods had low observations of dogs with skin conditions (between 0 and 7%). The highest prevalence of visible injuries was observed in primary sampling period four, where four of the 15 observed dogs were recorded with visible injuries. No dogs in study sites in Pescara were observed with a body condition score less than three. Most observations were of dogs with a body condition score three (over 60% across all primary sampling periods), or body condition score four (between 10 to 20% of observed dogs).

The back-calculated neutering coverage estimates for study sites in Pescara were between 20.0% and 69.2% of the average estimated free-roaming dog populations in 2018, and between 16.7% and 62.5% between January and July in 2019 (Table *18*).

4.3.2.2. Lviv, Ukraine

The prevalence of skin conditions was low across all study sites and primary sampling periods (less than 15%). Similarly, the prevalence of visible injuries was low across all study sites and sampling periods (most less than 15%). The highest prevalence of visible injuries was observed in study site two (site with direct management: three of 13 observed dogs, 23%) and study site four (no direct management: five of 25 observed dogs, 25%). Over 89% of body condition scores of observed dogs were three or above.

In study sites one and two (sites with direct management), between 79.7% and 130.9% of the average estimated populations were caught, neutered and released in 2018, and between 9.0% and 26.7% between January and July in 2019. These estimates may be subject to inaccuracies due to imprecise locations of release. Dog population management records included the street names where dogs had been released. As street names may refer to a street that runs within and outside of a study area, the numbers of dogs released may not directly relate to the free-roaming dog population within the study site. No dogs were directly caught, neutered and released in study site three, and only one dog had been released to study site four (Table *8*). Throughout the study period, none of the observed individuals recorded in this study transferred from an unneutered (i.e. untagged) to a neutered (i.e. tagged) state.

Table 18. Back calculated estimates of management coverage across study sites in study regions Pescara, Italy and Lviv, Ukraine.

Study region	Study site	Average no. dogs across primary period 1, 2 & 3 (2018)	No. dogs caught, neutered and released (2018)	Back calculated 2018 Coverage (%)	Average no. dogs across primary period 4 & 5 (2019)	No. dogs caught, neutered and released (Jan-July 2019)	Back calculated 2019 Coverage (%)
Pescara	1	15	4	26.7	12.0	4	33.3
	2	17	6	35.3	18.0	3	16.7
	3	20	4	20.0	16.0	10	62.5
	4	13	9	69.2	11.0	5	45.5
Lviv	1	68	89	130.9	78.0	7	9.0
	2	64	51	79.7	75.0	20	26.7
	3	99	0	0.0	94.0	0	0.0
	4	77	0	0.0	73.0	0	0.0

4.4. Discussion

Dog population size, dynamics and health status are important indicators of the effect of dog population management (as outlined in Chapter Two). In this study 53 dogs in Pescara and 182 dogs in Lviv were individually identified and re-sighted across all study locations and sampling periods between April 2018 and July 2019. The estimated population sizes varied between 11 and 22 per study site and primary sampling period in Pescara (Table 13, Figure 13) and 58 and 114 per study site and primary sampling period in Lviv (Table 13, Figure 14). This study found evidence for significant effects of market days and day of the week on detection probability in Lviv, but no evidence for significant effects of these variables in Pescara (Table 14). There was also evidence for a significant effect of sex on the probability of a dog remaining alive and in the population (apparent survival probability) in Lviv, but no evidence for a significant effect in Pescara (Table 14). The lack of evidence for effects of predictor variables in Pescara could be due to a lower sample size, as fewer individuals were observed in study sites in Pescara. In general, parameter estimates had wide confidence intervals, limiting the strength of the study's conclusions. In both study regions, few dogs were observed with skin conditions (less than 15%) or visible injuries (less than 25%). Most observations of dogs were with a normal body condition score.

In this study, Pollock's robust design mark-recapture method was successfully conducted on two free-roaming dog populations. Using a combination of closed and open mark-recapture methods allowed information about the demographic processes of these populations to be estimated. The model included random effects for individual dogs, allowing individual heterogeneity in apparent survival, recruitment and – most importantly – detection probability to be modelled. Failing to include individual heterogeneity in detection probabilities can bias parameter estimates, leading to over- or under-estimation of population size (264,269,271). Detection probability is likely to differ between individuals due to factors such as personality and past experiences with people. For example, free-roaming dogs that have had prior positive experiences with people, such as feeding, may have a higher detection probability (see Daniels, 1983 (27), classifications of human benefactors or predators).

In this study, a photographic method was used to identify individuals, limiting the impact of the “marking” on detection probability. Photographic methods are advantageous over other methods used to mark dogs, such as dyes that require animal contact (272). Handling and marking may increase the probability of capture effects that impact individual recapture probabilities. These include “trap-happiness” (increased probability of observing an individual) and “trap-shyness” (decreased probability of observing an individual) (97). Individual free-roaming dogs were successfully identified and re-identified through photographic methods. In this study, all individuals were assumed to be correctly re-identified. However, errors in capture histories could have occurred, particularly for less-distinct individuals. These errors can lead to less accurate parameter estimates. Most dogs were classified as very or moderately distinct (in total: Pescara, 47 dogs, 88%; Lviv, 150 dogs, 82%) and were more likely to be correctly re-identified. It is worth noting that higher percentages of indistinct individuals may occur in free-roaming dog populations in other geographic areas. The applicability of photographic mark-recapture methods may be limited in populations with high proportions of indistinct individuals. For these populations, use of tags (such as ear tags) or other long-term individually identifiable markings could be used, but are less advantageous as the use of tags often requires capture and handling in order to read individual identifiers. Additionally, photographic mark-recapture studies may benefit from photograph matching software to reduce error rates and increase accuracy of parameter estimates (273).

In the study regions, the average detection probability was slightly lower than those reported in other studies of free-roaming dogs (Pescara 0.27, 95% CI 0.05 to 0.54; Lviv 0.18, 95% CI 0.02 to 0.40) (*Table 12*), which range between 0.33 and 0.68 for dog populations in Brazil and India (31,122,272,274). Detection probability is dependent upon an individual being: (i) present in the study area, (ii) available for detection, and (iii) detected during mark-recapture surveys (275). The slightly lower detection probability reported in this study could be due to differences in dog population size (i.e. if population size and detection probability are correlated), in the structure of the study areas leading to lower visibility of dogs (e.g. rural versus urban environments), in human-dog interactions (i.e. more positive interactions leading to higher detection probability), or in the mark-recapture models used to estimate this parameter (274).

Detection probability not only differs between individuals within a survey but may also differ between surveys due to differences in environmental conditions. The effects of weather variables were tested to determine whether these could explain differences in detection probability (Table 14). There were no influences of rain or temperature on detection probability in either study region. These findings are supported by other studies, that found temperature to have weak (27) or no significant effect (274,276), and rain to have no significant effect on detection probability (27,276). Tiwari *et al.,* (2018) (274) suggest rain may decrease detection probability, however, the authors describe the potential confounding effect of wind velocity, which was associated with heavy rainfall and had a significant effect on detection probability. Other studies have described significant effects of cloud cover (27,274), with increasing cloud coverage increasing detection probability. Whilst no evidence for significant effects of temperature or rainfall were found in this study, future mark-recapture studies should consider recording more detailed information about weather conditions, such as wind velocity and cloud coverage.

Several studies describe differences in the detection probability of dogs due to time of day effects (i.e. morning and afternoon) (27,274,276,277). Future studies may wish to also consider the potential influences of day of the week. In Lviv, detection probabilities were lower for surveys conducted on the weekend. This may relate to changes in human behaviour and activity at the weekend compared to on weekdays. Temporal differences could relate to changes in human activity or behaviour (27). In this study, surveys were always conducted between 7am and 9am. However, if people are less likely to be travelling for work at the weekend, there might be a reduction in human activity. Similarly, this study found a significant effect of market events on detection probability. This may again relate to human activity and behaviour, such as high aggregations of people and potential food resources. Tiwari *et al.,* (2018) (274) also found higher detection rates related to human events. Human activity and behaviour (for example, due to events or public holidays) need to be considered in mark-recapture analyses, particularly when interpreting results across time or areas.

Throughout the study, and in both study regions, few lactating females (Pescara: one female, 7%; Lviv: two females, 5%) and no visibly pregnant females were observed. The low numbers of visibly pregnant and lactating females may suggest that the birth rates in these managed populations are low. Few juveniles were observed in either study region (Pescara: one juvenile, 2%; Lviv: nine juveniles, 5%), also potentially indicating a low birth rate. However, juveniles may have a lower detection probability, for example, if puppies are hidden with their mother, out of sight of the observer, in dens, bushes or under cars.

There are also limitations in determining age through observation. The age of the dog was not able to be directly measured; instead individuals were determined to be either juveniles or adults. Estimates could therefore have been skewed towards a higher percentage of adults in the population. Additionally, the six-month interval between the third and fourth primary sampling periods (Figure 11) presents limitations. Individuals born in October, after the third primary period, may have been recorded as adults in the fourth primary period in April, as juvenile features may have been less observable six months later.

In both Pescara and Lviv, higher percentages of male dogs were observed (male to female sex ratio: Pescara, 1.90:1; Lviv, 2.35:1). Higher percentages of males are reported in numerous studies (165,173,204,235–238,278) and may be explained by a human preference for male dogs (17,30,279,280), male biased litters (235,238), and potentially lower mortality rate of male dogs (204), one possible factor relating to the lack of reproductive burden. It may be easier to determine the sex of male dogs through observations in street surveys, compared to females. In this study, similar percentages of unknown individuals (Pescara:12 dogs, 23%; Lviv: 48 dogs, 26%) and female individuals (Pescara: 14 dogs, 26%; Lviv: 40 dogs, 22%) were observed. It might be that if the sex of the unknown individuals had been determined, the percentage of females may have increased, leading to a more balanced male to female ratio.

Survival probability is a confounded variable, as it describes both the probability of an individual remaining in the study site (i.e. no emigration) and remaining alive. This is why it is termed “apparent survival”. The average monthly apparent survival probabilities in Pescara (95% CI 0.81 to 1.00) and Lviv (95% CI 0.84 to 0.99) were both 0.93, and similar to those reported in other studies (122,237). This suggests that 7% of the population per month is removed through deaths, or by movement to other populations, such as the restricted owned dog population, or to another section of the city. The recorded lifespan of free-roaming dogs is low, often reported as under three years for populations in Africa and Asia (204,235,237,240,281), although estimates are lacking for free-roaming dog populations in Europe. Lower lifespan coupled with the high movement rate could explain the removal probability. These results may indicate a less stable free-roaming dog population, which has important implications for dog population management. If the removal rates are high, those involved in management should: (i) ensure management covers the entire city, as movement of dogs between sections of the city could quickly repopulate areas, reaching carrying capacity through either births or migration; and (ii) owned free-roaming dog populations need to be included in dog population management. If unowned free-roaming dogs are mainly targeted, there could still be a proportion of intact, owned free-roaming dogs that would not be affected by the management.

In Lviv, males had a lower apparent survival probability than females (average lower probability of 0.33, 95% CI 0.06 to 0.59). Movement of individuals is related to resources and, for males, these resources may include seeking female mates, possibly resulting in increased migration and lower apparent survival probabilities compared to females. This is supported by studies investigating dispersal behaviour of free-roaming dogs (21,26), that find greater dispersal and movement in intact males, compared to females.

There was no evidence for significant effects of study site (within study regions) on apparent survival probability. This is particularly interesting for Lviv, where the different study sites had different levels of management intensity. This possibly indicates that dog population management does not influence the birth rate or migration rate of dog populations. A study by Belo *et al.,* (2017), also found no evidence for a significant effect of management intervention on apparent survival rates (122). However, as there were only four study sites, these results should be interpreted with caution. If more sites were included, a significant effect of dog population management on the apparent survival probability might be observed. Additionally, similar percentages of neutered dogs were observed across all study sites in Lviv (Table 17), even though no management had been recorded in study sites three and four (Table *8*). This could possibly explain the lack of observed effect of study site on survival probability.

Similar to survival probability, entry probability is confounded between births, abandonment and immigration. Entry probability was challenging to estimate in this model, due to the parameter expanded data augmentation. As described above, the conditional entry probability is estimated and converted to a per capita entry probability. In Pescara, this varied between 0.09 (95% CI: 0.00-0.22) and 0.20 (95% CI: 0.00-0.38), and in Lviv, between 0.12 (95% CI: 0.00-0.24) and 0.42 (95% CI: 0.26-0.62) across primary periods and study sites (Table 13). These rates are slightly higher than those reported by Belo *et al.,* (2017) (122), of between 0.00 and 0.15 for free-roaming dog populations in Brazil. In Pescara, the per capita entry probabilities were lowest in April 2019, but showed a decreasing trend across the primary sampling periods, possibly indicating a more stable population. In Lviv, the entry probability peaked in April 2019, suggesting more individuals entered the population between October 2018 and April 2019. This may be due to the longer time between the third and fourth primary periods (6-months; Figure 11). There was also an increase in population size in April 2019 in Lviv (Figure 14). It is challenging to disentangled whether these individuals were recruited through births or immigration. As few juveniles were observed, this suggests that most recruitment was occurring through immigration. However, as described above, there are limitations in determining age through observation, particularly for dogs born in October and observed the following April. Disentangling abandonment from either births or immigration is further challenging, as dogs may be abandoned at any age. If individuals were recruited through births, there is some support of seasonal reproduction in Lviv. Although domestic dogs are capable of breeding throughout the year, there is support for synchrony in breeding patterns among females (30), particularly in India (282). Population management targeted prior to seasonal free-roaming dog breeding may be more successful at reducing births.

In Pescara, estimates of dog population size and density were much smaller than in Lviv (7 dogs km^{-2} in Pescara, and 40 dogs km^{-2} in Lviv). As dog population size correlates with human population size (12), the difference in population estimates could relate to the smaller human population sizes in the study villages/towns in Pescara, compared to those in the study sites in the city of Lviv. In Pescara, the population decreased over the study period. Whilst this may be related to the population management, determining an effect of management would require a study that included a baseline period (prior to management intervention), a control population, and an increased number of study sites. Additionally, the length of the study would need to be increased, particularly as modelling studies suggest the effect of management may take years to materialise (118,134,139,283). Population management over shorter periods of time could create more stable populations, prior to decreasing the population size, and this would be reflected by low recruitment and removal rates.

4.5. Conclusions

This study has described the dog population dynamics in managed populations of dogs in Pescara, Italy and Lviv, Ukraine using Pollock's closed robust design – a method that incorporates both open and closed mark-recapture methods. This study has identified that detection probability of dogs may be influenced by day of the week, and human events, such as markets. Future researchers conducting mark-recapture of free-roaming dog populations should consider controlling for these effects – statistically or through study design – to ensure surveys are comparable across time and between areas. The removal rates observed in these study populations indicate less stable dog populations. It is therefore recommended that future management is conducted across cities and incorporates management of owned dog populations (preventing reproduction through restricted movement or reproductive control).

Chapter 5. Assessing the effectiveness of dog population management through systems modelling

5.1. Introduction

The global domestic dog population, which is estimated to be around 700 million (1), can be divided into subpopulations depending on their relationship with humans and their restriction status: (i) dogs can live in shelters and be part of the shelter dog population (unowned, restricted); (ii) dogs may be owned and restricted (i.e. not free-roaming; owned restricted); (iii) owned and unrestricted (i.e. owned free-roaming); and (iv) dogs may be unowned and unrestricted (i.e. stray dogs, unowned free-roaming). Often the population of most interest for dog population management is the free-roaming dog population (i.e. the street dog population, which includes owned and unowned dogs) (47). These subpopulations are interactive and dynamic – individuals can move between the different sub-populations through time (Figure 19). For example, during a dogs' lifespan, it may spend time as part of the shelter dog subpopulation, be adopted and move into the owned dog subpopulation, and be abandoned, moving into the unowned stray dog subpopulation.

As outlined in Chapter Two (systematic review), dog population management often aims to reduce the size and improve the overall health of the free-roaming dog population in order to reduce or eliminate the risks they present (48,49). Population size can be reduced by decreasing recruitment into, and increasing removal from, the population (97). Recruitment into a population typically occurs through births and immigration, and removal through mortality and emigration (97). As the dog population consists of interacting subpopulations, migration not only occurs between free-roaming dog populations in different geographic locations, but also between the subpopulations, providing additional sources of recruitment. For example, the abandonment of dogs from the owned dog population may increase the unowned, unrestricted (i.e. the stray dog) population size.

Methods of dog population management may involve reproductive control, sheltering, culling, and responsible ownership campaigns (47,48). Dog population management through reproductive control is recommended by the OIE (98). Reproductive control is often applied through the surgical removal of the gonads, although other forms of sterilisation and contraception are available (110). This is often carried out through CNR, where dogs are caught on the street, neutered in a mobile or fixed-location clinic, and returned to the location of capture within a few days. Sheltering is also a commonly used approach (48): dogs are removed from the street and taken into a shelter, whence they may be rehomed, stay in the shelter for life, or euthanised (107–109). Historically, culling was commonly used to control free-roaming dog populations (102). This method is not recommended by the OIE as it is thought to be less effective than other methods (98). Particularly as a disease control method, culling is regarded as ineffective at eliminating diseases, such as rabies (156). Despite this, culling still occurs in some countries (48), such as Albania, Moldova, and Ukraine (47). Responsible ownership campaigns can target dog owner practices, including controlling reproduction and preventing risks to humans and other animals, for example through restricting their movement and relinquishing animals responsibly (i.e. not abandoning dogs to the street) (98). Responsible ownership is included as an objective in the OIE stray dog population control guidelines (98) and may often be included as part of CNR campaigns.

Dog population management aims to alter the rates of recruitment and/or removal to reduce the free-roaming dog population size. Both culling and sheltering aim to increase rates of removal from the free-roaming dog population: culling increases rates of removal by increasing mortality; and sheltering increases removal by moving free-roaming dogs to the shelter dog population. Both CNR and responsible ownership campaigns aim to decrease rates of recruitment to the free-roaming dog population: CNR aims to decrease recruitment by decreasing birth rates; and responsible ownership campaigns, depending on the approach, may aim to decrease recruitment by reducing the abandonment of owned dogs.

Regardless of the method, dog population management requires the investment of resources (e.g. staff, facilities, and equipment) and may require long periods of time for their impact to materialise and their effectiveness to be evaluated. It is useful to model the impact of different dog population management methods to assess their potential effectiveness, whilst considering the interacting system of dog subpopulations.

Systems dynamics modelling is an approach used to model aspects of real-world systems of dynamic processes and simulate system behaviour through time (284–287). Computer simulation models that are continuous – rather than discrete – in time are based on differential (or integral) equations and are made up of two basic components: stocks (state variables; e.g. population, subpopulations) and flows (processes that change the state variables; e.g. births and deaths) (284,286). Another defining feature of systems is feedback behaviour; the state variables and flows interact in feedback loops that create the observed system behaviour (284,286,287).

Systems dynamics modelling can be used to understand causes of system behaviour and evaluate potential action that may alter system behaviour (284–287). System dynamics modelling has been used to model systems in numerous disciplines, including business (288,289), biological (290), environmental (291,292), food (293), and health systems (294). Systems dynamics modelling is advantageous in that it allows complex and interactive systems to be modelled and the impact of interventions on model behaviour to be evaluated (284–287). They also allow the effect of interventions to be evaluated *in silico* systems where it would be impractical, costly, or unethical to carry out real-life experimental interventions (284–287).

Systems modelling can help us to understand the potential effect of dog population management and provide insight into the possible long-term effectiveness of different interventions in reducing street dog population numbers. Systems modelling can also help to inform us about the potential resources required to reduce population size, for example, the neutering coverage required to reduce population size by a desired amount. Using this information, the financial and logistical resources required for each intervention can be calculated, providing important information about the potential costs of interventions. As dogs in different subpopulations have different risks in terms of health and welfare, the projected change in different subpopulation size can also inform us about the potential health and welfare risks related to management efforts.

Previous studies have investigated dog population dynamics through system dynamics (118,136,297,298,137,139,145,147,149,156,295,296) and agent-based models (134,283). Agent-based models (also known as individual-based models) study systems at the individual level. These models explore heterogeneity among individuals, interactions between individuals, and the adaptive behaviour of individuals to elucidate system-level behaviour (299–301). Systems models investigate the systems at a higher level. Previous modelling of the impact of dog population management has investigated: reproductive control (118,134,298,135–137,139,145,149,283,295), culling (134,149,156), sheltering (139), policies for increased awareness of sterilization and responsible dog ownership (136), and vaccination coverage (i.e. studies investigating the effect of population management on disease dynamics) (147,149,156,296,297). The purpose of these models have been to assess the effect of dog population management on dog population sizes (118,134,135,139,145,283,295,298), euthanasia rates (136), and disease dynamics (147,149,156,296,297).

Most of the previous studies have modelled the dynamics within a single subset of the dog population (e.g. owned or free-roaming) (118,134,137,147,149,283,295–298). Few have explicitly modelled several subsets and considered the interactions between these subpopulations (135,136,139,145). Of these studies, none have modelled the effect of all management methods described above on population dynamics, health and welfare. For the purpose of assessing different dog population management intervention, it is important to model sources of street dog increase, including the interaction between owned, shelter and street dog populations. Modelling the dynamics between the subpopulations could provide greater insight into the effectiveness of dog population management interventions in reducing dog population size.

The aim of this study was to compare the impact of different dog population management methods on the sizes of the different subpopulations of dogs using a system dynamics modelling approach (Figure 19). In relation to the groupings suggested in the systematic review (Chapter Two), the subpopulations of dogs were the: (i) street dog population – free-roaming dogs, including owned unrestricted and unowned unrestricted; (ii) shelter dog population – unowned restricted dogs; and (iii) owned dog population – owned restricted. This study also aimed to calculate the staff-resources required and the welfare costs of each intervention. The management methods under investigation included sheltering, culling, catch-neuter-release, and responsible ownership. The results of the systematic review (Chapter Two) indicated that management practices often involve combinations of dog population management methods. To reflect this, combined CNR and sheltering, and combined CNR and responsible ownership were also investigated.

The aim was met through the following objectives:

1) Develop a systems model to assess the impact of dog population management methods on dog population size, using parameter estimates sourced from previous chapters and from peer-reviewed literature where possible.
2) Conduct sensitivity analysis on the model parameters.
3) Run simulations for seven population management strategies: (i) baseline (i.e. no population management); (ii) sheltering only; (iii) culling only; (iv) catch-neuter-release only; (v) responsible ownership only; (vi) combined sheltering and catch-neuter-release; and (vii) combined responsible ownership and catch-neuter-release. Assess the impact of management methods on dog population size, when methods are applied for different periodicities (continuous and annual control) and at different coverages (i.e. management to different percentages of the population).
4) Estimate the staff-resources required and the welfare costs of each simulated population management strategy.

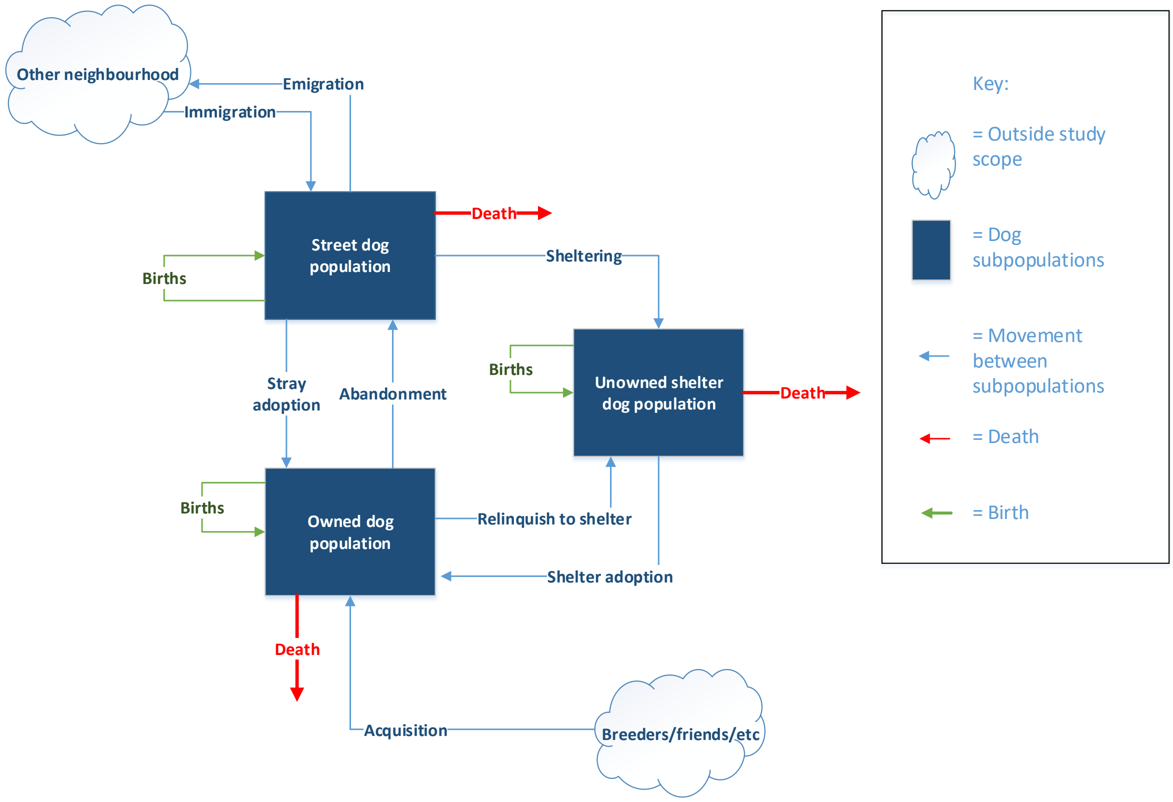

Figure 19. Process of dog subpopulation increase/decrease, including movement of dogs between different dog subpopulations.

5.2. Methods

5.2.1. Model description

This model described a population of dogs in an urban environment. The simulated environment was based on the city of Lviv, Ukraine. This city has an area of 182km^2 and a human population size of 717,803.

A causal loop diagram (Figure *20*) was constructed to describe the system of dog subpopulations and the influences of dog population management. The systems dynamics model divided the dog population into the following subpopulations (state variables/stocks): (i) street dog population (i.e. the free-roaming dog population, including both unowned and owned free-roaming), (ii) shelter dog population (unowned restricted), and (iii) owned dog population (owned restricted). The different subpopulations change in size by individuals flowing between the different subpopulations (intrinsically modelled) or from flows extrinsically modelled (e.g. acquisition of dogs from breeders and friends, increasing the owned dog population size). The model was kept simple in that different dog age and sex categories were not modelled explicitly. A more complex model would require estimates of rates for these different categories, which are challenging to obtain for all the described dog populations. This simplified model captures the overall dynamics, most importantly the flows that the management methods alter in order to reduce population size.

Ordinary differential equations were used to describe the systems model. The differential equations were written in R version 3.6.1 (222), and solved with 0.01 step sizes using the package “deSolve” (302), with the Runge–Kutta fourth-order method (303). For the baseline model, Equation 4, Equation 5, and Equation 6 were used to describe the system of dog populations in the absence of management.

Equation 4. Baseline street dog population.

$$\frac{dS}{dt} = \left(r_s \times S \times \left(1 - \frac{S}{K_s}\right)\right) + (\alpha \times O) - (\delta \times S)$$

Equation 5. Baseline shelter dog population.

$$\frac{dH}{dt} = (\gamma \times O) - (\beta \times H) - (\mu_h \times H)$$

Equation 6. Baseline owned dog population.

$$\frac{dO}{dt} = \left(r_o \times O \times (1 - \frac{O}{K_o})\right) + (\beta \times H) + (\delta \times S) - (\alpha \times O) - (\gamma \times O)$$

In the baseline model, the street dog population (*Equation 4*) increases through the street dog intrinsic growth rate (r_s), and abandonment of dogs from the owned dog population (α), and decreases through adoption to the owned dog population (δ). The growth rate is the sum of the effects of births, deaths, immigration and emigration, which are not modelled separately. The maximum intrinsic growth rate (also known as the Malthusian parameter, r_{max}) describes the maximum potential growth of the population. A population cannot increase indefinitely as it is limited by its environment to a carrying capacity (304). In this model, the growth rate of the street dog population is reduced depending on the population size in relation to the carrying capacity, through the logistic equation ($r_{real} = r_{max}(1-S/K_s)$) (305). This therefore models the population growth close to r_{max} when the population size is close to zero and models a negative population growth when the population is at or above the carrying capacity (i.e. population growth is a depicted by a sigmoid curve). In the baseline simulation, the street dog population rises over time, until it stabilises at an equilibrium size.

The shelter dog population (*Equation 5*) increases through relinquishment of owned dogs (γ) and decreases through the adoption of shelter dogs to the owned dog population (β). There is no carrying capacity for the shelter dog population, as it is assumed that more shelters will be built to house sheltered dogs as is necessary.

The owned dog population (*Equation 6*) increases through the owned dog growth rate (r_o), adoption of shelter dogs (β), and adoption of street dogs (δ); and decreases through abandonment of owned dogs (α), and relinquishment of owned dogs to the shelter dog population (γ). The growth rate of the owned dog population (r_o) combines the birth rate, death rate, and acquisition rate and was modelled as density dependent by the limit to growth logistic formula ($1-O/K_o$).

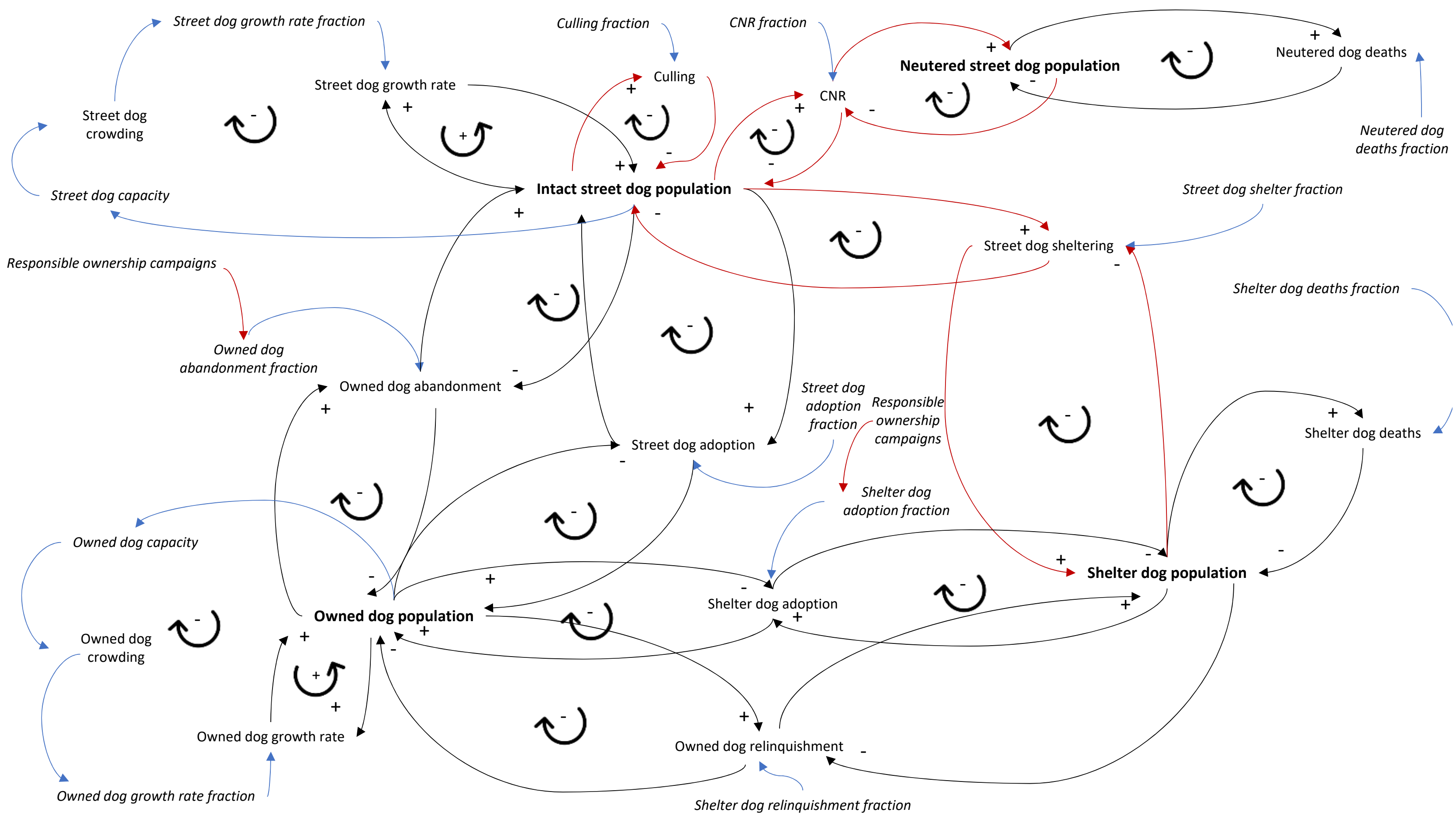

Figure 20. Causal loop diagram of the system of street, shelter and owned dog populations. Blue lines depict the dynamics of the subpopulations in the baseline scenario (i.e. no population management), red lines depict the dynamics in the intervention scenarios. Balancing loops are depicted by a negative symbol and arrow, reinforcing loops are depicted by a positive symbol and arrow.

5.2.2. Parameter estimates

Parameter estimates were extrapolated from thesis Chapters Three and Four and from literature (Table 19).

5.2.2.1. Initial population sizes (state variables)

Initial sizes of the dog populations were estimated for the baseline simulation. Initial population sizes for simulations including interventions were determined by the equilibrium population sizes from the baseline simulation (i.e. the stable population size, the points at which the populations were no longer increasing/decreasing).

To provide an initial street dog population size (*S*), the mark-recapture estimates for study sites in Lviv (Chapter Four) were converted to dogs km^{-2} and extrapolated to provide a city-wide estimate of approximately 14,000 dogs. I inflated this estimate, to account for the ongoing population management in Lviv, to an assumed initial population size of 20,000 dogs. The carrying capacity for street dogs in this urban environment depends on the availability of resources (i.e. food, shelter, water, and human attitudes and behaviour (98)). The carrying capacity is challenging to estimate for the street dog populations. In this systems model, I estimated that the street dog population was at a carrying capacity of 20,000 dogs.

The shelter dog population depends on the number of shelters in a city, and the number of dogs housed in these shelters. This model assumed that as dogs moved into the shelter dog population, the shelter population increased, but did not reach a capacity (i.e. more resources were created to house dogs, such as kennels). This allowed calculation of the resources required to house the number of shelter dogs. An initial shelter dog population size was estimated based on five currently registered shelters in Lviv (VIER PFOTEN International, personal communication), providing an initial shelter dog population (*H*) of 3,750 dogs (approximately 750 dogs per shelter).

The initial owned dog population (*O*) was extrapolated from the dog ownership estimates provided in the public attitude and dog ownership questionnaire (Chapter Three). The level of ownership reported in Ukraine was 56% and most owners had only one dog. In a city the size of Lviv (human population size: 717,803), and estimating approximately four people per household, this equated to an initial owned dog population (*O*) of 100,492 dogs. The owned dog population size was assumed to be at the carrying capacity (K_o).

5.2.2.2. Flows

Abandonment rate

Estimating the rate at which owned dogs are abandoned (α) is difficult, as owners are likely to under-report abandonment of dogs. The results of the public attitude and dog ownership questionnaire (Chapter Three) provided an indication of the rate of owned dog abandonment of between 0 and 0.0045 per dog over its lifetime. Given the likely under-reporting, and potential biases associated with questionnaire surveys, it can be assumed that the actual rate of abandonment is higher. Hsu, Severinghaus & Serpell (2003) reported a higher rate of abandonment of 0.05 per dog-owning lifetime in Taiwan (189), with a higher rate of 0.32 of respondents answering that they knew of someone who had abandoned a dog in their dog-owning lifetime (189). Fielding & Plumridge (2005) (191) in The Bahamas report an abandonment rate of around 0.05 per year, equating to approximately 0.004 abandonment rate per month. Given there may be differences in abandonment rates between different countries, and the likely under-reporting by respondents in the questionnaire, I estimated a monthly abandonment rate of slightly lower than reported by Fielding & Plumridge (2005) (191) of 0.003.

Adoption rate of shelter dogs/Rehoming rate

Shelter rehoming rates vary across shelters and countries, reported rates vary between 0.07 and 0.43 of the shelter population per year (306–312). Data from shelters in Lviv average at around 0.47 rehoming rate per year, equating to a rehoming rate of approximately 0.04 of the shelter dog population per month. Not all shelters within the city may be as successful, therefore I assumed a 0.025 rehoming rate (β) per month.

Intrinsic growth rate of street dog population

The intrinsic growth rate of a population (also referred to as the Malthusian parameter) describes the growing potential of a population. This rate can be estimated simply by births minus deaths (137,149), leading to estimates of 0.01 per month ((137) estimated using parameters from free-roaming dog populations in the USA by (244)) and 0.02 per month ((149) estimated using parameters from free-roaming dog populations in Tanzania (239)). Calculating the intrinsic growth rate using this simple calculation may not necessarily reflect the maximum intrinsic growth rate, instead reflecting the growth rate for a population under their current conditions (305). Maximum intrinsic growth rate can be estimated using fecundity and survivorship (e.g. Lotka equation (313–315)). In terms of dog populations, Acosta-Jamett *et al.,* (2010) (236) estimated the intrinsic growth rate of 0.02 per month for an owned population of dogs in Chile. Intrinsic growth rates are population specific (i.e. different populations may have different maximum intrinsic growth rates). To account for this factor, I modelled intrinsic growth rate at 0.03 per month and investigated the impact of altering the growth rate on the projected population sizes, at: 0.01 per month (slower growing population); 0.06 per month (faster growing population), and 0.10 per month (very fast-growing population).

Growth rate of owned dogs

As studies have reported a stable owned dog population over time (146), I assumed that demand for dogs was met quickly through a supply of dogs from owned dog births, breeders and friends. The maximum growth rate of owned dogs (r_o) was therefore assumed to be higher than that of street dog growth rate (r_s), at 0.07 per month.

Relinquishment rate of owned dogs

The rate of owned dog relinquishment was also difficult to estimate, as studies tended to report the percentage of the shelter dog population that have been relinquished each year, rather than how this equated to the percentage of the owned dog population. In Chapter Three, a relinquishment rate between 0.001 and 0.007 per dog-owning lifetime was reported. New *et al.,* (2004) (316) conducted a survey on households in the USA and reported an annual relinquishment rate of 0.008. I assumed the rate of owned dog relinquishment (γ) was the same as reported by New *et al.,* (2004) (316) at 0.008 per year, equating to 0.0007 per month.

Street dog adoption rate

There was evidence from the questionnaire survey in Chapter Three that some dog owners acquired their dogs from the street dog population (Bulgaria 35.5%, Italy 24.8%, and Ukraine 34.6%). An average (across the study countries) of 32% of owned dogs had been acquired from the street dog population. I assumed the street dog adoption rate (δ) was lower than the shelter adoption rate, at 0.007 per month.

Shelter dog death rate

In this simulation, I assumed shelters operated with a "no kill" policy (i.e. dogs were not killed in shelters as part of population management). The shelter dog death rate was included to incorporate deaths due to behavioural problems, health problems and natural mortality (e.g. due to age). I assumed that a shelter dog had a life expectancy of 10 years, slightly shorter than the life expectancy of owned dogs (between 12 to 14 years (317)). This equates to a shelter dog death rate (μ_h) of 0.008 per month.

Neutered dog death rate after release

Free-roaming dog death rates vary by age, sex, association with people (i.e. access to resources), and geographic location. Reported estimates vary between 0.15 and 0.52 per year, equating to approximately between 0.01 and 0.04 per month and a life expectancy of two to seven years (165,235,236,239). Using these reported estimates, I modelled neutered street dog death rate (μ_s) explicitly for the CNR intervention at a minimum death rate of 0.02 per month. I modelled a density dependent death rate (i.e. when the population becomes closer to the carrying capacity the death rate is greater). The death rate was a non-linear function of population size and carrying capacity modelled using a table lookup function (see Appendix D, Figure D1).

Table 19. Parameter description, parameter value, and minimum and maximum values used in the sensitivity analysis for the systems model. Rates are per month.

Parameter	Description	Value	Min	Max	Unit	Reference
S	Initial street dog population	20,000	NA	NA	Dogs	Extrapolated from Chapter Four
H	Initial shelter dog population	3750	NA	NA	Dogs	Assumption
O	Initial owned dog population	100,492	NA	NA	Dogs	Extrapolated from Chapter Three
K_s	Carrying capacity of street dog population	20,000	15,000	25,000	Dogs	(137)
K_o	Carrying capacity of owned dog population	100,492	90,000	110,000	Dogs	Extrapolated from

Parameter	Description	Value	Min	Max	Unit	Reference
						Chapter Three
α	Abandonment rate of owned dogs to street population	0.003	0.001	0.006	1/month	Assumption
β	Adoption rate of shelter dogs to owned population	0.025	0.015	0.035	1/month	(306–312) and Assumption
r_s	Maximum growth rate of street dog population	0.03	0.01	0.1	1/month	(137,149)
r_o	Maximum growth rate of owned dog population	0.07	0.0357	0.1125	1/month	Assumption
γ	Relinquishment rate of owned dogs to shelter population	0.0007	0.0003	0.001	1/month	Assumption
δ	Adoption rate of street dogs to owned population	0.007	0.0035	0.0105	1/month	Extrapolated from Chapter Three

Parameter	Description	Value	Min	Max	Unit	Reference
μ_h	Death rate of shelter dogs	0.008	0.005	0.02	1/month	Assumption
μ_s	Minimum death rate of neutered street dogs	0.02	NA	NA	1/month	(137,149)

5.2.3. Interventions

Six intervention scenarios were modelled (*Table 20*): sheltering; culling; CNR; responsible ownership; combined CNR and responsible ownership; and combined CNR and sheltering.

5.2.3.1. Sheltering intervention

To simulate a sheltering intervention, a proportion of the street dog population was removed and added to the shelter dog population at sheltering rate (σ). In the sheltering intervention, the populations were described by *Equation 7* (street dog population), *Equation 8* (shelter dog population), and *Equation 6* (owned dog population).

Equation 7. Street dog population with sheltering intervention

$$\frac{dS}{dt} = \left(r_s \times S \times \left(1 - \frac{S}{K_s}\right)\right) + (\alpha \times O) - (\delta \times S) - (\sigma \times S)$$

Equation 8. Shelter dog population with sheltering intervention.

$$\frac{dH}{dt} = (\gamma \times O) - (\beta \times H) - (\mu_s \times H) + (\sigma \times S)$$

5.2.3.2. Culling intervention

To simulate a culling intervention, a proportion of the street dog population was removed through culling (χ). In the culling intervention, the populations were described by Equation 9 (street dog population), *Equation 5* (shelter dog population), and *Equation 6* (owned dog population).

Equation 9. Street dog population with a culling intervention.

$$\frac{dS}{dt} = \left(r_s \times S \times \left(1 - \frac{S}{K_s}\right)\right) + (\alpha \times O) - (\delta \times S) - (\chi \times S)$$

5.2.3.3. CNR intervention

To simulate a CNR intervention, an additional stock was added to the system and was described by Equation 10: (iv) the neutered street dog population (*N*; neutered, free-roaming). In this simulation, a proportion of the intact (*I*) street dog population was removed and added to the neutered street dog population. A neutering rate (φ) was added to the differential equations describing the intact street and the neutered street dog populations. Neutering was assumed to be lifelong (e.g. CNR through the gonadectomy); a neutered street dog could not re-enter the intact street dog subpopulation. Neutered street dogs were removed from the population through the density dependent neutered dog death rate (μ_s);

death rate increased when the population was closer to the carrying capacity. In the CNR intervention, the populations were described by: Equation 10 (neutered street dog population); Equation *11* (intact street dog population); Equation 5 (shelter dog population); and Equation 6 (owned dog population). The total street dog population was calculated by combining the (i) intact street dog population and (iv) neutered, street dog population.

Equation 10. Neutered street dog population stock

$$\frac{dN}{dt} = (\varphi \times I) - (\mu_n \times N) - (\delta \times N)$$

Equation 11. Intact street dog population with neutering intervention.

$$\frac{dI}{dt} = \left(r_s \times I \times \left(1 - \frac{(I + N)}{K_s}\right)\right) + (\alpha \times O) - (\delta \times I) - (\varphi \times I)$$

5.2.3.4. Responsible ownership intervention

To simulate a responsible ownership intervention, I described the system of dog populations using Equation 4 (street dog population), Equation 5 (shelter dog population) and Equation 6 (owned dog population), but decreased the rate of abandonment (α) and increased the rate of shelter adoption (β).

5.2.3.5. Combinations of intervention

Combinations of interventions were also simulated: combined sheltering and CNR; and combined responsible ownership and CNR. To simulate combined sheltering and CNR, the dog populations were described by: Equation 12 (street dog population); Equation 10 (neutered street dog population); Equation 8 (shelter dog population); and Equation 6 (owned dog population). Combined CNR and sheltering interventions were simulated at half-coverage (e.g. intervention rate of 0.7 was simulated by 0.35 neutered and 0.35 sheltered).

Equation 12. Street dog population with combined CNR and sheltering interventions.

$$\frac{dI}{dt} = \left(r_s \times S \times \left(1 - \frac{(I + N)}{K_s} \right) \right) + (\alpha \times O) - (\delta \times I) - (\varphi \times I) - (\sigma \times I)$$

To simulate combined responsible ownership and CNR, the populations were described by: Equation 10 (neutered street dog population); Equation *11* (street dog population); Equation 5 (shelter dog population); and Equation 6 (owned dog population). The rate of abandonment (α) was decreased and the rate of shelter adoption (β) was increased.

5.2.4. Intervention length, periodicity and coverage

All simulations were run for 70 years. Initial population sizes were set to the baseline equilibrium levels. Interventions were applied for two lengths of time: (i) the full 70-year duration of the simulation; and (ii) a five-year period followed by no further intervention, to simulate a single period of investment in population management. In each of these simulations, I modelled the interventions at two periodicities: (i) a continuous intervention (e.g. a proportion of dogs neutered and released per month) and (ii) an annual intervention (intervention applied once per year). Interventions were run at three coverages: low, medium, and high. For continuous interventions, sheltering (σ), culling (χ), and CNR (φ) were applied continuously during the length of the intervention. For annual interventions, σ, χ, and φ were applied to the ordinary differential equations using a forcing function applied at 12-month intervals. In simulations that included responsible ownership intervention, the decrease in owned dog abandonment (α) and the increase in shelter adoption (β) was assumed instantaneous and continuous (i.e. rates did not change throughout the intervention). Table *20* describes the parameter rates for the different coverages and periodicities.

5.2.5. Testing the impact of different street dog intrinsic population growth rates

To test the impact of different intrinsic population growth rates, interventions were run continuously for the duration of the simulation at three additional growth rates: 0.01, 0.06 and 0.10. From this simulation, I calculated: (i) equilibrium population size; and (ii) percent decrease in street dog population size.

Table 20. Description of intervention parameters and coverages for simulations applied at continuous and annual periodicities.

		Coverage					
		Low		**Medium**		**High**	
Intervention	**Parameter**	**Continuous**	**Annual**	**Continuous**	**Annual**	**Continuous**	**Annual**
Culling	Culling rate (χ)	0.0167	0.2	0.0333	0.4	0.0583	0.7
Sheltering	Sheltering rate (σ)	0.0167	0.2	0.0333	0.4	0.0583	0.7
CNR	Neutering rate (φ)	0.0167	0.2	0.0333	0.4	0.0583	0.7
Responsible ownership	Abandonment rate (α)	0.0021	0.0021	0.0012	0.0012	0.0003	0.0003
	Adoption rate (β)	0.0325	0.0325	0.04	0.04	0.0475	0.0475
Combined CNR & responsible ownership	Neutering rate (φ)	0.0167	0.2	0.0333	0.4	0.0583	0.7
	Abandonment rate (α)	0.0021	0.0021	0.0012	0.0012	0.0003	0.0003
	Adoption rate (β)	0.0325	0.0325	0.04	0.04	0.0475	0.0475

		Coverage					
		Low		Medium		High	
Intervention	**Parameter**	**Continuous**	**Annual**	**Continuous**	**Annual**	**Continuous**	**Annual**
Combined CNR & sheltering	Sheltering rate (σ)	0.00835	0.1	0.01665	0.2	0.02915	0.35
	Neutering rate (φ)	0.00835	0.1	0.01665	0.2	0.02915	0.35

5.2.6. Model outputs

The primary outcome of interest was the impact of interventions on street dog population size. For interventions applied for the duration of the simulation, I calculated: (i) equilibrium population size for each population; (ii) percent decrease in street dog population; (iii) costs of intervention in terms of staff-time; and (iv) an overall welfare score. For interventions applied for a five-year period, I calculated: (i) minimum street dog population size and percent reduction from initial population size; (ii) the length of time between the end of the intervention and time-point at which the street dog population reached an equilibrium size; (iii) equilibrium population size; (iv) cost of intervention in terms of staff-time; and (v) an overall welfare score.

Cost calculations

The costs of population management interventions vary by country (e.g. staff salaries vary between countries) and by the method of application (e.g. method of culling, or resources provided in a shelter). To enable a comparison of the resources required for each intervention, the staff-time (staff-working-months) required to achieve the intervention coverage was calculated. While this does not incorporate the full costs of an intervention, as equipment (e.g. surgical equipment), advertising campaigns, travel costs for the animal care team (if not locally based), and facilities (e.g. clinic or shelter costs) are not included, it can be used as a proxy for intervention cost. Using data provided from VIER PFOTEN International, I estimated the average number of staff required to catch and neuter/shelter/cull the street dog population and to house the shelter dog population in each intervention. The number of dogs that can be cared for per shelter staff varies by shelter. To account for this, I estimated two staff-to-dog ratios (low and high). Table *21* describes the staff requirements for the different interventions. For interventions including responsible ownership campaigns, it was estimated that a low coverage campaign required two full-time members of staff, a medium coverage campaign required three, and a high coverage campaign required four.

Using the projected population sizes, the staff-time required for each staff type (e.g. number of veterinarian-months of work required) was calculated for each intervention. Relative salaries for the different staff types were estimated (Table *21*). The relative salaries were used to calculate the cost of the interventions by:

[*(staff-time required)* x *(relative salary)*] x (€20,000).

Where €20,000 is the estimated annual salary of a European veterinarian. This allowed relative staff-time costs to be compared between the different interventions. Average annual costs were reported.

Table 21. Staff required for interventions and the number of dogs processed per staff per day.

Staff type	Baseline	CNR	Sheltering	Culling	Responsible ownership	Dogs/Staff/Day	Relative salary
Veterinarian	No	Yes	No	No	No	6	1
Veterinary nurse	No	Yes	No	No	No	8	0.65
Dog catchers	No	Yes	Yes	Yes	No	13	0.56
Kennel staff	Yes	Yes	Yes	Yes	Yes	13 (low) 120 (high)	0.5
Campaigner	No	No	No	No	Yes	NA	0.75

Welfare calculations

To provide overall welfare scores for each of the interventions, I followed the method described by Hogasen *et al.,* (2013) (139). Hogasen *et al.,* (2013) (139) have previously estimated welfare scores, on a one to five scale, for each of the dog subpopulations. This scale is based on the Five Freedoms (i. freedom from hunger and thirst, ii. freedom from discomfort, iii. freedom from pain, injury or disease, iv. freedom to express normal behaviour, and v. freedom from fear and distress (318,319)) and was calculated using expert opinions from 60 veterinarians in Italy. The scores were weighted by the participants self-reported knowledge of different dog subpopulations.

2.8 for shelter dogs (W_H); 3.5 for owned dogs (W_O); 3.1 for neutered street dogs (W_N); and 2.3 for intact street dogs (W_I).

Using these estimated welfare scores, I calculated an overall welfare score for the total dog population based on the model's projected population sizes for each subpopulation. Welfare scores were calculated using Equation 13. For interventions running for the duration of the simulation, the welfare score was calculated at time point (*t*) when the population reached an equilibrium size. For interventions running for five years, the welfare score was calculated at time point (*t*) at the end of the five-year intervention. The percentage change in welfare scores from the baseline simulation were reported.

Equation 13

$$Welfare\ score = \frac{H_t \times W_H + O_t \times W_O + N_t \times W_N + I_t \times W_I}{H_t + O_t + N_t + I_t}$$

5.2.7. Model validation and sensitivity analysis

The behaviour of the baseline model was evaluated to ensure simulated numbers of dogs in the different populations reached an equilibrium. A global sensitivity analysis was conducted on all parameters described in the baseline simulation (Table 19). A Latin square design algorithm was used in package “FME” (320) to sample the parameters within their range of values (Table 19). The effects of altering individual parameters (local sensitivity analysis) on the population equilibrium was also examined using the Latin square design algorithm to sample each parameter, individually, within their range of values (Table 19). Sensitivity analyses were run for one-hundred simulations over 600 months (50 years) solved with 0.01 step sizes.

5.3. Results

5.3.1. Model validation and sensitivity analysis

The model simulated the sizes of street, owned and shelter dog populations within realistic boundaries (e.g. no population size estimates below zero). A global sensitivity analysis was performed to assess the interaction of a range of parameter values on the size of the dog populations. Over the 50-year simulations, the (A) simulated street dog populations stabilised at an equilibrium of a minimum 14,267 and a maximum 35,011 dogs; (B) shelter dog populations stabilised at a minimum of 596 and a maximum of 4140 dogs; (C) owned dog population stabilised at a minimum of 84,737 and a maximum of 109,236 dogs (Figure 21). Results of sensitivity analysis for individual parameters ranges on the population equilibrium levels are presented in the Appendix D, Figures D2 and D3.

5.3.2. Simulation results

5.3.2.1. Results for interventions applied for full duration of simulation (70 years)

Table *22* outlines the impact of interventions applied for the full duration of the simulation when interventions were applied both continuously and annually at low, medium and high coverages. All interventions reduced the street dog population size. The overall greatest reduction in street dog population size (90% reduction) was achieved by combined high coverage CNR and responsible ownership applied continuously.

Figure 22, Figure 23, and Figure 24 show the results of interventions run annually for the street, shelter and owned dog populations. As annual interventions did not reach a single stable equilibrium point but varied between two points due to the annual interventions, the average of the minimum and maximum equilibrium level was reported. The greatest overall reduction for annual interventions was achieved by combined CNR and responsible ownership applied at a high coverage. This reduced street dog equilibrium population size by an average of 89%. At medium coverages, combined CNR and responsible ownership had the greatest reduction in street dog equilibrium population size by an average 55%. When interventions were applied annually at low coverages, culling achieved the greatest reduction in street dog equilibrium population size by an average of 29%.

Figure 25, Figure 26 and Figure 27 show the results of interventions run continuously for the street, shelter and owned dog populations. At high and medium continuous coverages, combined CNR and responsible ownership achieved the greatest reductions in street dog equilibrium population size, by 90% and 57% respectively. At low continuous coverages, the greatest reduction in street dog equilibrium population size was achieved by culling, which reduced the street dog population size by 31%. Sheltering (31% reduction) and combined CNR and responsible ownership (29% reduction) both similarly reduced street dog equilibrium population size.

For both interventions applied annually and continuously, there was little impact of CNR and culling on shelter dog population size. Responsible ownership and combined CNR and responsible ownership slightly reduced shelter dog population size. This is due to the increased shelter adoption rate (β). Sheltering and combined CNR and sheltering increased shelter dog population size through an increased sheltering rate (σ) moving street dogs to the shelter dog population (Table *22* and Figure *23*).

For both interventions applied annually and continuously, CNR and culling reduced owned dog population size. This is due to a reduction in the street dog population size which therefore reduced the number of dogs moving into the owned dog population through street adoption (δ). Interventions including responsible ownership (responsible ownership and combined CNR and responsible ownership) increased the owned dog population size through an increase in the shelter adoption rate (β). Interventions including sheltering (sheltering and combined CNR and sheltering) also increased owned dog population size through an increase in the shelter dog population which increased the number of dogs moving to the owned dog population through shelter adoption (β) (Table *22* and Figure *24*).

When comparing interventions applied continuously and annually, the interventions applied continuously had a marginally greater reduction in dog population size than interventions applied annually. Figure 28 shows the proportion of the street dog populations that are neutered for interventions that included CNR when applied continuously and annually. Overall, the greatest proportion of neutered dogs was 0.77, achieved by annually applied high coverage combined CNR and responsible ownership.

To account for differences in staff-to-dog ratios in shelters, a low (13 dogs per staff member) and a high (120 dogs per staff member) staff-to-dog ratio was calculated. The cheapest intervention overall was responsible ownership applied continuously at a high coverage (average annual costs €120,690 for high, and €761,314 for low staff-to-dog ratio; Table *22*). This was only slightly cheaper than combined CNR and responsible ownership applied continuously at high coverage (€130,727 for high, and €762,187 for low staff-to-dog ratio). The most expensive intervention was sheltering applied continuously at high coverages (€849,490 for high, and €7,753,805 for low staff-to-dog ratio). For interventions applied annually (responsible ownership is not included as it was assumed to have continuous effects), culling was the cheapest intervention for all coverages for high staff-to-dog ratios, and combined CNR and responsible ownership was the cheapest intervention for all coverages for low staff-to-dog ratios.

The greatest improvement in overall welfare score was achieved by combined CNR and responsible ownership for interventions applied continuously and annually at all coverages (Table *22*), improving the welfare score by 6.58% and 6.71% respectively. The lowest improvement in welfare score was by responsible ownership at low coverages, which improved the welfare score by 0.57%.

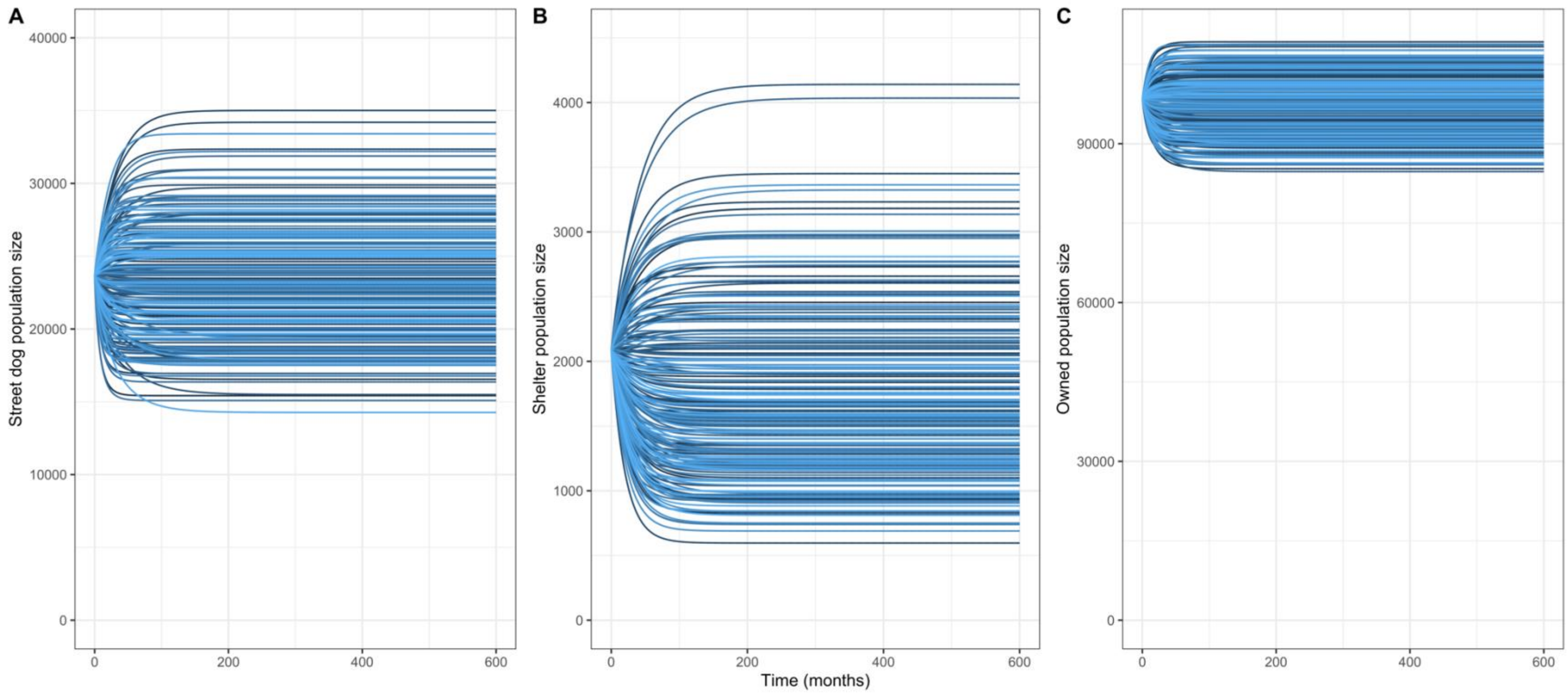

Figure 21. Results of global sensitivity analysis on the (A) street, (B) shelter, and (C) owned dog population sizes. Simulations generated 100 times and run for 1000 months (83-years).

Table 22. Impact of interventions on street (S), shelter (H) and owned (O) dog population equilibrium levels and percent change from baseline population equilibrium levels for interventions applied for the duration of the simulation at low, medium and high coverages. The intervention with the greatest reduction in street dog population size for each periodicity-coverage combination is highlighted in grey. The greatest increase in welfare scores and the lowest average annual costs for each periodicity-coverage combination are highlighted in bold.

			Equilibrium population size			**Percentage population change (%)**			**Welfare score and % change**	**Average annual cost (€)**	
										Shelter staff-to-dog ratio	
Periodicity	Coverage	Intervention	S	H	O	S	H	O		High	Low
NA	NA	Baseline	23651	2086	98358	0	0	0	3.26 (NA)	119,559	1,103,620
Annual	Low	CNR	19364	2065	97358	-18	-1	-1	3.33 (2.13%)	164,965	1,179,519

Periodicity	Coverage	Intervention	**Equilibrium population size** S	H	O	**Percentage population change (%)** S	H	O	**Welfare score and % change**	**Average annual cost (€)** **Shelter staff-to-dog ratio** High	Low
		CNR & responsible ownership	17130	1702	98454	-28	-18	0	**3.35 (2.84%)**	159,548	**1,002,944**
		0.5 CNR & 0.5 sheltering	18316	5598	98720	-23	168	0	3.31 (1.54%)	351,178	3,048,653
		Culling	**16690**	2072	97671	**-29**	-1	-1	3.31 (1.62%)	**131,028**	1,142,971
		Sheltering	16882	10063	100428	-29	382	2	3.28 (0.76%)	588,204	5,367,903
	Medium	CNR	17232	2054	96854	-27	-2	-2	3.37 (3.27%)	181,908	1,191,651

Periodicity	Coverage	Intervention	**Equilibrium population size** S	H	O	**Percentage population change (%)** S	H	O	**Welfare score and % change**	**Average annual cost (€)** **Shelter staff-to-dog ratio** High	Low
		CNR & responsible ownership	**10714**	1445	99117	**-55**	-31	1	**3.42 (4.77%)**	156,501	**877,309**
		0.5 CNR & 0.5 sheltering	15113	6664	98587	-36	219	0	3.34 (2.60%)	429,451	3,687,716
		Culling	11630	2061	97155	-51	-1	-1	3.36 (2.99%)	**134,410**	1,146,945
		Sheltering	11898	13217	101004	-50	533	3	3.31 (1.62%)	784,217	7,143,262
	High	CNR	15570	2047	96523	-34	-2	-2	3.39 (4.07%)	196,557	1,203,011

Periodicity	Coverage	Intervention	**Equilibrium population size** S	H	O	**Percentage population change (%)** S	H	O	**Welfare score and % change**	**Average annual cost (€)** **Shelter staff-to-dog ratio** High	Low
		CNR & responsible ownership	**2682**	1261	100007	**-89**	-40	2	**3.47 (6.58%)**	139,026	**770,623**
		0.5 CNR & 0.5 sheltering	12187	7046	98364	-48	238	0	3.37 (3.48%)	466,462	3,961,066
		Culling	7231	2051	96698	-69	-2	-2	3.40 (4.33%)	**136,569**	1,144,708
		Sheltering	7474	14015	100849	-68	572	3	3.35 (2.65%)	851,283	7,738,607
	Low	CNR	19088	2064	97292	-19	-1	-1	3.34 (2.32%)	162,359	1,176,433

Periodicity	Coverage	Intervention	**Equilibrium population size** S	H	O	**Percentage population change (%)** S	H	O	**Welfare score and % change**	**Average annual cost (€)** **Shelter staff-to-dog ratio** High	Low
Continuous		CNR & responsible ownership	16836	1701	98392	-29	-18	0	**3.36 (3.01%)**	157,107	1,000,141
		0.5 CNR & 0.5 sheltering	17971	5722	98720	-24	174	0	3.31 (1.70%)	366,744	3,131,743
		Culling	**16229**	2071	97612	**-31**	-1	-1	3.32 (1.84%)	130,634	1,147,611
		Responsible ownership	21739	1719	99475	-8	-18	1	3.28 (0.57%)	**124,844**	**976,036**

Periodicity	Coverage	Intervention	Equilibrium population size			Percentage population change (%)			Welfare score and % change	Average annual cost (€) Shelter staff-to-dog ratio	
			S	H	O	S	H	O		High	Low
		Sheltering	16436	10450	100553	-31	401	2	3.29 (0.87%)	611,772	5,588,233
	Medium	CNR	16922	2053	96786	-28	-2	-2	3.37 (3.48%)	172,574	1,181,859
		CNR & responsible ownership	**10277**	1445	99071	**-57**	-31	1	**3.42 (4.94%)**	150,133	870,750
		0.5 CNR & 0.5 sheltering	14607	6722	98564	-38	222	0	3.35 (2.80%)	435,248	3,736,621
		Culling	10917	2059	97072	-54	-1	-1	3.37 (3.32%)	132,644	1,144,582

Periodicity	Coverage	Intervention	**Equilibrium population size** S	H	O	**Percentage population change (%)** S	H	O	**Welfare score and % change**	**Average annual cost (€)** / **Shelter staff-to-dog ratio** High	Low
		Responsible ownership	19466	1466	100547	-18	-30	2	3.30 (1.22%)	**120,863**	**851,095**
		Sheltering	11193	13438	101065	-53	544	3	3.32 (1.80%)	799,722	7,300,451
	High	CNR	15177	2046	96461	-36	-2	-2	3.40 (4.28%)	176,965	1,183,033
		CNR & responsible ownership	**2477**	1261	99994	**-90**	-40	2	**3.48 (6.71%)**	130,727	762,187

Periodicity	Coverage	Intervention	**Equilibrium population size** S	H	O	**Percentage population change (%)** S	H	O	**Welfare score and % change**	**Average annual cost (€)** **Shelter staff-to-dog ratio** High	Low
		0.5 CNR & 0.5 sheltering	11571	7034	98320	-51	237	0	3.38 (3.70%)	460,738	3,969,868
		Culling	6445	2049	96612	-73	-2	-2	3.41 (4.70%)	132,734	1,140,277
		Responsible ownership	16560	1281	101555	-30	-39	3	3.33 (2.04%)	**120,690**	**761,314**
		Sheltering	6674	13929	100805	-72	568	2	3.35 (2.89%)	849,490	7,753,805

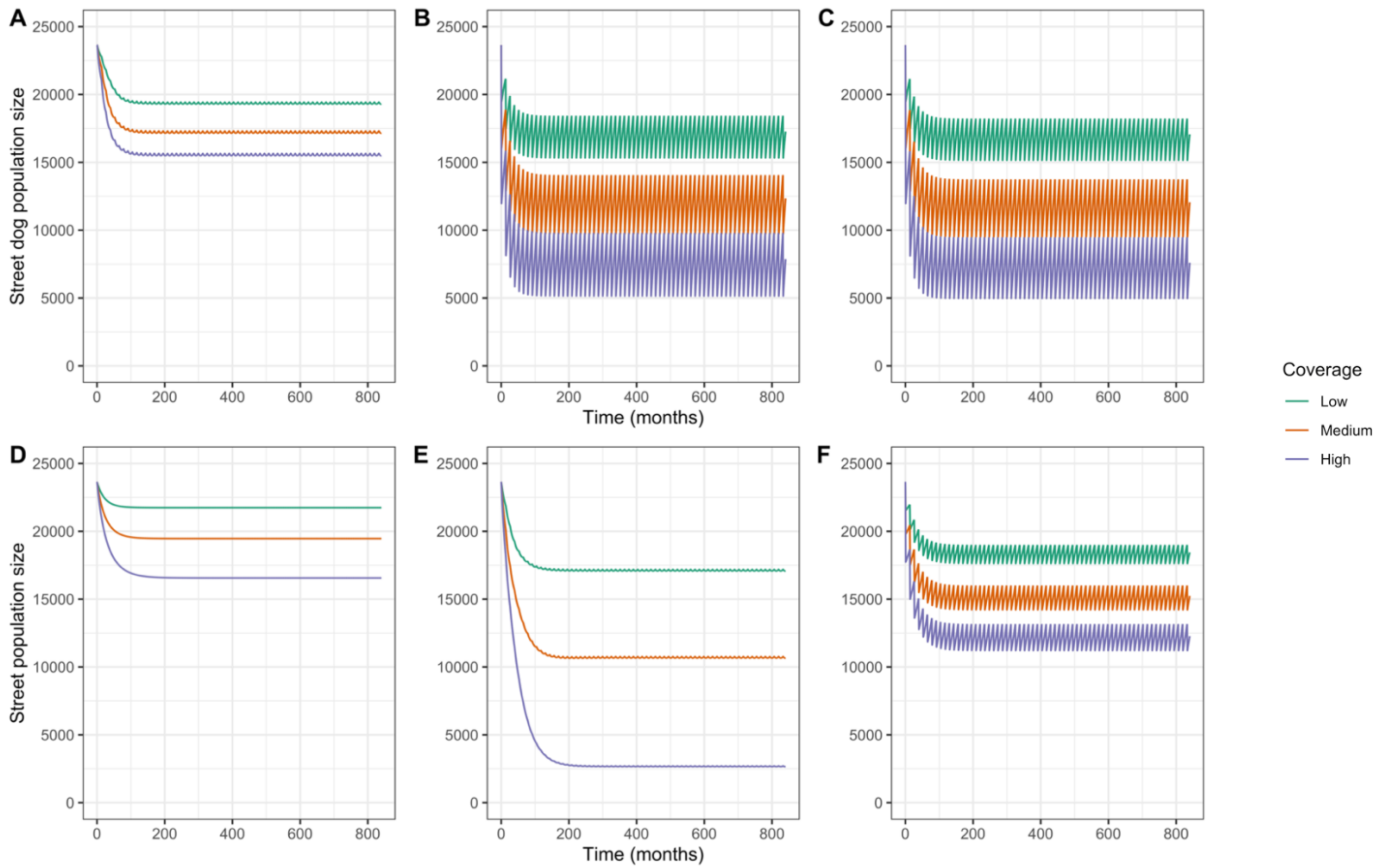

Figure 22. Impact of annual interventions on street dog population. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering run for duration of simulation at low, medium and high coverages.

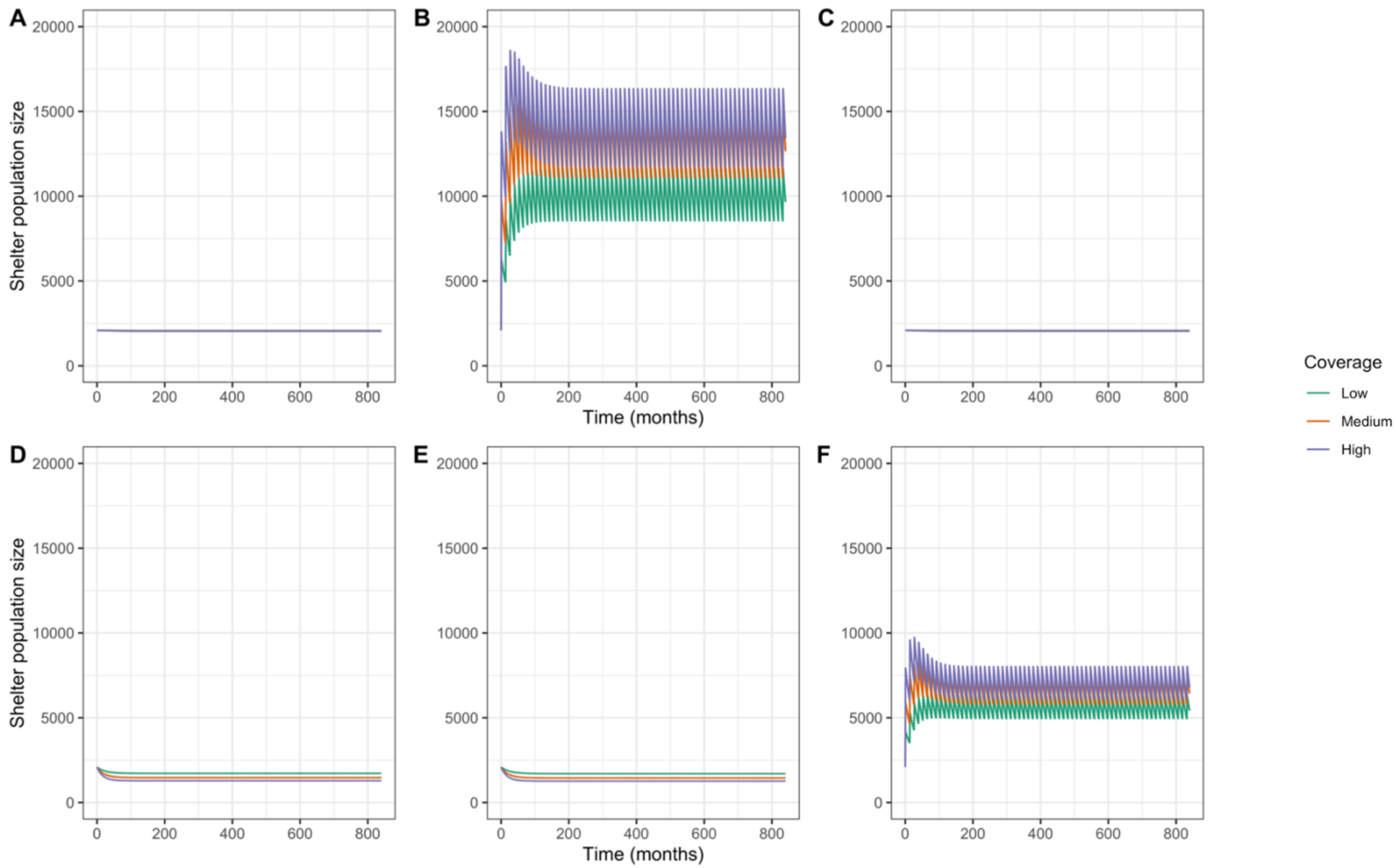

Figure 23. Impact of annual interventions on shelter dog population. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering run for duration of simulation at low, medium and high coverages.

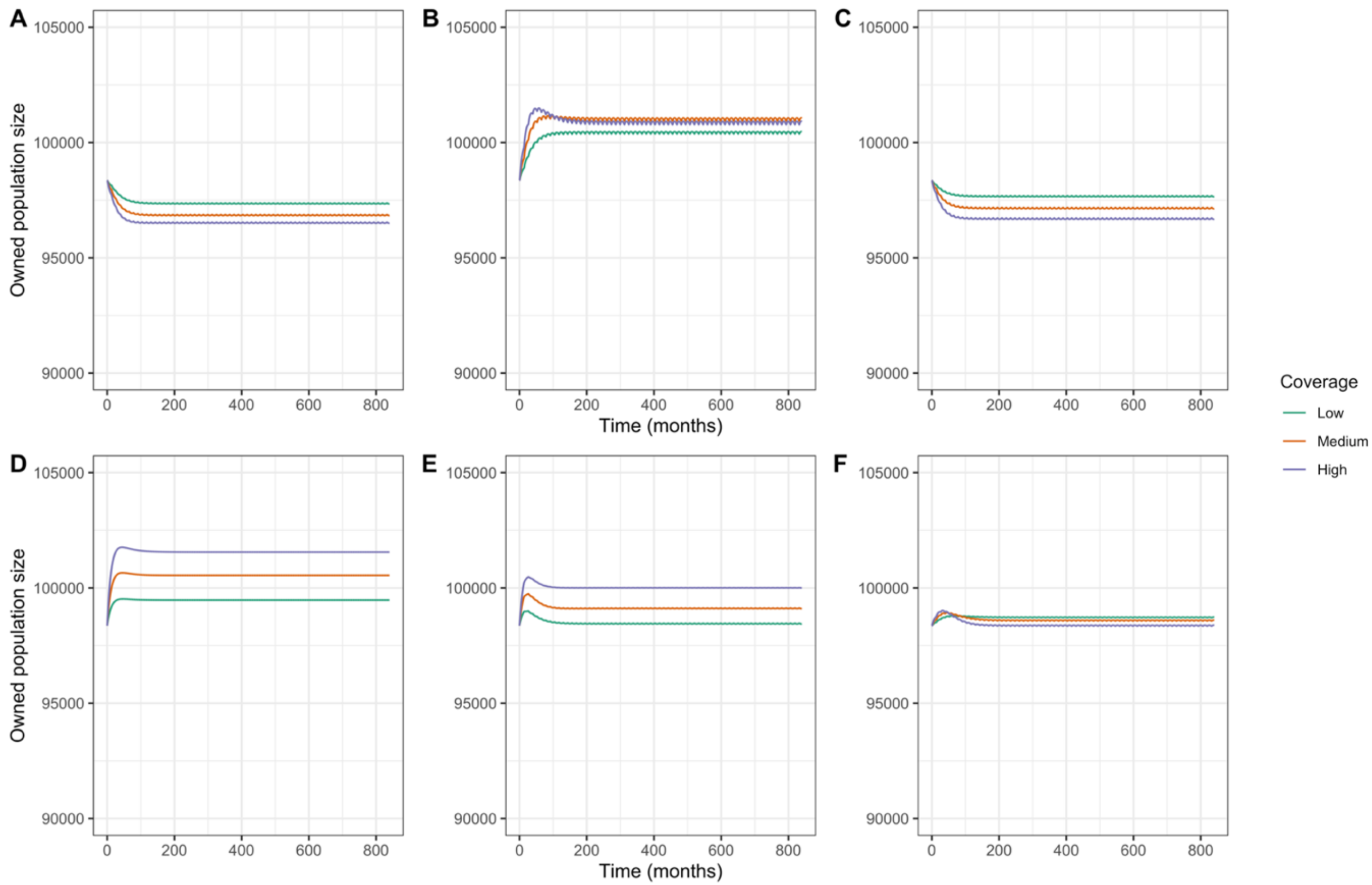

Figure 24. Impact of annual interventions on owned dog population. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering run for duration of simulation at low, medium and high coverages.

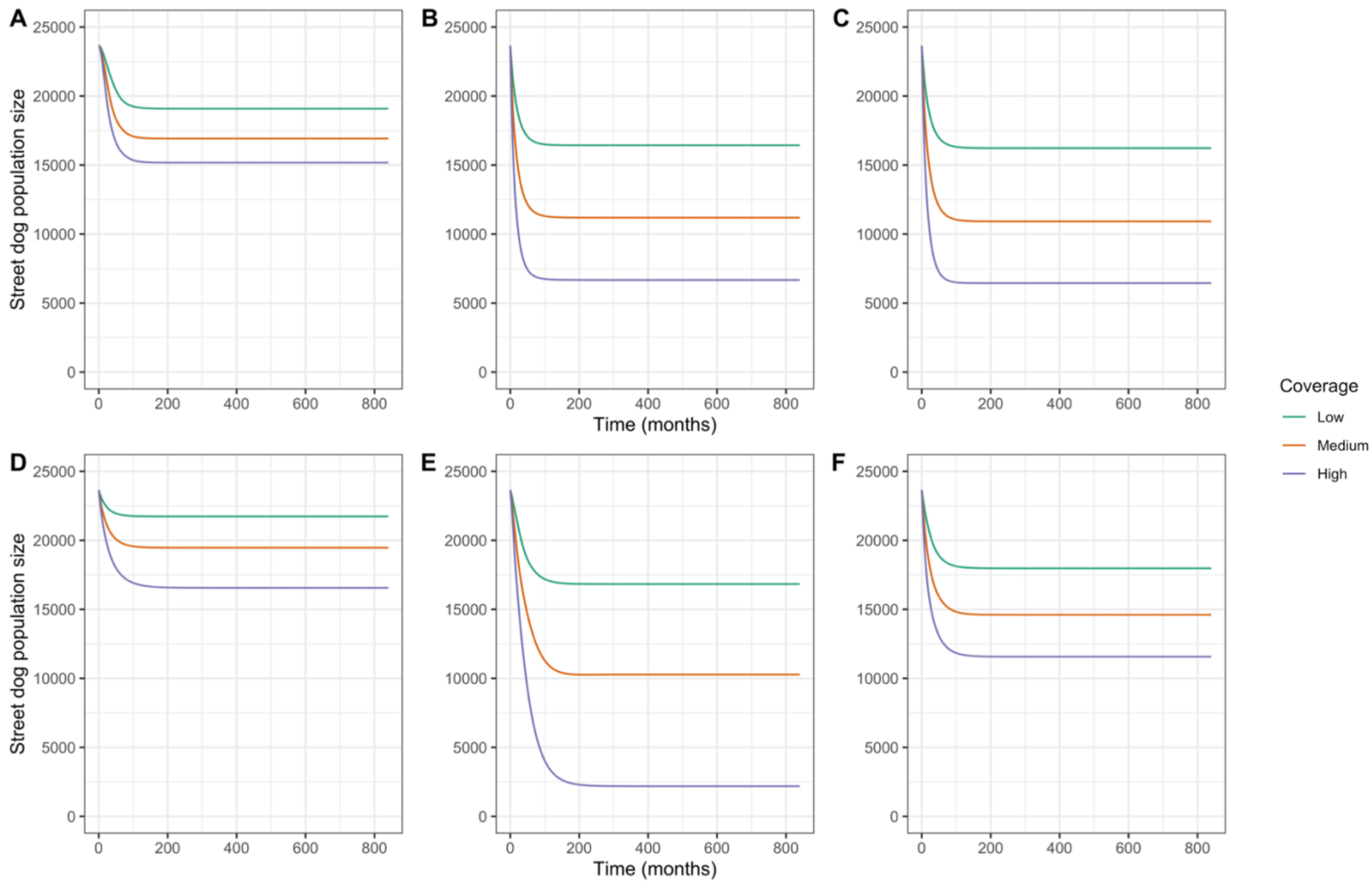

Figure 25. Impact of continuous interventions street dog population size. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering run for duration of simulation at low, medium and high coverages.

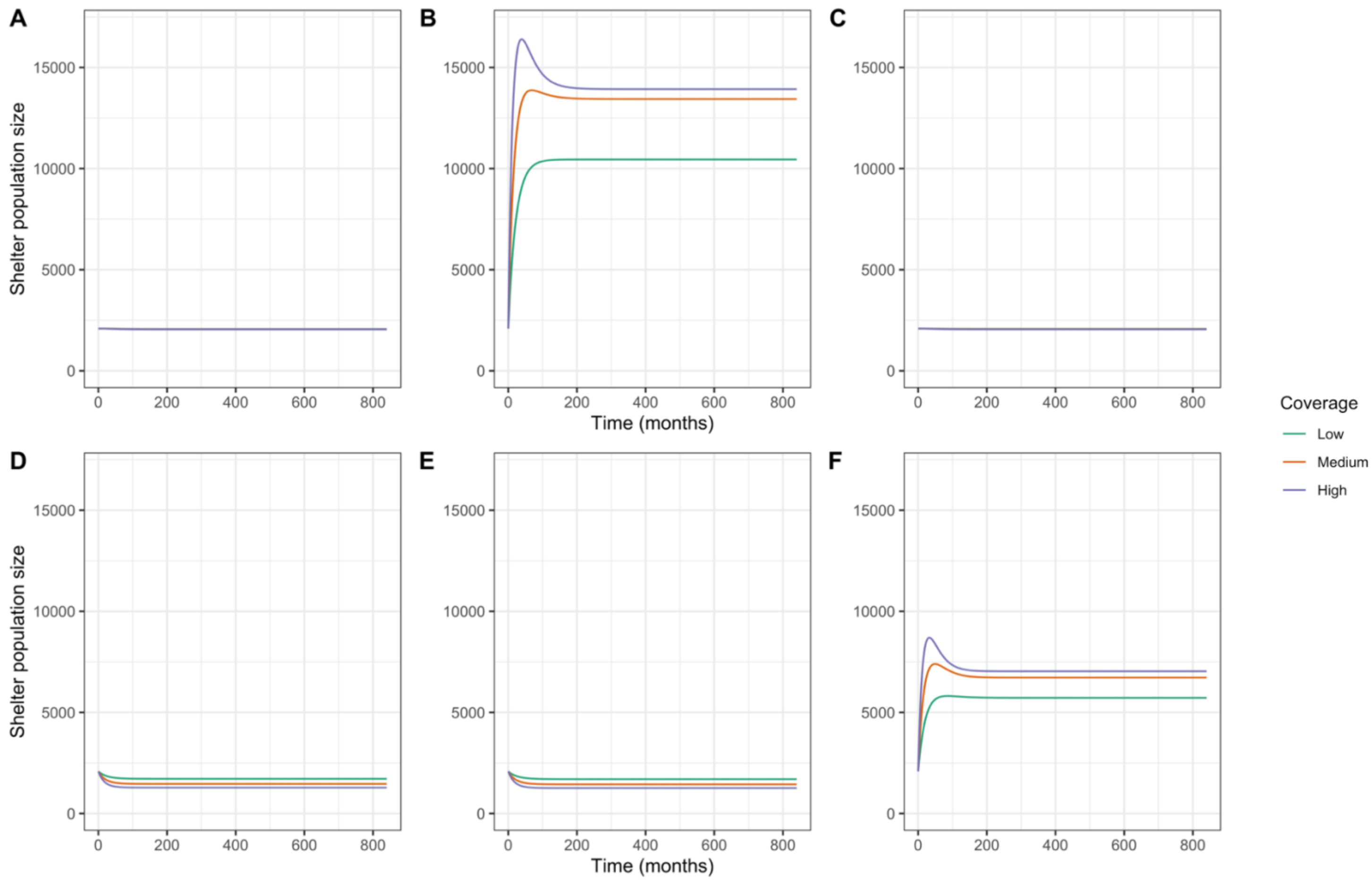

Figure 26. Impact of continuous interventions on shelter dog population size. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering run for duration of simulation at low, medium and high coverages.

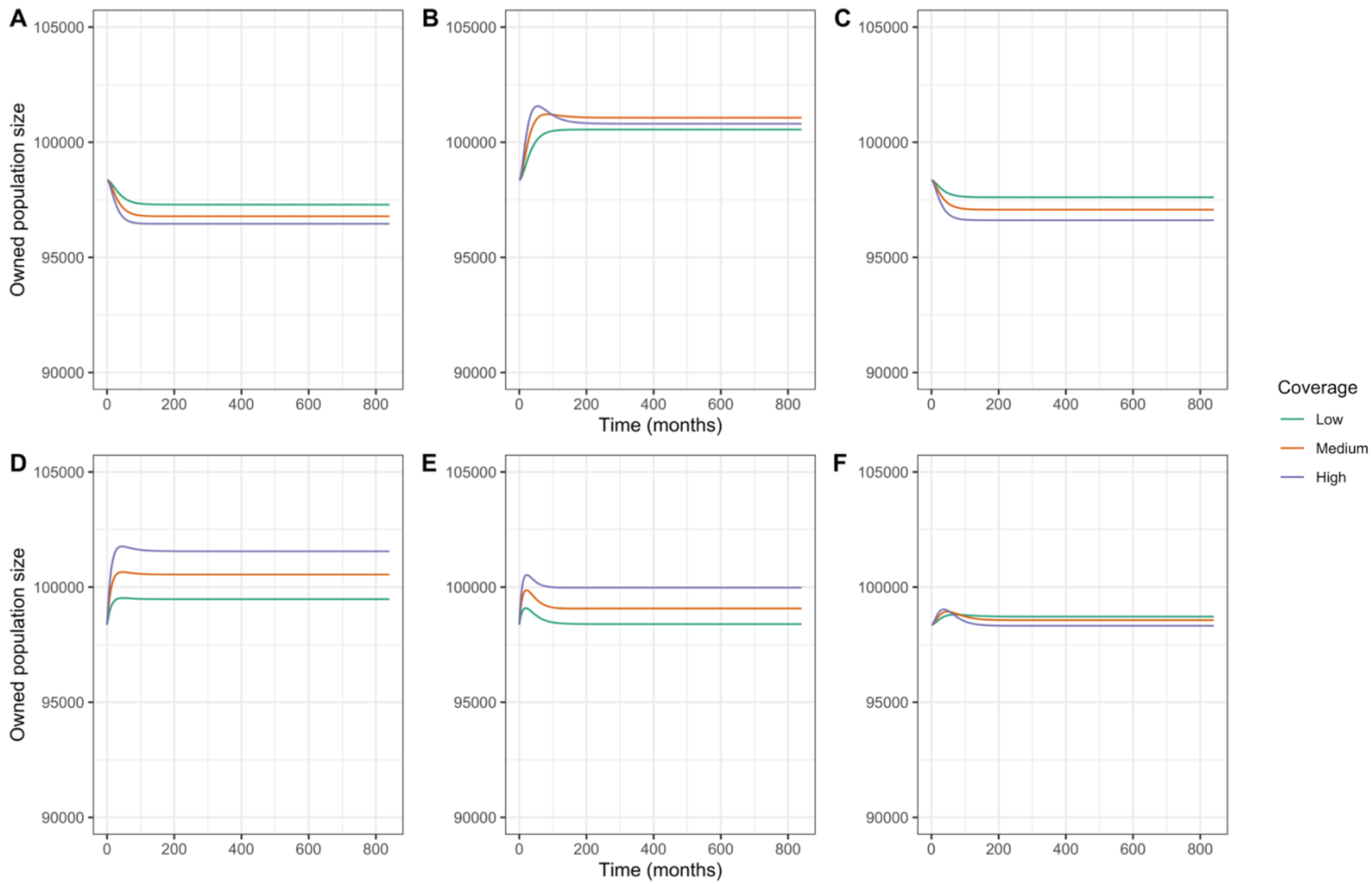

Figure 27. Impact of continuous interventions on owned dog population size. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering run for duration of simulation at low, medium and high coverages.

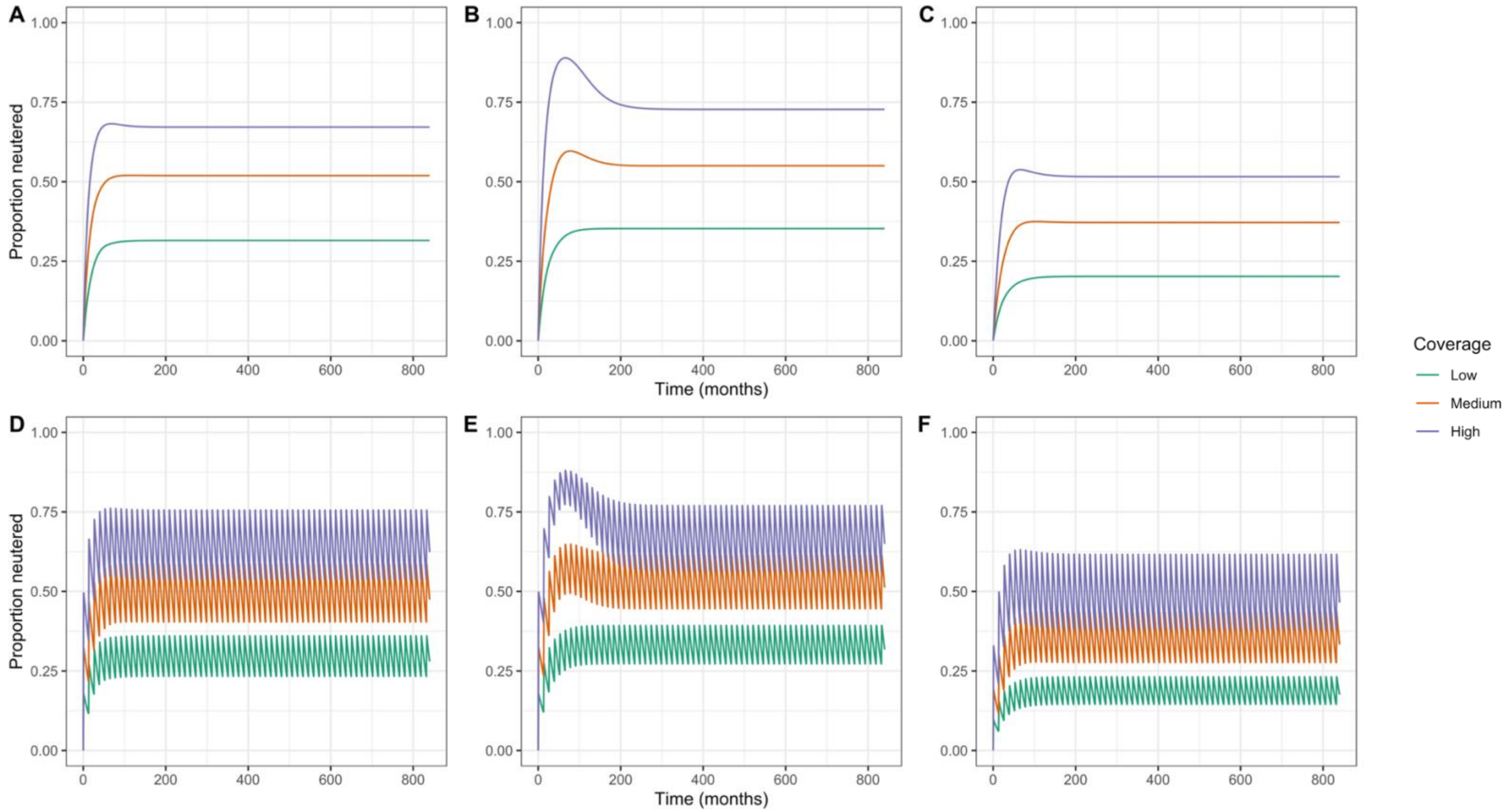

Figure 28. Proportion of street dogs neutered for interventions including CNR and applied for duration of the simulation at low, medium and high coverages. Interventions are: (A) continuously applied CNR, (B) continuously applied CNR and responsible ownership, (C) continuously applied CNR and sheltering, (D) annually applied CNR, (E) annually applied CNR and responsible ownership, and (F) annually applied CNR and sheltering.

5.3.2.2. Results for interventions applied for a single five-year period

Table 23 outlines the results for interventions run for five years. Figure 29 and Figure 30 illustrate the impact of interventions run for five-years annually and continuously on street dog population size. The overall greatest reduction in street dog population size was achieved by culling applied annually at high coverage (77% reduction). For interventions applied annually at all coverages, culling achieved the greatest reduction in street dog population size by 34% (low), 57% (medium) and 77% (high). For interventions applied continuously at all coverages, culling achieved the greatest reduction in street dog population size by 29% (low), 51% (medium) and 71% (high).

For interventions applied annually, the longest length of time between the end of the intervention and the point at which the street dog population returned to an equilibrium level was achieved by combined CNR and responsible ownership for low (21.4 years) and medium coverages (22.8 years), and CNR for high coverages (23.3 years) (Table 23). The shortest length of time was sheltering for low (12.1 years), medium (13.7 years) and high coverages (15.5 years). For interventions applied continuously, the longest length of time between the end of the intervention and the street dog reaching an equilibrium size for low and medium coverages was achieved by combined CNR and responsible ownership at 21.7 and 23.0 years respectively. For high coverages, this was achieved by CNR at 23.6 years. The shortest length of time was achieved by culling for low coverages (11.5 years), and by sheltering for both medium (14.1 years) and high coverages (15.9 years).

The intervention with the lowest total cost over the 5-year intervention was annually applied combined CNR and responsible ownership at a low coverage (€556,958 at high and

€1,094,419 at low staff-to-dog ratios; Table 23). The most expensive intervention was sheltering applied annually at a high coverage (€6,326,746 at high and €57,130,659 at low staff-to-dog ratios).

The greatest improvement in overall welfare scores for both annual and continuous interventions was achieved by combined CNR and responsible when applied at a high coverage (increase of 5.90% for both annual and continuous; Table 23). Responsible ownership applied continuously had the least improvement in welfare score when applied at a low coverage. This reduced the welfare score by 0.53%.

5.3.2.3. Impact of altering intrinsic growth rate

The effect of changing intrinsic growth rate for each intervention was investigated for interventions run continuously for the duration of the simulation at low, medium, and high intervention coverage. For all interventions, increasing intrinsic growth rate decreases the impact of the intervention on the percentage reduction in the street dog equilibrium population size (Figure 31). At medium and high intervention coverages, combined CNR and responsible ownership achieved the greatest reduction in equilibrium population size, regardless of the street dog intrinsic growth rate. At low coverages, both culling and combined CNR and responsible ownership achieved similar reduction in equilibrium population size as street dog intrinsic growth rate increased.

Table 23. Impact of five-year intervention on minimum street dog population size and time taken between end of intervention and equilibrium street dog population size. The intervention with the overall longest time to reach baseline population size is highlighted in grey. The intervention with the greatest reduction in street dog population size, the longest time to reach baseline population size, the greatest increase in welfare score, and the lowest cost for each periodicity-coverage combination are highlighted in bold.

Periodicity	**Coverage**	**Intervention**	**Minimum street dog population size & % change**	**Time to reach baseline population levels (years)**	**Welfare score and % change**	**Total cost over 5-years (€)** Shelter staff-to-dog ratio High	Low
Annual	Low	CNR	19961 (-16%)	21.2	3.32 (1.96%)	1,263,209	8,520,890
		CNR & responsible ownership	18114 (-23%)	**21.4**	**3.34 (2.54%)**	**556,958**	**1,094,419**
		0.5 CNR & 0.5 sheltering	18228 (-23%)	19.6	3.30 (1.38%)	2,282,216	19,370,844
		Culling	**15579 (-34%)**	16.2	3.31 (1.53%)	943,537	8,204,915

Periodicity	Coverage	Intervention	Minimum street dog population size & % change	Time to reach baseline population levels (years)	Welfare score and % change	Total cost over 5-years (€) Shelter staff-to-dog ratio High	Low
		Sheltering	15675 (-34%)	12.1	3.28 (0.73%)	3,414,227	31,010,055
	Medium	CNR	17869 (-24%)	22.4	3.36 (3.11%)	1,513,271	8,759,252
		CNR & responsible ownership	13476 (-43%)	**22.8**	**3.40 (4.34%)**	**785,016**	**1,274,732**
		0.5 CNR & 0.5 sheltering	15035 (-36%)	21.1	3.34 (2.37%)	3,126,698	26,048,699
		Culling	**10097 (-57%)**	17.5	3.35 (2.83%)	987,236	8,238,010
		Sheltering	10236 (-57%)	13.7	3.31 (1.48%)	5,014,886	45,411,896
	High	**CNR**	16179 (-32%)	**23.3**	3.39 (3.99%)	1,772,355	9,006,790

Periodicity	Coverage	Intervention	Minimum street dog population size & % change	Time to reach baseline population levels (years)	Welfare score and % change	Total cost over 5-years (€) Shelter staff-to-dog ratio High	Low
		CNR & responsible ownership	7873 (-67%)	23.1	**3.45 (5.90%)**	**960,719**	**1,411,083**
		0.5 CNR & 0.5 sheltering	12219 (-48%)	22	3.37 (3.27%)	3,827,517	31,367,111
		Culling	**5359 (-77%)**	18.6	3.40 (4.21%)	1,032,471	8,271,403
		Sheltering	5501 (-77%)	15.5	3.34 (2.39%)	6,326,746	57,130,659
Continuous	Low	CNR	19849 (-16%)	21.5	3.33 (2.09%)	1,234,124	8,494,359
		CNR & responsible ownership	18098 (-23%)	**21.7**	**3.35 (2.64%)**	1,263,452	7,721,065

Periodicity	Coverage	Intervention	Minimum street dog population size & % change	Time to reach baseline population levels (years)	Welfare score and % change	Total cost over 5-years (€) Shelter staff-to-dog ratio High	Low
		0.5 CNR & 0.5 sheltering	18589 (-21%)	19.9	3.32 (1.72%)	2,424,068	20,305,284
		Culling	**16695 (-29%)**	11.5	3.32 (1.71%)	939,377	8,202,583
		Responsible ownership	21874 (-8%)	13.9	3.28 (0.53%)	**936,131**	**7,406,597**
		Sheltering	16815 (-29%)	12.4	3.29 (0.82%)	3,274,307	29,754,623
	Medium	CNR	17749 (-25%)	22.8	3.37 (3.27%)	1,412,592	8,662,778
		CNR & responsible ownership	13561 (-43%)	**23.0**	**3.40 (4.43%)**	1,373,641	7,168,954
		0.5 CNR & 0.5 sheltering	15506 (-34%)	21.5	3.34 (2.51%)	3,031,781	25,139,044

Periodicity	Coverage	Intervention	Minimum street dog population size & % change	Time to reach baseline population levels (years)	Welfare score and % change	Total cost over 5-years (€) Shelter staff-to-dog ratio	
						High	Low
		Culling	**11593 (-51%)**	17.9	3.36 (3.12%)	971,352	8,225,412
		Responsible ownership	19882 (-16%)	15.4	3.30 (1.11%)	**931,501**	**6,746,551**
		Sheltering	11783 (-50%)	14.1	3.31 (1.60%)	4,795,326	43,519,778
	High	**CNR**	16041 (-32%)	**23.6**	3.40 (4.16%)	1,540,301	8,780,229
		CNR & responsible ownership	8162 (-65%)	23.3	**3.45 (5.90%)**	1,402,874	6,652,303
		0.5 CNR & 0.5 sheltering	9784 (-59%)	22.8	3.38 (3.69%)	3,743,138	31,680,742
		Culling	**6888 (-71%)**	18.9	3.41 (4.55%)	994,097	8,237,713

Periodicity	Coverage	Intervention	Minimum street dog population size & % change	Time to reach baseline population levels (years)	Welfare score and % change	Total cost over 5-years (€)	
						Shelter staff-to-dog ratio	
						High	Low
		Responsible ownership	17615 (-26%)	16.4	3.32 (1.76%)	**940,810**	**6,215,166**
		Sheltering	7102 (-70%)	15.9	3.34 (2.54%)	6,047,848	55,081,519

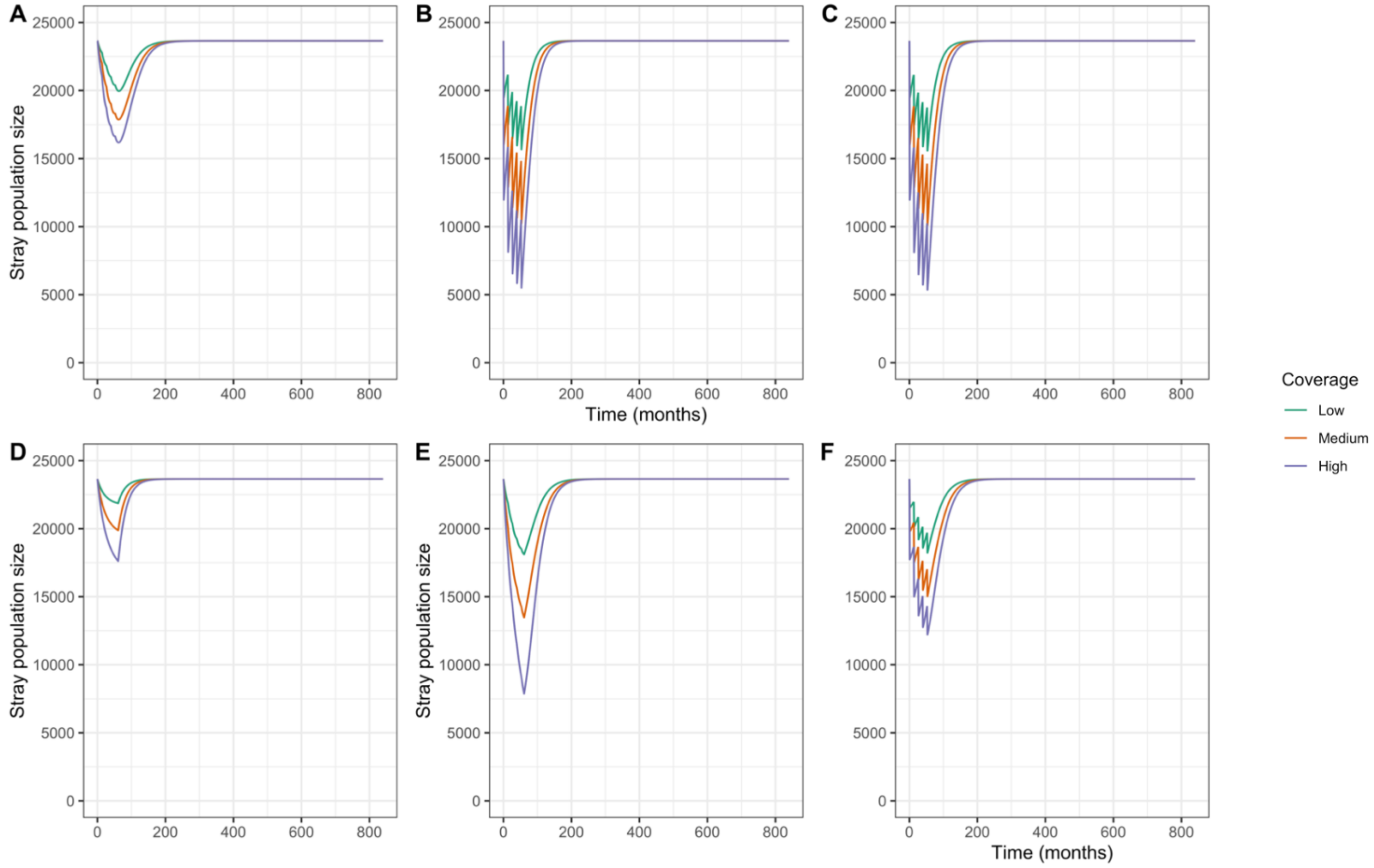

Figure 29. Impact on street dog population size of annual interventions run for five-years of simulation. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering at low, medium and high coverages.

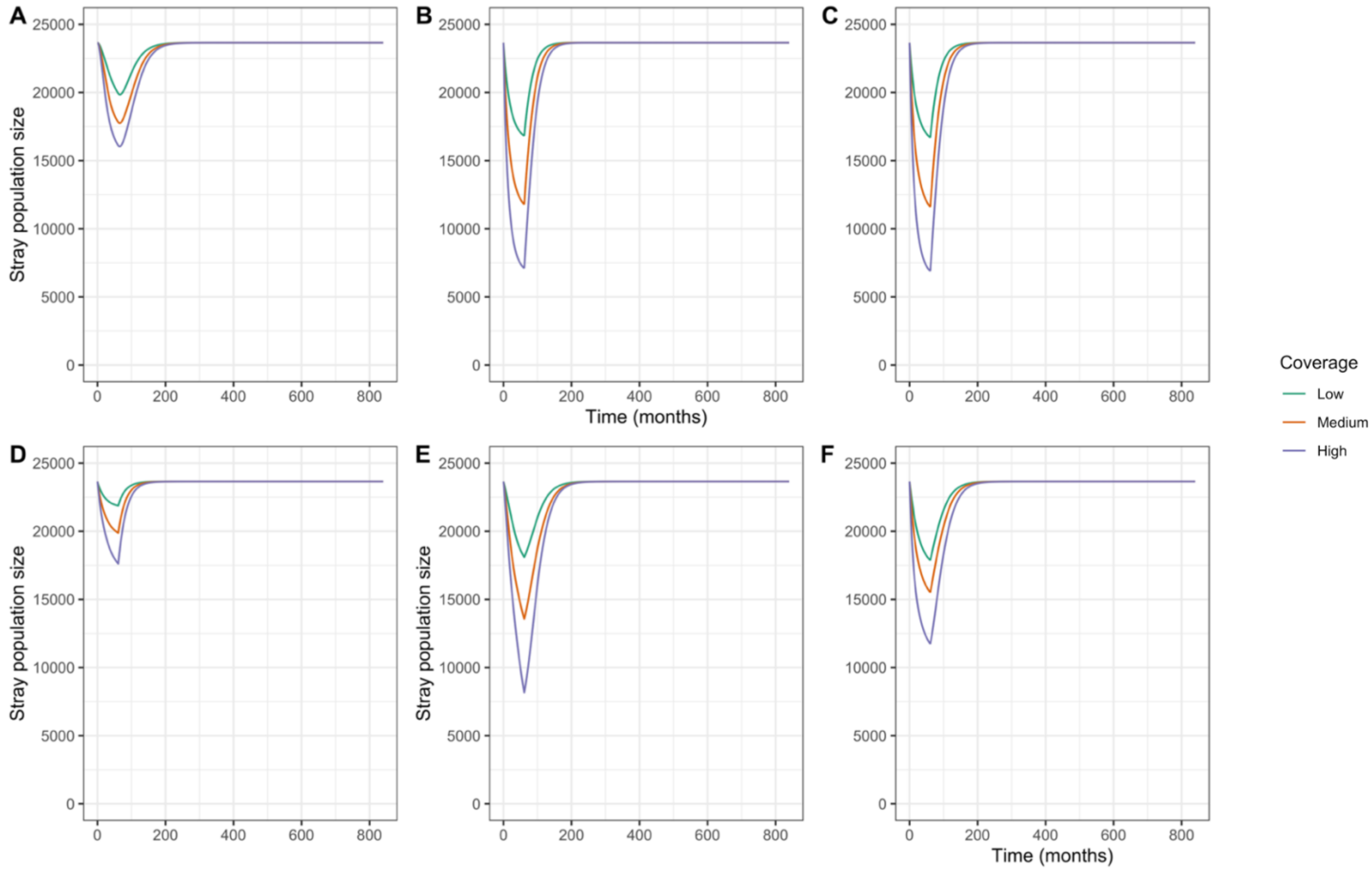

Figure 30. Impact on street dog population size of continuous interventions run for first five-years of simulation. Interventions are: (A) CNR, (B) sheltering, (C) culling, (D) responsible ownership, (E) CNR and responsible ownership and (F) CNR and sheltering at low, medium and high coverages.

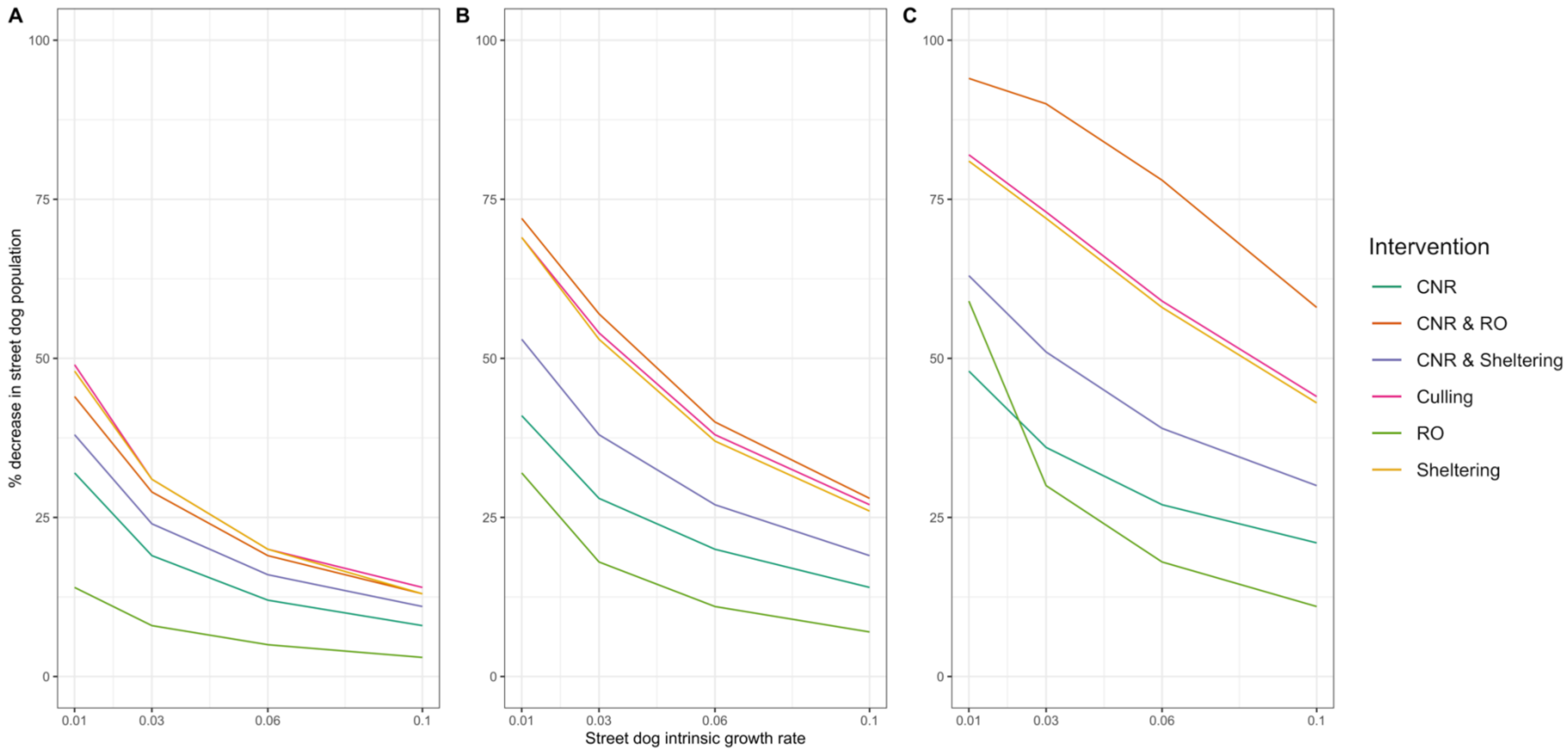

Figure 31. Impact of altering street dog intrinsic growth rate on the percentage decrease in street dog equilibrium population size when interventions are run continuously for duration of simulation. Coverages are: (A) low, (B) medium, and (C) high.

5.4. Discussion

The effectiveness of dog population management interventions was assessed using a modelling approach that incorporated an interactive system of dog subpopulations. Few previous modelling studies have investigated the effect of interventions on dog populations whilst (i) explicitly incorporating the interactions between the different subpopulations, (ii) modelling a range of management methods at different periodicities and coverages, and (iii) also providing comprehensive estimates of the welfare impacts and costs. The results of this study indicate that combined CNR and responsible ownership applied continuously at high coverage may be most effective at reducing street dog population size when applied over longer periods of time (Table *22*). Culling may be more effective over shorter periods of time but, compared to methods such as CNR and combined CNR and responsible ownership, the population may return more quickly to an equilibrium population size once management has ended (Table 23). In addition to providing insight into the impact of dog population management methods on dog population size, it is important to understand the financial resources required to achieve population reduction, as well as considering the welfare costs of such methods. The results of this study indicate that responsible ownership and combined CNR and responsible ownership may be the least costly methods, in terms of staff-resources required (Table *22*, Table 23). CNR and responsible ownership applied at a high coverage may also more greatly improve the overall welfare score of the dog populations compared to other methods (Table *22*, Table 23).

5.4.1. Effects on population size

Over longer periods of time, combined CNR and responsible ownership was most effective in reducing street dog population size (Table *22*). This may be explained by the method targeting more than one flow that has the potential to increase the population size. In this systems model, combined CNR and responsible ownership targeted several flows into and between the dog subpopulations: it prevented the street dog population from increasing through births and abandonment, and it increased the adoption of dogs from the shelter dog population to the owned dog population. This combined method had a synergistic effect: neither CNR nor responsible ownership applied in isolation was as effective at reducing street dog population size (Figure *22*).

There has been increasing interest in the use of CNR to manage free-roaming dog populations (Chapter Two – Systematic Review), and empirical studies have reported CNR to be effective in reducing population sizes between 12% over 1.5 years and 40% over 12 years (117,118,132,133). There has been less focus on the impact and effectiveness of responsible ownership campaigns on street dog population size or human behaviour change (Chapter Two, Systematic review). The results of this systems model suggest that targeting efforts to reduce abandonment is as important as directing efforts to reduce the population's birth rate. These findings are in line with those reported in previous modelling studies. These studies found that owned dog abandonment had the potential to dampen the impact of CNR interventions (137,139,145). Without targeting multiple flows, the potential for the population to increase in size remains. Future dog population management efforts should aim to identify the sources of population increase (i.e. abandonment or immigration) to understand the potential impact of CNR and other interventions. In addition, future studies should aim to measure the impact of responsible ownership campaigns, in combination with CNR efforts, in order to identify the most effective strategies to reduce abandonment rates and increase responsible ownership practices.

In this model, interventions were run over two lengths of time: for the full 70-year period of the simulation and for a five-year period. In simulations where interventions were applied for five-years, culling was more effective at reducing the street dog population size at all management coverages (Table 23). At continuously applied high coverage, CNR and responsible ownership was most effective at reducing street dog population size. These results are similar to that reported by Amaku *et al.,* (2010) (137), but differ to the findings of Yoak *et al.,* (2016) (134), who found culling to be less effective at reducing street dog population size when modelled at the same intensity as CNR. This difference may be due to the differences in the intervention coverages modelled.

Both CNR and combined CNR and responsible ownership were more effective at maintaining the street dog population at a lower size for longer than other interventions (i.e. it took longer for the population to return to an equilibrium level). Individuals that have been removed through culling or sheltering may quickly be replaced through births or immigration, resulting in the population quickly returning to the carrying capacity. The longer lasting effects of neutering may be explained by the neutered individuals remaining in the population and dampening the potential for population growth, as they do not contribute to births.

In this study, the effects of applying interventions at two periodicities and at different intervention coverages were explored. In practice, dog population management may be applied to a population of free-roaming dogs in a city or town periodically, or it may be applied through a continuous effort. For example, charities may visit a city or town to conduct CNR using a mobile clinic or temporary surgery once per year, or there may be a fixed location clinic where government agencies or charities neuter a consistent proportion of the population throughout the year. The results of this study suggest that, when applied at similar coverages, both continuously and annually applied interventions will reduce population size to similar levels (Table *22*). When applied annually, interventions that remove a proportion of the population, such as culling and sheltering, may cause the street dog population to fluctuate in size between intervention efforts (Figure 25).

Three intervention coverages were modelled in this study, and overall, interventions applied at higher coverages were more effective at reducing street dog population size (Table *22* and Table 23). Coverages were often not reported in empirical studies (see Chapter Two, Systematic review), possibly due to the temporal, logistical, and statistical resources required to estimate dog population size. The results of this study suggest that the impact of management is reduced when the intrinsic growth rate of a population is high (Figure 31). This means that, in fast growing populations, the coverages would need to be higher than that applied in slow growing populations in order for an intervention to have the same effect on population size.

5.4.2. Effects on cost

This costs analysis is limited in that it does not encompass the full cost of the interventions, including the training (e.g. in catching dogs, performing surgeries), facilities (e.g. clinics, kennels) and equipment that are required. For example, a responsible ownership campaign may cost around €100,000 for advertising alone (VIER PFOTEN International, personal communication), and this is not incorporated into the analysis. As outlined by the systematic review (Chapter Two), the cost of management was rarely provided by studies. Where costs do exist, they exist in disparate datasets: differing by country (i.e. country specific costs) and methods of application. For example, for CNR, costs may be lower for interventions that involve less staff-training and shorter pre- and post-surgical holding times, but may compromise dog health and welfare as a result (321). Similarly, costs of running a shelter will vary depending on the shelter environment and management: shelters with larger dog-pen sizes, less enrichment, and lower staff-to-dog ratios may be less costly, but may also compromise health and welfare (322). The data is also currently unavailable to quantify the costs required for a responsible ownership campaign to reduce the abandonment of owned dogs by a quantified amount. To fully assess and compare the costs of different interventions requires integration of multiscale datasets across the dog population management field. Whilst this study does not encompass the full costs of interventions, calculating the staff-time costs required allowed some evaluation of intervention costs on a comparable scale.

It is not surprising that interventions including sheltering were most expensive overall (Table *22* and Table 23). Sheltering ultimately increases the shelter dog population size, and if the rehoming rates stay the same, greater staff resources are required to care for the shelter dog population. To allow resources to be estimated without a killing intervention, this model did not include the killing of shelter dogs to reduce the shelter dog population. Several countries have a no kill policy for shelter dogs (323), only allowing euthanasia for behavioural or health problems. In these countries, sheltering as a method of population control may result in an increase in the shelter dog population and, without an improvement in rehoming rates, has the potential to lead to life-long stays in shelters and overcrowding. As this method is costly, it is potentially only a feasible option for higher income countries (48).

The cheapest intervention overall in terms of staff costs was responsible ownership campaigns. Responsible ownership campaigns did not require dog catchers, veterinarians or veterinary nurses. When applied alone, this method was the least effective at reducing the street dog population size. Combined CNR and responsible ownership was more effective at reducing the population size and was only marginally more costly than responsible ownership alone. As this method was effective in reducing population size, fewer dog catchers, veterinarians and nurses were required throughout the simulation, making it more cost-efficient in the long-term.

Culling and CNR were more similar in costs, in terms of staff-resources, than might be anticipated (Table *22* and Table 23). Whilst CNR requires higher-paid workers (i.e. veterinarians and veterinary nurses), as the simulation progressed, there were fewer intact dogs to neuter and fewer veterinarians were required to maintain the intervention coverage. Culling required a higher number of dog catchers to maintain the intervention coverage throughout the simulation, resulting in there being less of a difference between culling and CNR in terms of staff-resources.

5.4.3. Effects on welfare

In addition to population size, welfare measures are important indicators of dog population management impact (49). In this study, we measured the effect of the interventions using an overall welfare score, based on the number of dogs in each subpopulation, as described by Hogasen *et al.,* (2013) (139). The greatest improvement in welfare score, compared to the baseline simulation, was achieved by combined CNR and responsible ownership. This is due to an overall reduction in street dog population size and an increase in the proportion of street dogs that were neutered, whose welfare is rated more highly than intact street dogs.

This method of assessing welfare uses aggregated welfare scores, weighted by self-reported knowledge of dog subpopulations provided by veterinarians in Italy (49). The scores are specific to Italian subpopulations, and there may be some differences between the perceived welfare of dog subpopulations between different countries. For example, the welfare of the street dog population in one country may be greater than another, due to country-specific risks to dog health and welfare. It is challenging to compare the welfare impact due to a lack of comparable welfare data within and between subpopulations (Chapter Two, Systematic review). Using this overall welfare score allows us to compare the potential welfare impact of different interventions on overall welfare.

Dog population management methods may also have a short-term impact on dog health and welfare, depending on the method used. For example, there are important welfare risks related to CNR interventions, depending on dog handling procedures, standards of surgery, and post-operative care (321,324). The impact of culling on dog welfare also depends on the method used. Historically, culling methods have been inhumane (93,181). In some locations, mass killing is carried out by distributing poisons, most commonly strychnine (93) which is not a recommended method of killing from an animal welfare perspective (48). In locations where poisoning is not used, the methods to restrain the dogs may also be of welfare concern. For example, methods of physical restraint include the holding of body parts by rope or metal tongs which can cause laceration or tissue damage (93). Once restrained, methods to kill dogs have included electrocution, carbon monoxide poisoning and drowning (93). These methods are not recommended by the World Organisation for Animal Health (OIE) but are still employed in some areas (48). These additional welfare concerns should be considered when determining appropriate dog population management intervention.

5.4.4. Limitations

There were several assumptions that were made by this model:

1. This model did not differentiate between different age and sex categories. All individuals were assumed to contribute equally to the dynamics occurring between the different sub-populations. Currently the data is lacking at the level necessary to model the flows between subpopulations for different age and sex categories. Further study to determine these rates would be beneficial for informing future understanding of the dynamics between dog subpopulations.
2. The model also did not consider changes to human demographics. Whilst it incorporated human behaviour change, it did not include possible human population growth. Growing human populations could increase the carrying capacity for street dog population and also increase the owned dog population. This may affect the overall dynamics but may not necessarily affect the outcome of the effectiveness of population management methods.
3. This model did not include the effects of immigration and emigration explicitly. If interventions occur in neighbourhoods, instead of homogeneously throughout a city, there is the potential that this could increase movement of dogs from other parts of the city.
4. The ability of the methods to be applied at consistent coverages was assumed, regardless of the street dog population size. In reality, it may be more challenging to find dogs when the street dog population size is smaller.

5.5. Conclusions

Systems dynamics modelling is a useful tool for investigating the potential impact of different dog population management methods. Overall, combined CNR and responsible ownership may be the most effective at reducing street dog population size, maintaining the population at a lower size, whilst also improving the overall welfare score of dogs, at low costs in terms of staff-resources. Future dog population management would benefit from identifying and targeting all potential flows that may increase the street dog population size (such as abandonment and immigration). Future studies are required to measure the impact of interventions, such as responsible ownership campaigns on human behaviour change.

Chapter 6. Discussion and conclusions

The aim of this thesis is to investigate and compare the impact of dog population management methods on free-roaming dog population dynamics, health and welfare, in terms of their sustainability, effectiveness and efficiency. The studies conducted to meet this aim have synthesised the existing evidence for the effectiveness of dog population management and provided important data for focal countries in Europe on public attitudes, dog ownership practices and free-roaming dog population dynamics, health and welfare. Using this data, the work in this thesis contributes to the understanding of the effects of dog population management using a system dynamics modelling approach to identify methods that are effective at maintaining lower population sizes of free-roaming dogs. This information is important for directing future dog population management efforts in selecting the most effective and efficient approach to reduce free-roaming dog population size.

6.1. The impact of dog population management on free-roaming dog population dynamics, health and welfare

6.1.1. Existing evidence for the effectiveness of dog population management methods

There is a lack of evidence on the impact of different dog population management methods on population dynamics, health and welfare (49). This evidence is vitally important in determining the most effective methods at reducing the risks associated with free-roaming dogs, whilst considering the resources required in order to achieve this reduction. The work presented in this thesis contributes to filling this evidence gap. Chapter Two (systematic review) is the first study to synthesise the reported effects of dog population management on (i) dog population demographics; health and welfare; (ii) public attitudes; (iii) public health risks; and (iv) risks to wildlife populations. The results of this identified that most management methods were associated with positive effects (e.g. a reduction in public health risks, an improvement of dog welfare, or a reduction in population size). Methods involving fertility control (e.g. CNR) were found to be most frequently investigated and reported, and had the greatest reported effect on dog population size in both observational (117,118,132,133) and modelling studies (118,134–139). The findings of the systematic review have important implications for future dog population management, suggesting that methods involving fertility control may be most effective at reducing free-roaming dog numbers, whilst also improving health and welfare.

6.1.2. The importance of considering public attitudes and dog ownership practices

This thesis has highlighted the importance of considering local public attitudes and dog ownership practices in the development of effective dog population management approaches. Including these social factors will ensure that both the community and organisations involved in dog population management work cohesively towards a shared goal. The results of Chapter Three provide a baseline for public attitudes and dog ownership information in focal countries within Europe. These results evidenced that the majority of surveyed respondents wanted to see a reduction in free-roaming dog numbers, and felt that this should be achieved through sheltering, catch-neuter-release, and by controlling the breeding of owned dogs. The public attitude towards dog population management methods mirrored the methods found to be most effective at reducing population numbers in the systems model. Taken together, these findings suggest that combined CNR and responsible ownership will be a publicly acceptable method of reducing free-roaming numbers in the focal European countries.

The results of Chapter Three have also identified associations between public attitudes and dog ownership practices with gender, religious beliefs, age, education level, reason for dog ownership, previous experience with free-roaming dogs, and country of residence. These associations could be further investigated to understand the underlying reasons for attitudes and ownership practices, and to target responsible ownership interventions to influence the behaviour of those less likely to practice responsible ownership. This may help to ensure responsible ownership interventions are effective at reducing free-roaming dog numbers.

6.1.3. The impact of management on free-roaming dog population size and dynamics

This thesis investigates the importance of understanding the processes of recruitment and removal in free-roaming dog populations in order to evaluate the potential impact of dog population management. Chapter Four (mark-recapture) is the first study to quantify the rates of recruitment and removal in free-roaming dog populations using Pollock's robust design mark-recapture method. Monitoring free-roaming dog populations through Pollock's robust design mark-recapture is advantageous as it allows more robust estimates of population size, recruitment and removal (249,251). The results of this mark-recapture study suggest that study populations in both Italy and Ukraine were dynamic with relatively high rates of recruitment and removal. As few juveniles were observed in the study populations, the results of this chapter potentially indicate that recruitment and removal may be occurring by movement between dog subpopulations (e.g. from local owned or neighbouring free-roaming dog populations). These results have important implications for future dog population management, emphasising the importance of management efforts incorporating owned dog populations (e.g. encouraging neutering of owned dogs) and covering the entire city to reduce the risk of dog movement between sections of the city hindering management efforts.

Building on the results of the previous chapters, Chapter Five (systems model) is the first to quantify the impact of multiple dog population management methods applied at varying periodicities and intensities when explicitly considering the interacting system of dog subpopulations. This thesis provides the first evidence that methods combining CNR and responsible ownership will be most effective at reducing and maintaining a lower dog population size over the long-term, whilst also being cost-effective and improving the overall welfare of the dog populations. The results of the systems model provide guidance for future management, suggesting that fertility control methods will have synergistic effects, if coupled with interventions that target other sources that increase free-roaming dog population size, such as reducing the rate of owned dog abandonment. These results highlight the importance of incorporating the interactions between all dog subpopulations when evaluating the potential impact of different dog population management methods. Where dog population management efforts do not target these potential sources of dog population increase, the effect of any method of management can be dampened.

The systems model identified owned dog abandonment as a potentially important source of free-roaming dog population increase. These results are supported by other studies (137,139,145). For example, Santos Baquero *et al.,* (2016) (145) report in their modelling study that the rate of owned dog abandonment is more influential than the rate of neutering in determining unowned free-roaming dog population size. This has important implications for future dog population management efforts, suggesting that efforts should be directed towards CNR coupled with responsible ownership campaigns (e.g. working with local communities to improve responsible ownership practices). Efforts encouraging responsible ownership may help to reduce abandonment of owned dogs to the free-roaming dog population, as responsible ownership requires that dog owners are responsible for their dog and any of its offspring for the duration of their life or until they are transferred to another owner (98). The results of this thesis support that responsible ownership is an essential component of effective dog population management (98). Responsible ownership can be encouraged through education to increase awareness of responsible ownership practices, to improve knowledge of dog behaviour and increase awareness of the risks related to free-roaming dog populations. Responsible ownership can be further encouraged through legislation, such as increasing penalties for irresponsible behaviour.

The results of this thesis also highlight the importance of identifying the most effective method of improving dog ownership practices. Results reported in Chapter Two (systematic review) identified that published studies do not evaluate the effect of responsible ownership campaigns on indicators of management impact (49). This may be due to challenges in quantifying dog ownership practices. Questionnaires are often used to describe dog ownership practices in a population (124,125,192–201,135,202–211,146,212,213,184,185,187,189–191), however, due to the self-selection process involved in the recruitment for questionnaire studies, these are subject to biases. It is particularly challenging to accurately quantify the rate of owned dog abandonment, as this is likely to be underreported in questionnaire surveys (189). Future studies and those involved in dog population management may consider quantifying abandonment through focus groups or using local shelter relinquishment figures as an indicator of the level of dog abandonment in a community.

In order to reduce abandonment, it is important that future studies identify the potential causes of abandonment. Chapter Three (public attitudes and dog ownership) is the first study to report public attitudes and dog ownership practices for populations in Bulgaria, Italy and Ukraine. The results of Chapter Three showed that respondents most frequently relinquished or abandoned dogs due to behavioural problems. These results are supported by other studies investigating dog ownership practices (189,226,325). My findings suggest that future responsible ownership interventions could focus on improving knowledge of dog behaviour, and providing assistance to owners in this regard, in order to reduce the risk of owned dog relinquishment to shelters and abandonment to the street.

The results of this thesis primarily apply to free-roaming dog populations in Europe. Populations in other geographic locations may differ in their movement within and between the subpopulations and, as such, I urge caution in applying the results outside of Europe. Rates of recruitment are likely to be influenced by geographic and cultural factors and thus are population specific. For example, this thesis studied urban dogs, but for the study of rural dogs, the larger home range sizes reported (8) may affect movement between populations. Cultural factors within countries, such as religious beliefs, may affect public attitudes towards population management. Respondents from the questionnaire surveys in the focal countries were majority Christian, whereas other areas with free-roaming dogs, such in parts of Asia may have a different faith majority. For example, in Thailand, the majority faith is reported to be Buddhist (326) and a previous study suggests that neutering may be against Buddhist beliefs (229). As such, CNR may be a less publicly acceptable method of population control in these areas. In areas with lower abandonment rates and/or opposition to neutering, combined CNR and responsible ownership interventions may be less effective. Although caution should be taken in applying the results, this thesis provides a systems model that can be used by researchers and those involved in dog population management by applying specific parameter values for local dog populations to identify the most effective and efficient management methods, including determining effective periodicities and intensities.

6.1.4. The impact of management on public health risks

Arguably the most pressing public health challenge related to free-roaming dogs is their contribution to the spread of rabies in humans (60). Dogs are a maintenance host of this virus and account for 99% of human-rabies transmissions (60). Rabies causes an estimated 60,000 deaths annually (61) and is a disease that disproportionately affects lower-income countries (327). A primary motive for dog population management is therefore to reduce the risk of rabies transmission from dogs to humans (60). In terms of rabies control, previous studies have identified that vaccination coverage of dogs may be more important than dog population reduction (181). CNR is important epidemiologically because: (i) it is combined with vaccination, therefore increasing the vaccinated coverage (328); (ii) it can reduce population turnover (149,165); and (iii) it creates a demographically older, vaccinated population, that may be important for reducing the transmission of infectious diseases (329). Dog population management through culling or sheltering may not differentiate between vaccinated and unvaccinated individuals (164). When the aim of population management is to increase vaccination coverage, the indiscriminate removal of vaccinated individuals may ultimately be counterproductive in terms of disease control. This has the potential to reduce the overall vaccination coverage to below the critical level required to halt disease transmission, thus hindering disease control (164). It is also to be considered that the removal of individuals may increase the transmission of pathogens, as compensatory breeding increases the number of new born, unvaccinated and susceptible individuals, further lowering the vaccination coverage (149,165). Amplified migration and movement as a consequence of the removal of dogs in one location has the potential to increase the movement of exposed or infected individuals, therefore facilitating disease transmission (330).

Although I did not model vaccination coverage explicitly in the systems model, dogs neutered during CNR interventions are often vaccinated against rabies. It can be assumed that the neutered proportion of the population also represents the vaccinated proportion. The results of the systems model therefore help to identify methods that may maintain a higher vaccination coverage. The intervention that achieved the highest neutering coverage was high coverage CNR and responsible ownership applied annually, although this was only marginally different to the continuously applied intervention. Interventions applied annually caused the neutered coverage to fluctuate in populations. This may have important negative consequences for disease control. The results of the systems model have implications for future rabies management, suggesting that combined CNR and responsible ownership may also be effective at maintaining high vaccination coverage and therefore have the potential to aid in the reduction of rabies prevalence.

6.1.5. The impact of management on risks to wild and domestic animals

CNR and responsible ownership may also be the best method for reducing the impact of free-roaming dogs on wild and domestic animals, by reducing the overall dog population size. Dogs are often an introduced predator, threatening the survival of native species (see *Doherty et al.,* (2017) (43) for review) and predating on livestock, with their kills often mistaken for that of other species (20,37,40,90). Reducing the number of roaming dogs has direct benefits to wildlife and livestock populations that are at risk of predation (20,37–40,77), and wildlife populations that are at risk of competition (13), hybridisation (42,79,80), and pathogen pollution (41,75,76) from free-roaming dogs.

6.1.6. The impact of management on health and welfare for free-roaming dogs

Free-roaming dog populations can often be at risk of poor health and welfare states (9,46,91,92). Dog population management is often conducted with the aim of improving free-roaming dog health and welfare (49). The systematic review results indicate that population management methods involving fertility control have generally positive effects on dog health and welfare, although some negative associations were also reported (e.g.

increased prevalence of ectoparasites). Using a composite welfare score, the results of the systems model also indicate that methods combining fertility control and responsible ownership will have the greatest improvement to the overall welfare of the dog population.

6.2. Implications and recommendations

The work presented in this thesis has advanced our understanding of the potential impact of different dog population management methods on dog population size, whilst considering the potential costs in terms of welfare and resources. Below I outline key recommendations, based on this work, for future dog population management interventions and for the continued assessment of management methods.

6.2.1. Effective and efficient management methods

The key result of this thesis is that methods targeting multiple sources of population increase, such as combined CNR and responsible ownership campaigns, will be most effective at reducing free-roaming dog population size, whilst also being cost-effective and improving dog health and welfare. Organisations involved in dog population management should therefore consider combining CNR with responsible ownership campaigns. These interventions should be applied continuously at high coverage to ensure management is effective and efficient at reducing population size, whilst being cost-effective in the long-term. To ensure a high intervention coverage, the size of the targeted free-roaming dog population should be estimated prior to population management commencing (e.g. using closed mark-recapture methods, or methods that reliably estimate a large proportion of the population (274,331). Estimating the size of the population allows those involved to make the necessary preparations to ensure the intervention can be applied at a high coverage (e.g. aiming for a 60-80% neutering coverage).

Potential sources of dog population increase in local free-roaming dog populations should be identified, including births, immigration from a neighbouring population, and temporary or permanent immigration from owned dog populations (e.g. owned dogs temporarily entering the free-roaming population if unrestricted, or permanently through abandonment). This will help to target the most appropriate dog population management methods. For example, if abandonment is high, efforts can be targeted to reduce owned dog abandonment. Sources of population increase could potentially be identified using a combination of open mark-recapture (such as Jolly-Seber (246,247), Cormack-Jolly-Seber (246–248), and Pollock's robust design (249)) and household questionnaire surveys to help identify sources of recruitment (e.g. abandonment) (36,165,204,235–237).

6.2.2. Incorporating public attitudes and dog ownership practices

Prior to implementing dog population management, there is a need to gauge the level of public acceptance for the method and management aims, and to understand the dog ownership practices and public attitudes in the area in order to target at-risk groups for irresponsible dog ownership practices. Public attitudes towards dog population management and dog ownership practices should be measured through questionnaire surveys or interviews with focus groups. In addition to a baseline understanding of public attitudes and dog ownership practices, those involved should conduct repeated surveys to monitor the impact of dog population management on human behaviour, particularly for interventions targeting responsible dog ownership.

6.2.3. Monitoring and assessing the effectiveness of dog population management methods

As dog population management is conducted for a number of reasons (e.g. to reduce public health risks, improve free-roaming dog health and welfare, or to reduce the risks to livestock and wildlife) many different measures have been used to assess management impact. This makes it difficult to compare the effect of different management methods using the studies that have been conducted so far. Future research should use common metrics to measure the impact of dog population management (see (49) for overview of indicators of management impact).

A large number of studies investigating the effect of dog population management published to date had poor reporting quality and study design. Importantly, many studies failed to report the management intensity, including the coverage and length of management applied. These are fundamental factors that are required to fully evaluate the impact of dog population management. In order to fully assess the impact of population management in future empirical studies, it is important that studies:

1. Increase reporting quality (see (127,128,170–172) for reporting guidelines). Studies should report details of experimental design, study subjects, statistical analysis, modelling approaches, power and sample size calculations. For dog population management, this also means authors should report defined target dog populations ((i) unowned, free-roaming; (ii) owned, free-roaming; (iii) unowned, restricted; and (iv) owned restricted). Importantly, studies should also report the management intensity (coverage and length that management was applied) and cost.
2. Improve experimental and statistical modelling approaches. Studies should aim to use intervention (e.g. randomised control trials) or observational (e.g. cohort studies) study design that allows causality to be determined. Statistical modelling

approaches can be used to deal with the limitations in inferring causal relationships using observational data, such as directed acyclic graphs (174,175), or process based modelling approaches (177).

6.3. Limitations of the studies

There are limitations in the work presented in this thesis due to logistical and temporal constraints, and also due to a lack of existing data that allows the impact of dog population management to be fully assessed.

I first acknowledge that the low sample sizes obtained in the mark-recapture study resulted in greater uncertainty in parameter estimates and in finding evidence for effects of predictor variables. This is particularly a limitation in Pescara, as few individuals were observed in the study sites. Whilst there was greater uncertainty in parameter estimates, the Bayesian approach taken to analyse this data was advantageous in that it allowed the uncertainty in parameter estimates to be quantified and was valid for dealing with these smaller sample sizes (220).

The length of the mark-recapture study (15 months) also allowed limited assessment of dog population dynamics. Studies that take place over a number of years (e.g. five years or longer) are advantageous as they allow more robust estimates of changes in population size, recruitment, and removal rates. Shorter studies may result in estimates that are subject to changes in population dynamics due to weather, social and political events. It was outside the feasibility of this study to monitor dog population dynamics over an extended period of time. Whilst the length of the mark-recapture study is a limitation, the results still provide valid estimates of seasonal population dynamics, health and welfare throughout this 15-month period. The parameters estimated in this study provide some of the first estimates of health, welfare, population size, and rates of recruitment and removal for free-roaming dog populations in Europe and can be used to guide future dog population management in these locations. There would be real value in continuing to monitor populations in these areas over a much longer time period if possible.

The mark-recapture study would also have benefitted from an intervention study design. It would be advantageous to assess the population dynamics before, during and after dog population management. It is challenging to find a population that has had no management historically. It can be assumed that most free-roaming dog populations have had some level of management applied. This has implications for previous studies, as the challenges in determining historical dog population management represent a barrier that may have prevented these studies from taking into account their effect on subsequent management interventions. The temporal constraints in this project indicate that an intervention study design would also have had limitations. The effect of dog population management may take years to be observed (118,134,139,283), therefore a short term intervention study may not capture the possible effects of dog population management. The mark-recapture study in this thesis considered historical dog population management and determined whether there were differences in population dynamics between populations in areas with different levels of population management.

I also acknowledge that modelling studies are simplifications of reality and there are limitations in extrapolating the results of the systems model to real-life dog populations. In Chapter Five I discussed several assumptions made in the systems model; namely that the systems model did not consider (i) varying rates of movement for different age and sex categories; (ii) the effect of immigration and emigration explicitly; or (iii) the potential effect of population size on capture success (e.g. it may be harder for dog catchers to find dogs if there are fewer dogs in the population). Modelling these factors could allow more accurate predictions of the effects of dog population management.

Currently the data is lacking at the level of detail necessary to model these factors. The model presented in this thesis still captured the overall dynamics, importantly allowing us to assess the impact of different interventions whilst considering the dynamic system of dog subpopulations.

In Chapter Five I also discussed the limitations in both the cost and welfare assessments. Primarily, the cost analysis does not encompass the full cost of interventions (e.g. including training, facility, or equipment costs), and the welfare scores are subject to bias as they rely on aggregated perceived welfare scores of Italian dog subpopulations from veterinarians. Although these are important limitations, I felt that it was better to provide these initial assessments of the potential costs and welfare impacts of dog population management using staff-resources as a proxy for costs, and rudimentary estimations of overall welfare scores. The costs of management as well as the short- and long-term welfare implications are important to consider when evaluating different management methods.

Despite these limitations, the findings in this thesis still provide important data for focal European countries on population dynamics, health and welfare. The results of this thesis help to fill the evidence gap on the effectiveness of different dog population management methods.

6.4. Future work

This project takes vital steps in understanding the dynamics of dog populations and the potential impact of dog population management. It also provides data on public attitudes and dog ownership information in three focal countries, estimates of population dynamics, health and welfare for dog populations in Europe, and offers a model for assessing the impact of dog population management whilst considering the dynamics between dog subpopulations. Further work is required to continue this research over longer time periods in the focal countries, provide similar data on dog populations in other geographical locations, and to provide more robust estimates for the rates of movement between different dog subpopulations. Details for potential further work are outlined below.

6.4.1. Disentangling the processes of recruitment and removal in free-roaming dog populations

This study highlights the importance of considering the dynamics within and between different dog subpopulations. First and foremost, it is important that future studies aim to provide robust estimates of the rates of movements within and between dog subpopulations. This requires disentangling the processes of recruitment and removal to provide rates of intrinsic growth, mortality, birth, abandonment, emigration and immigration (both to neighbouring populations and from different subpopulations) for different sexes and age groups within free-roaming dog populations. Disentangling the processes of recruitment and removal is a challenging task. For example, while mark-recapture methods incorporating age cohorts have been used for other species to disentangle births from immigration (332), in free-roaming dog populations, these methods would not be of use, as dogs may be abandoned at any age. Instead, disentangling these processes may require working with local communities to assist in these estimates, for example through questionnaire surveys or interviews with focus groups. To allow better assessment of the impact of population management methods, future studies should aim to address the question: *What are the dominant sources (i.e. births, abandonment or immigration) of free-roaming population increase*?

6.4.2. Longitudinal data on population dynamics

The results of the systematic review highlight the lack of longitudinal data on free-roaming dog populations dynamics, health and welfare. This data is required to determine the long-term impact of dog population management. Assessing the long-term impact of population management in empirical studies requires that studies (i) use common metrics; (ii) report baseline values prior to population management being implemented; and (iii) report historical information of dog population management in the area. Longitudinal datasets on population size, dynamics, demographics, health, welfare and risks to public health and wildlife populations should be collected, wherever possible, as measures of longer-term management impact. This information is especially important in order to improve and refine management methods (49). It would be beneficial that future studies monitor the impact of dog population management over several years in order to address the question: *What is the long-term impact of dog population management on population demographics, dynamics, health and welfare?*

6.4.3. Accurately and efficiently estimating dog population size

Leading on from the above, long-term monitoring of the impact of dog population management requires temporal, logistical and financial resources. Dog population size is an important indicator of the impact of management methods. Reducing population size is a commonly stated goal of interventions (49) and can also be used as a proxy for risk to public health, livestock and wildlife. The methods used to calculate dog population size have often involved simple counts that fail to account for imperfect detection of individuals (173). These methods may be advantageous in that they require fewer resources in terms of logistics, time and statistical knowledge. However, they fail to provide an estimate of population size. Estimates of true population size are often required to guide management methods, such as determining the number of individuals that need to be vaccinated or sterilised as part of a successful management campaign. Studies have suggested alternative methods of reliably estimating 70% of the population and have the potential to aid in population management planning and monitoring (274,331). As longitudinal studies of changes to dog population size are required, there is a need to balance good quality population size estimation against the resources required (e.g. temporal, logistical and statistical knowledge). Future studies should focus on answering the question: *What method(s) of estimating dog population size provide the most accurate estimates, whilst maintaining the lowest costs logistically (e.g. number of surveyors, number of study areas required), financially, and in terms of statistical expertise?*

6.4.4. Assessing the effectiveness of responsible ownership interventions

The results of this thesis have identified that interventions that improve responsible ownership practices could be an important component of dog population management, yet evaluation of the impacts of responsible ownership interventions are lacking. Indicators of responsible ownership include (i) prevalence of roaming owned dogs; (ii) prevalence of neutering or measures to prevent reproduction, (iii) level of care (including vaccination); and (iv) the level of dog abandonment in a community. Future efforts should aim to assess the impact of responsible ownership interventions on free-roaming dog population dynamics, in order to address the question: *How should responsible ownership interventions be conducted in order to improve responsible ownership practices?*

6.4.5. Assessing the costs of dog population management methods

The results of this thesis provide an initial comparison of the costs of different dog population management methods. As outlined previously, this assessment was limited, as it did not include the full costs of interventions. To determine the cost-effectiveness of different management methods, periodicities and coverages, there is a need to calculate the total costs of interventions, when considering the training (e.g. in catching dogs, performing surgeries), facilities (e.g. clinics, kennels) and equipment that are required. Determining the costs of interventions is challenging, as the data exists in disparate datasets: differing by country (i.e. country specific costs) and methods of application. There is a need to integrate these datasets across the dog population management field. Future studies should also aim to address the question: *What is the most cost-effective method (including periodicities and coverages) of reducing free-roaming dog population size?*

6.4.6. Assessing the welfare impacts of dog population management methods

Similarly, this thesis provides rudimentary estimations for the effects of dog population management on dog welfare. This enables a comparison to be made between the management methods but lacks overall detail in allowing full evaluation of welfare impacts. Further study is required to provide a comprehensive assessment of the short- and long-term welfare impact of management methods. For example, it has been highlighted that there are potential health and welfare risks associated with CNR (321,324). Future work should focus on the assessment of the immediate and long-term welfare impacts of dog population management in order to answer the questions: (i) *What are the short- and long-term welfare impacts of dog population management interventions?* And (ii) *What actions can be taken to reduce the health and welfare risks associated with catch-neuter-release?*

6.5. Conclusions

The work presented in this thesis advances understanding of the impact of dog population management on dog population dynamics, health and welfare. I have provided a synthesis of the reported impact of dog population management on measures of management impact and identified the need for increased studies that have improved reporting quality and study design that would allow the effect of management methods to be assessed. Dog population management targets the recruitment and removal of the free-roaming dog population. This study provides estimates of these parameters for free-roaming dog populations in parts of Europe. Future work is needed to further disentangle these rates, in order to identify flows that might maintain or increase free-roaming dog population size. There is a clear lack of reporting with regards to the impact of management methods on human behaviour change. This thesis has highlighted the importance of human behaviour and dog ownership practices in dog population management. Changing human behaviour is vitally important in ensuring that population management efforts create lasting change.

Appendix A

Supporting material related to Chapter Two.

Table A1. Key words and combinations. The columns represent the key word categories (separated by "AND" in the search) and rows display word variations (separated by "OR" in the search).

Key word	1	2	3	4
	AND	AND	AND	
	"Dog"	Stray*	Kill*	"Population"
	"Dogs"	"Feral"	Cull*	Control*
	"Canine"	Untame*	Euthan*	Restrain*
	"Canines"	Undomesticat*	Destroy*	Constrain*
		"Street"	Extermin*	Limit*
		Free-roam* (free-roaming)	Execut*	Restrict*
		Roam* (roaming)	Slaughter*	Manag*
		Unrestrict*	Terminat*	Dynamic*
		Free-rang*	"Lethal"	"Ecology"
		Rang*	Shelter*	Demograph*

Key word	1	2	3	4
		Abandon*	Rehom*	
		Unrestrain*	“Sanctuary”	
		Unconfin*	Adopt*	
			Rescue centre	
			Neuter*	
			Sterili* (sterilise)	
			Infertil*	
			Fert* (fertility)	
			Reproduc*	
			Breed*	
			Desex*	
			Castrat*	
			Contracept*	
			Birth*	
			Spay	

Inter-observer reliability:

The inter-observer reliability check resulted in 97% (146/150) agreement in stage one; and 60% (18/30) agreement at stage two.

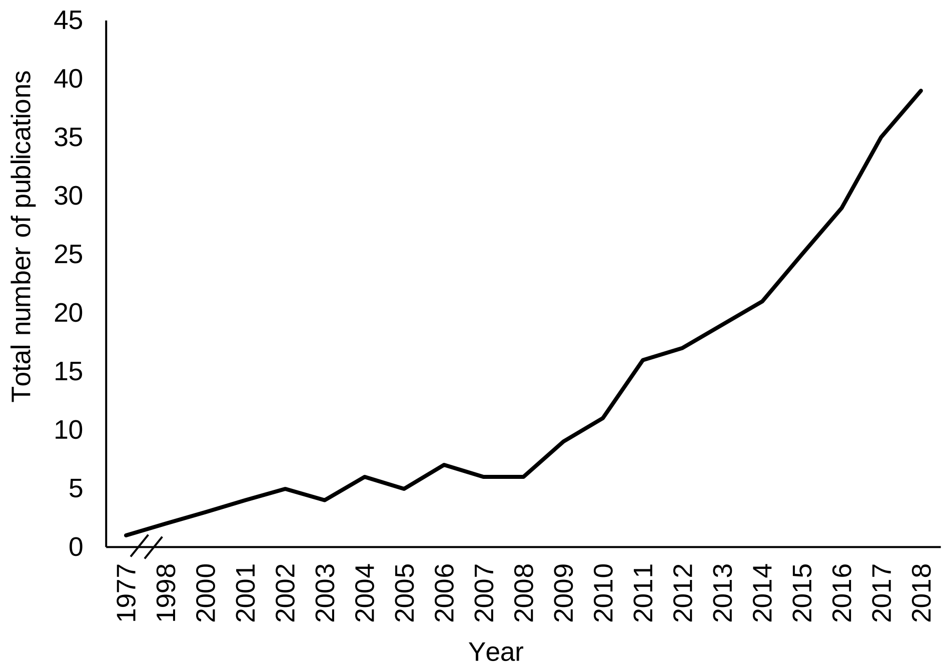

Figure A1. Cumulative number of publications in the final corpus per year between 1977 and 2018. Note the break in year from 1977 to 1998.

Table A2. Papers in the final corpus by subject, dog population management method, country, economic status of that country, and funding organisation.

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
(131)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Charity and University
(137)	Neutering (CNR) and Culling (indiscriminate)	USA	North America	North America	High income	Government and University
(145)	Neutering (CNR) and neutering (owned) and sheltering (rehoming)	Multiple	Multiple	Multiple	Multiple	Government and University
(135)	Neutering (owned)	Brazil	South America	South America	Upper middle income	Charity, Government, and University

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
(116)	Neutering (CNR) and sheltering	Italy	Europe	European Union	High income	Not reported
(122)	Neutering (CNR) and sheltering	Brazil	South America	South America	Upper middle income	Government and University
(150)	Culling (indiscriminate)	Multiple	No specific	No specific	No specific	University
(143)	Neutering (CNR) and sheltering	Canada	North America	North America	High income	Government and University
(149)	Immunocontraceptive & culling (indiscriminate)	Multiple	No specific	No specific	No specific	Government and University
(146)	Neutering (CNR)	Brazil	South America	South America	Upper middle income	University

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
(129)	Sheltering (rehoming)	Turkey	Europe/Asia	Europe	Upper middle income	University
(152)	Neutering (undefined) and Culling (indiscriminate)	Cyprus	Europe	European Union	High income	Government
(147)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Charity, Government and University
(136)	Neutering (CNR) and neutering (owned) and sheltering (rehoming)	USA	North America	North America	High income	Charity

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
(133)	Neutering (CNR)	Brazil	South America	South America	Upper middle income	Charity, Government and University
(132)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Charity
(139)	Neutering (CNR) and sheltering	Italy	Europe	European Union	High income	Government and University
(156)	Culling (indiscriminate)	China	Asia	Asia	Upper middle income	Government and University
(34)	Sheltering	Spain	Europe	European Union	High income	Government
(138)	Neutering (owned) and owned dog confinement	Mexico	South America	Central America	Upper middle income	University

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
(121)	Neutering (CNR) and Culling (indiscriminate)	Sri Lanka	Asia	Asia	Upper middle income	Government
(140)	Culling (indiscriminate)	No specific	No specific	No specific	No specific	University
(141)	Taxation	No specific	No specific	No specific	No specific	University
(154)	Culling (infected dogs)	Brazil	South America	South America	Upper middle income	Government and University
(144)	Neutering (undefined) & Sheltering	Thailand	Asia	Asia	Upper middle income	Government and University
(153)	Neutering (owned) and Culling (indiscriminate)	Cyprus	Europe	European Union	High income	Government
(130)	Neutering (CNR) & Sheltering	Serbia	Europe	Europe	Economy in transition	University

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
	(transportation of dogs)					
(117)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Charity
(148)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Government and Charity
(142)	Neutering (owned) and sheltering	Canada	North America	North America	High income	Charity and University
(120)	Neutering (CNR)	Bangladesh	Asia	Asia	Lower middle income	Charity and Government
(91)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Charity and University

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
(118)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Charity and University
(119)	Neutering (CNR)	India	Asia	Asia	Lower middle income	Charity and University
(134)	Neutering (CNR) and Culling (indiscriminate)	India	Asia	Asia	Lower middle income	Charity and University
(158)	Neutering and waste management	India	Asia	Asia	Lower middle income	University
(155)	Culling (infected dogs)	Brazil	South America	South America	Upper middle income	Charity and University
(157)	Culling (indiscriminate)	China	Asia	Asia	Upper middle income	Government and University

Author	Dog population management method	Country	Continent	Geographical Region	Economy status*	Funding type/driving organisation**
(151)	Culling (indiscriminate)	Chad	Africa	Africa	Low income	Charity and Government

* Economy status defined by The World Bank 2019 country income classification (126).

** Includes funding organisation and author affiliations.

Table A3. Number of papers investigating combinations of dog populations.

Dog population under investigation	Number of papers from final corpus investigating dog population
Only free-roaming owned dogs	1 (2.6%)
Only free-roaming unowned dogs	5 (12.8%)
Free-roaming unowned and free-roaming owned	19 (48.7%)
Free-roaming unowned, free-roaming owned and restricted owned	7 (17.9%)
Free-roaming unowned, free-roaming owned, restricted owned and shelter dogs	3 (7.7%)
Free-roaming unowned and shelter dogs	1 (2.6%)
Free-roaming owned and restricted owned	1 (2.6%)
Undefined	2 (5.1%)

Table A4. Number (and percentage) of published articles from the final corpus that measure the impact of the management method(s) studied.

Impact Measure	No. Papers	
Dog Health & Welfare		
Fertility control	4	(10.3%)
Fertility control and sheltering	1	(2.6%)
Sheltering	1	(2.6%)
Dog Demographics		
Fertility control	4	(10.3%)
Fertility control and culling	2	(5.1%)
Fertility control and movement restriction	1	(2.6%)
Fertility control and sheltering	5	(12.8%)
Taxation	1	(2.6%)
Public Attitude		
Fertility control	1	(2.6%)
Fertility control and sheltering	2	(5.1%)
Public Health		
Culling	7	(17.9%)
Fertility control	3	(7.7%)
Fertility control and culling	4	(10.3%)
Fertility control and sheltering	1	(2.6%)
Sheltering	1	(2.6%)
Wildlife		
Fertility control	1	(2.6%)
Total Papers	39	(100%)

Table A5. Summary of the reporting of study quality indicators in final corpus (excluding modelling studies). X indicates no metric was reported, □ indicates metric was reported and – indicates metric was not applicable for the study type.

Paper	Reporting of power calculation	Reporting of sample size calculation	Control population included	Reporting of inter-observer reliability	Reporting of baseline characteristics	Reporting quality indicator score
(34)	X	X	X	-	X	0% (0/4)
(91)	□	□	□	-	-	100% (3/3)
(117)	X	X	X	-	X	0% (0/4)
(118)	X	X	X	X	□	20% (1/5)
(119)	X	X	□	□	-	25% (1/4)
(120)	-	-	X	-	-	0% (0/1)
(121)	X	X	X	-	□	25% (1/4)
(122)	-	-	□	X	□	67% (2/3)
(131)	X	X	X	□	□	40% (2/5)
(132)	X	X	X	-	-	0% (0/3)
(148)	X	X	X	□	□	40% (2/5)
(146)	□	□	X	□	□	80% (4/5)
(129)	X	X	X	-	-	0% (0/3)

Paper	Reporting of power calculation	Reporting of sample size calculation	Control population included	Reporting of inter-observer reliability	Reporting of baseline characteristics	Reporting quality indicator score
(152)	X	X	X	-	✓	20% (1/4)
(153)	X	X	X	-	✓	20% (1/4)
(116)	X	X	X	-	-	0% (0/3)
(142)	X	X	X	-	✓	20% (1/4)
(144)	-	-	X	-	X	0% (0/2)
(143)	X	X	X	✓	-	20% (1/4)
(130)	X	X	X	-	-	0% (0/3)
(133)	-	-	X	-	✓	50% (1/2)
(154)	X	X	X	-	✓	20% (1/4)
(155)	X	X	✓	-	✓	50% (2/4)
Percentage reporting study quality indicators [a]	11%	11%	17%	71%	80%	

[a] Calculated as a percentage of those studies where this quality indicator is applicable.

Appendix B

Supporting material related to Chapter Three.

1. Facebook adverts:

Four Facebook adverts were used to increase recruitment of participants to complete the questionnaire. The adverts in English were:

Advert 1:

Headline 1: We would like to hear your opinion on stray dogs!

You are being invited to participate in this research project as we are looking to recruit a wide range of people from many different backgrounds so that we can have a clear idea of public attitudes towards stray dogs.

Advert 2:

Headline 2: Your opinion on stray dogs- take the survey!

We are conducting a study on the stray dog populations in Europe and internationally. Stray dog overpopulation is a global problem which is of public health, animal welfare and environmental concern. Let us know your opinion on stray dogs.

Advert 3:

Headline 3: Volunteers Required

We would like to hear your opinion about your local stray dog problem! Help us now by filling out our questionnaire.

Advert 4:

Headline 4: Assist us by letting us know your opinion

The STRAYS project investigates and compares different methods for long-term stray dog population management through a series of computer simulations. This will allow us to directly quantify the long-term effectiveness and sustainability of the catch-neuter-release method compared to other stray dog population management methods (including sheltering and culling).

2. English copy of questionnaire

Section 1) Socio-demographic information

1) What is your age?

Under 18	
18 to 24	
25 to 34	
35 to 44	
45 to 54	
55 to 64	
65 to 74	
75 and over	
No answer	

2) Which gender do you identify as?

Male	
Female	
Non-binary	
Other (please state)	
No answer	

Other: ……………………………………………………………

3) What is your occupation?

Employed	
Unemployed	
Student	
Seeking work	
Housewife/husband	
Retired	
No answer	
Other (please state)	

Other: …………………………………………………………

4) Education status:

No schooling	
Primary education (between ages 5 and 12)	
Secondary education (between ages 11 and 18)	
Higher education (University or colleges)	
No answer	

5) Nationality:

…………………………………………..

6) Religious beliefs

Atheist, Agnostic, Baha'i, Buddhist, Candomblé, Christian, Hindu, Jain, Jehovah's Witnesses, Jewish, Mormon, Muslim, Paganism, Rastafarian, Santeria, Shinto, Sikh, Spiritualist, Taoism, Unitarianism, Zoroastrianism, No answer,

Other: …………………………………………………………

7) Relationship status

Single	
Married	
Cohabitating	
Divorced/widowed	

No answer	

8) Number of people living in household:

1	2	3	4	5	More than 5	No answer

9) Number of children in household

1	2	3	4	5	More than 5	No answer

Section 2) Dog Ownership Practices

10) Do you own a dog?

Yes	
No	
No answer	

If no, please skip to **section 3**. If yes, continue in **section 2**.

11) How many male dogs do you own?

0	1	2	3	4	5	More than 5	No answer

12) How many female dogs do you own?

0	1	2	3	4	5	More than 5	No answer

13) How many of your dog(s) are:

Under 1 year old	1 to 3 years old	Over 3 years old	No answer

14) Are your dogs registered and identified?

Yes	
No	
I don’t know	
No answer	

15) What is your main reason for owning a dog(s)? Please select as many as you wish.

For practical reasons e.g. to guard house or for hunting	
For pleasure and company e.g. as a pet or companion	
No answer	
Other (please state)	

Other: ………………………………………………………………

16) Where did you get your dog(s)?

A dog shelter	
Internet	
A shop	
A breeder	
Bred my own	
Found	
From a friend/family	
No answer	
Other (please state)	

Other: ………………………………………………………………

17) Did you pay for your dog?

Yes	

No	
No answer	

18) How old was/were your dog(s) when you got him/her?

Puppy	
Adult	
No answer	

19) Have any of your male or female dog(s) had puppies?

Yes	
No	
Don’t know	
No answer	

If **yes**,

20) Considering all of your dogs, in total how many times have your dog(s) had puppies?

Once	
Twice	
Three times or more	
No answer	

21) What did you do with the puppies? Please mark all that apply.

Kept the puppies	
Gave them to a shelter	
Phoned authorities	
Gave to a friend	
Sold the puppies	
Let them free in the street	
Euthanised them at a clinic	

No answer	
Other (please state)	

Other: ………………………………………………………………

22) Do you prevent your dog(s) from breeding?

Yes	
No	
No answer	
Other	

Other: ………………………………………………………………

23) If **yes**, how do you prevent your dog(s) from breeding?

Surgical neutering	
Restricting male and female contact	
No answer	
Other (please state)	

Other: ………………………………………………………………

24) If **no**, what is your main reason for not preventing your dog(s) from breeding?

Cost	
A dog should reproduce at least once	
Believe dog is too young to be neutered	
Neutering is against religious beliefs	
Neutering causes weight gain	
Neutering modifies the dog’s behaviour	
Neutering is a risk to the dog’s health	
No answer	
Other (please state)	

Other: ………………………………………………………………

25) Do you feed your dog every day?

Yes	
No	
No answer	

26) Do you give your dog water every day?

Yes	
No	
No answer	

27) Do you provide shelter for your dog every day?

Yes	
No	
No answer	

28) Do you vaccinate your dog(s)?

Yes	
No	
No answer	

29) Do you allow your dog(s) to go outside, in the street, unsupervised?

Always	
Sometimes	
Never	
No answer	

30) Have you ever given up a dog?

Yes	
No	
No answer	

If no, go to question 33

31) If yes, did you:

Give the dog to a shelter	
Phone authorities	
Give to friend	
Sell	

Let free	
Euthanise at a clinic	
No answer	
Other (please state)	

Other: ……………………………………………………………

32) If yes, what was your reason for giving up a dog?

Lost interest	
Animal behavioural problem	
Cost	
No answer	
Other (please state)	

Other: ……………………………………………………………

Section 3) Attitudes Towards Stray Dogs

33) Have you seen dogs free on the street

Today	
In the past week	
In the past month	
In the past year	
Never	
No answer	

34) Have you ever felt physically threatened by dogs in the street?

Yes	
No	
No answer	

35) Have you ever been attacked by dogs in the street?

Yes	
No	
No answer	

36) Have you or any of your family members been bitten by dogs in the street in the last 12 months?

Yes	
No	
No answer	

37) Do you ever provide care for stray dogs by (please choose as many as necessary):

Feeding	
Providing water	
Providing shelter	
None	
No answer	

Please select your level of agreement with the following statements:

38) **I do not like stray dogs being present in the streets around my home or work.**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

39) **It is a good thing for the public to provide shelter for stray dogs.**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

40) **It is unacceptable for the public to feed stray dogs.**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

41) **I feel physically threatened by stray dogs.**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

42) **Stray dogs spread diseases.**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

43) **Stray dogs are a threat to the safety of children.**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

44) **Stray dogs spread rubbish and faeces**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

45) **It is unacceptable for the public to provide water for stray dogs.**

Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree	No answer

46) Who do you think should be responsible for managing stray dogs (such as by providing care and/or preventing an increase in stray dogs)? Pick the top three.

National government	
Municipality government	
Public veterinarians	
Private veterinarians	
Police	
Volunteer organisations	
Garbage control	
Nobody	
No answer	
Other (please state)	

Other: ………………………………………………………………

47) Do you think an increase in stray dogs should be prevented?

Yes	
No	
No answer	

48) If **yes**, how do you think stray dogs should be prevented (please pick as many as necessary)?

Public education campaigns for responsible dog ownership	
School education campaigns	
Sanctions for abandoning dogs	
No answer	
Other (please state)	

Other: ………………………………………………………………

49) Would you prefer to see:

No stray dogs	Fewer stray dogs	You do not mind stray dogs	More stray dogs	No answer

50) If you would prefer to see no dogs or fewer dogs on the street, how do you think stray dogs should be reduced (please pick as many as necessary)?

Remove dogs and put in shelters	
Catch-neuter-return of strays	
Controlling the birth rate of owned dogs	
Culling	
No answer	
I do not mind dogs on the street	
Other (please state)	

Other: …………………………………………………………………

3. Answer option to question "*Are your dog(s) registered and identified*" in Bulgarian questionnaire

For the question "*Are your dog(s) registered and identified*" in the Bulgarian questionnaire the answer option "*No – none of them*" was not included due to a translation error. As this answer is not included in any statistical analysis, I present the descriptive results for the other answer options, which are the same as the options available for the Italian and Ukrainian questionnaires.

4. Descriptive results of questionnaire

Table B1. Number of respondents in Bulgaria, split by oblasts in Bulgaria.

Total respondents	**5434**	**%**
Blagoevgrad	119	2.2%
Burgas	251	4.6%
Varna	629	11.6%
Veliko Tarnovo	181	3.3%
Vidin	76	1.4%
Vratsa	80	1.5%
Gabrovo	96	1.8%
Sofia city	1643	30.2%
Dobrich	83	1.5%
Kardzhali	39	0.7%
Kyustendil	45	0.8%
Lovech	64	1.2%
Montana	52	1.0%
Pazardzhik	123	2.3%
Pernik	62	1.1%
Pleven	149	2.7%
Plovdiv	449	8.3%
Razgrad	84	1.5%
Ruse	140	2.6%
Silistra	47	0.9%
Sliven	76	1.4%
Smolyan	39	0.7%
Sofia (province)	380	7.0%

Total respondents	**5434**	**%**
Stara Zagora	211	3.9%
Targovishte	55	1.0%
Haskovo	87	1.6%
Shumen	100	1.8%
Yambol	50	0.9%
No answer	24	0.4%

Table B2. Number of respondents in Italy, split by regions in Italy.

Total respondents	**3468**	**%**
Abruzzo	123	3.5%
Basilicata	37	1.1%
Calabria	73	2.1%
Campania	240	6.9%
Emilia-Romagna	281	8.1%
Friuli-Venezia Giulia	90	2.6%
Lazio	309	8.9%
Liguria	137	4.0%
Lombardia	597	17.2%
Marche	68	2.0%

Total respondents	**3468**	**%**
Molise	16	0.5%
No answer	20	0.6%
Piemonte	281	8.1%
Puglia	166	4.8%
Sardegna	130	3.7%
Sicilia	241	6.9%
Toscana	253	7.3%
Trentino-Alto Adige	43	1.2%
Umbria	105	3.0%
Valle d'Aosta	7	0.2%
Veneto	251	7.2%
No answer	0	0%

Table B3. Number of respondents in Ukraine, split by oblasts in Ukraine.

Total respondents	**19323**	**%**
Cherkasy	638	3.3%
Chernihiv	419	2.2%
Chernivtsi	415	2.1%
Dnipropetrovsk	1702	8.8%
Donetsk	639	3.3%

Total respondents	**19323**	**%**
Ivano-Frankivsk	816	4.2%
Kharkiv	990	5.1%
Kherson	467	2.4%
Khmelnytskyi	587	3.0%
Kiev	3640	18.8%
Kirovohrad	448	2.3%
Luhansk	199	1.0%
Lviv	1789	9.3%
Mykolaiv	564	2.9%
Odessa	934	4.8%
Poltava	744	3.9%
Rivne	436	2.3%
Sumy	412	2.1%
Ternopil	513	2.7%
Transcarpathia	362	1.9%
Vinnitsa	632	3.3%
Volyn	457	2.4%
Zaporizhzhia	765	4.0%
Zhytomyr	478	2.5%
No answer	277	1.4%

Table B4. Demographic information about respondents in Bulgaria, Italy and Ukraine.

	Bulgaria	%	Italy	%	Ukraine	%
Total respondents	**5434**		**3468**		**19323**	
Age						
18 - 24	1172	21.6	852	24.6	3742	19.4
25 - 34	1209	22.2	648	18.7	6049	31.3
35 - 44	1011	18.6	378	10.9	3983	20.6
45 - 54	1112	20.5	573	16.5	3269	16.9
55 - 64	658	12.1	729	21.0	1764	9.1
65 - 74	211	3.9	229	6.6	368	1.9
75 and over	11	0.2	30	0.9	22	0.1
No answer	50	0.9	29	0.8	126	0.7
Gender						
Female	4754	87.5	2882	83.1	16832	87.1
Male	552	10.2	505	14.6	2238	11.6
Other	5	0.1	4	0.1	5	0.0
No answer	123	2.3	77	2.2	248	1.3
Occupation						
Employed	3707	68.2	1611	46.5	13521	70.0
Unemployed	171	3.1	195	5.6	374	1.9
Student	688	12.7	661	19.1	1266	6.6
Seeking work	124	2.3	176	5.1	633	3.3
Housewife/husband	161	3.0	214	6.2	1590	8.2
Retired	343	6.3	303	8.7	1051	5.4
Other	81	1.5	187	5.4	268	1.4

	Bulgaria	%	Italy	%	Ukraine	%
No answer	159	2.9	121	3.5	620	3.2
Education status						
No schooling	3	0.1	0	0.0	32	0.2
Primary education	22	0.4	5	0.1	38	0.2
Secondary education	2002	36.8	254	7.3	2555	13.2
Tertiary education	3258	60.0	3129	90.2	15637	80.9
No answer	149	2.7	80	2.3	1061	5.5
Religious beliefs						
Religious*	3743	68.9	1457	42.0	13011	67.3
Not religious	812	14.9	1521	43.9	3677	19.0
Other	65	1.2	57	1.6	470	2.4
No answer	814	15.0	433	12.5	2165	11.2
Relationship status						
Single	1391	25.6	1411	40.7	4829	25.0
Married	1667	30.7	939	27.1	9138	47.3
Cohabiting	1338	24.6	531	15.3	2224	11.5
Divorced/widowed	502	9.2	303	8.7	2095	10.8
No answer	536	9.9	284	8.2	1037	5.4
No. people in household						
1	563	10.4	467	13.5	895	4.6
2	1885	34.7	1157	33.4	4752	24.6
3	1272	23.4	694	20.0	5099	26.4
4	896	16.5	605	17.4	4067	21.0

	Bulgaria	%	Italy	%	Ukraine	%
5	190	3.5	196	5.7	1498	7.8
More than 5	72	1.3	59	1.7	1375	7.1
No answer	556	10.2	290	8.4	1637	8.5
No. children in household						
0	2708	49.8	1654	47.7	6520	33.7
1	1143	21.0	585	16.9	5812	30.1
2	696	12.8	668	19.3	3941	20.4
3	100	1.8	166	4.8	813	4.2
4	17	0.3	41	1.2	182	0.9
5	4	0.1	10	0.3	66	0.3
More than 5	10	0.2	4	0.1	114	0.6
No answer	756	13.9	340	9.8	1875	9.7
Dog owner						
Yes	3528	64.9	2581	74.4	10797	55.9
No	1836	33.8	865	24.9	8349	43.2
No answer	70	1.3	22	0.6	177	0.9

* Religious options included: Baha'i, Buddhism, Christianity, Candomble, Hinduism, Jainism, Johavah's Witnesses, Judaism, Mormonism, Islam, Paganism, Rastafarianism, Santeria, Shintoism, Sikhism, Spiritualism, Taoism, Unitarianism, and Zoroastrianism.

Table B5. Respondents answers to questions about ownership practices in Bulgaria, Italy and Ukraine.

	Bulgaria	%	Italy	%	Ukraine	%
Number of dog owner respondents	**3528**		**2581**		**10797**	
No. male dogs						
0	1168	33.1	882	34.2	3112	28.8
1	1773	50.3	1243	48.2	5206	48.2
2	347	9.8	286	11.1	1166	10.8
3	103	2.9	76	2.9	258	2.4
4	28	0.8	19	0.7	77	0.7
5	10	0.3	12	0.5	27	0.3
More than 5	21	0.6	25	1.0	49	0.5
No answer	78	2.2	38	1.5	902	8.4
No. female dogs						
0	1307	37.0	797	30.9	3468	32.1
1	1516	43.0	1215	47.1	4556	42.2
2	393	11.1	353	13.7	1179	10.9

	Bulgaria	%	Italy	%	Ukraine	%
3	102	2.9	96	3.7	413	3.8
4	38	1.1	38	1.5	131	1.2
5	28	0.8	17	0.7	62	0.6
More than 5	30	0.9	28	1.1	127	1.2
No answer	114	3.2	37	1.4	861	8.0
Dog(s) registered (R) and identified (I) **						
Yes - all of them	2570	72.8	2479	96.0	R: 4713 I: 4482	R: 43.7 I: 41.5
No - none of them	NA***	NA***	27	1.0	R: 4238 I: 3647	R: 39.3 I: 33.8
Some of them	309	8.8	46	1.8	R: 641 I: 561	R: 5.9 I: 5.2
I don't know	136	3.9	0	0.0	R: 569 I: 1206	R: 5.3 I: 11.2
No answer	513	14.5	29	1.1	R: 636	R: 5.9

	Bulgaria	%	Italy	%	Ukraine	%
					I: 901	I: 8.3
Main reason for owning a dog(s)						
For practical reasons e.g. to guard house or for hunting	44	1.2	21	0.8	958	8.9
For pleasure and company e.g. as a pet or companion	3017	85.5	2263	87.7	7631	70.7
Practical and pleasure	65	1.8	96	3.7	984	9.1
Practical and other	0	0.0	0	0.0	14	0.1
Pleasure and other	47	1.3	64	2.5	64	0.6
Practical, pleasure and other	0	0.0	4	0.2	11	0.1
Other	245	6.9	122	4.7	867	8.0
No answer	110	3.1	11	0.4	268	2.5
Respondents got dog(s) from: *						
A dog shelter	341	9.7	986	38.1	1070	9.9
Internet	520	14.7	228	8.8	1311	12.1
A shop	214	6.1	60	2.3	232	2.1

	Bulgaria	%	Italy	%	Ukraine	%
A breeder	492	14.0	481	18.6	2866	26.5
Bred my own	208	5.9	279	10.8	716	6.6
Found on the street	1,252	35.5	641	24.8	3734	34.6
From a friend/family	1,149	32.6	590	22.8	3015	27.9
Other	71	1.6	113	4.4	271	2.5
No answer	56	2.0	21	0.8	99	0.9
Paid for dog(s)						
Yes - all of them	1195	33.9	380	14.7	3834	35.5
No - none of them	1748	49.5	1821	70.6	5216	48.3
Some of them	473	13.4	355	13.8	1429	13.2
No answer	112	3.2	25	1.0	318	2.9
Age of dog(s) when received by respondent						
All puppy (<1 year)	2683	76.0	1521	58.9	8233	76.3
All adult (1> year)	289	8.2	419	16.2	1140	10.6
Some puppy, some adult	524	14.9	639	24.8	1375	12.7

	Bulgaria	%	Italy	%	Ukraine	%
No answer	32	0.9	2	0.1	49	0.5
Owned dog(s) reproduced						
Yes	780	22.1	333	12.9	2534	23.5
No	2674	75.8	2186	84.7	7885	73.0
Don't know	63	1.8	54	2.1	199	1.8
No answer	11	0.3	8	0.3	179	1.7
Total number of times owned dog(s) have reproduced						
Once	521	14.8	205	61.6	1263	49.8
Twice	170	4.8	77	23.1	560	22.1
Three times or more	93	2.6	45	13.5	542	21.4
No answer	2744	77.8	6	1.8	170	6.7
Outcome of owned dog(s) puppies *						
Kept the puppies	241	30.9	143	42.9	703	7.3
Gave them to a shelter	10	1.3	0	0.0	46	0.5

	Bulgaria	%	Italy	%	Ukraine	%
Phoned authorities	5	0.6	3	0.9	NA	NA
Gave to a friend	577	74.0	160	48.0	1858	19.3
Sold the puppies	162	20.8	96	28.8	1028	10.7
Let them free in the street	3	0.4	0	0.0	15	0.2
Euthanised them at a clinic	1	0.1	4	1.2	60	0.6
Other	133	17.1	40	12.0	1329	13.8
No answer	1381	59.6	4	1.2	5365	55.8
Prevent dog(s) from breeding						
Yes - all of them	2805	79.5	2105	81.6	6024	55.8
No - none of them	218	6.2	217	8.4	1770	16.4
Some of them	124	3.5	152	5.9	1038	9.6
Other	45	1.3	49	1.9	241	2.2
No answer	336	9.5	58	2.2	1724	16.0
If yes, how prevent dog(s) from breeding: *						
Surgical neutering	1424	50.8	1689	65.3	3828	35.3

	Bulgaria	%	Italy	%	Ukraine	%
Restricting male and female contact	1550	55.3	887	34.3	4052	37.4
Other	20	0.70	215	8.30	429	4.0
If no, main reason for not preventing dog(s) from breeding:						
Cost	9	4.1	11	5.1	77	4.4
A dog should reproduce at least once	82	37.6	75	34.6	242	13.7
Believe dog is too young to be neutered	18	8.3	23	10.6	116	6.6
Neutering is against religious beliefs	6	2.8	0	0.0	19	1.1
Neutering causes weight gain	3	1.4	1	0.5	9	0.5
Neutering modifies the dog’s behaviour	10	4.6	14	6.5	60	3.4
Neutering is a risk to the dog’s health	32	14.7	24	11.1	286	16.2
Other	24	11.0	35	16.1	158	8.9
No answer	34	15.6	34	15.7	803	45.4
Respondent feeds dog(s) every day						
Yes	3524	99.9	2576	99.8	10767	99.7

	Bulgaria	%	Italy	%	Ukraine	%
No	2	0.1	3	0.1	19	0.2
No answer	2	0.1	2	0.1	11	0.1
Respondent give dog(s) water every day						
Yes	3516	99.7	2575	99.8	10724	99.3
No	3	0.1	4	0.2	54	0.5
No answer	9	0.3	2	0.1	19	0.2
Respondent provides provide shelter for dog(s) every day						
Yes	3524	99.9	2575	99.8	10573	97.9
No	3	0.1	2	0.1	38	0.4
No answer	1	0.0	4	0.2	186	1.7
Respondent vaccinates dog(s)						
Yes	3295	93.4	2483	96.2	8845	81.9
No	172	4.9	75	2.9	1668	15.4
No answer	61	1.7	23	0.9	284	2.6

	Bulgaria	%	Italy	%	Ukraine	%
Respondent allow dog(s) to go outside, in the street, unsupervised (free-roaming)						
Always	366	10.4	29	1.1	382	3.5
Sometimes	1039	29.5	162	6.3	1764	16.3
Never	2082	59.0	2377	92.1	8571	79.4
No answer	41	1.2	13	0.5	80	0.7
Respondent has given up a dog(s)						
Yes	33	0.9	181	7.0	676	6.3
No	3474	98.5	2386	92.4	9950	92.2
No answer	21	0.6	14	0.5	171	1.6
If yes, respondent:						
Give the dog to a shelter	2	6.1	19	10.5	13	1.9
Phone authorities	0	0.0	8	4.4	NA	NA
Give to friend	13	39.4	133	73.5	506	74.9
Sell	0	0.0	9	5.0	23	3.4

	Bulgaria	%	Italy	%	Ukraine	%
Let free	16	48.5	0	0.0	47	7.0
Euthanise at a clinic	1	3.0	0	0.0	8	1.2
Other	0	0.0	11	6.1	65	9.6
No answer	1	3.0	1	0.6	14	2.1
If yes, reason for giving up a dog(s):						
Lost interest	1	3.0	1	0.6	7	1.0
Animal behavioural problem	9	27.3	66	36.5	161	23.8
Cost	0	0.0	5	2.8	63	9.3
Other	13	39.4	104	57.5	306	45.3
No answer	10	30.3	3	1.7	139	20.6

** Multi answer question: Percentage of respondents who selected each answer option (i.e. 100% would indicate that all respondents chose this option)*

*** Ukraine registered and identified two separate options.*

**** Answer option not available in the Bulgarian questionnaire. See appendix for details.*

Table B6. Respondents answers to questions about attitudes to free-roaming dogs in Bulgaria, Italy and Ukraine.

	Bulgaria	%	Italy	%	Ukraine	%
Number of respondents	**5434**		**3468**		**19323**	
Seen dogs free on the street						
Today	3983	73.3	534	15.4	14934	77.3
In the past week	1144	21.1	630	18.2	3564	18.4
In the past month	178	3.3	557	16.1	583	3.0
In the past year	91	1.7	937	27.0	102	0.5
Never	2	0.0	650	18.7	10	0.1
No answer	36	0.7	160	4.6	130	0.7
Ever felt physically threatened by dogs in the street						
Yes	1679	30.9	373	10.8	7905	40.9
No	3685	67.8	3060	88.2	11138	57.6
No answer	70	1.3	35	1.0	280	1.4
Ever been attacked by dogs in the street						

	Bulgaria	%	Italy	%	Ukraine	%
Yes	1174	21.6	147	4.2	5129	26.5
No	4188	77.1	3306	95.3	13978	72.3
No answer	72	1.3	15	0.4	216	1.1
Respondent or family members been bitten by dogs in the street in the last 12 months						
Yes	500	9.2	55	1.6	2900	15.0
No	4857	89.4	3403	98.1	16146	83.6
No answer	77	1.4	10	0.3	277	1.4
Provide care for stray dogs by: *						
Feeding	4911	90.6	1831	53.7	13045	67.5
Providing water	3847	71.0	1508	44.2	5721	29.6
Providing shelter	1886	34.8	647	19.0	1882	9.7
None	341	6.3	970	28.5	4050	21.0
No answer	85	1.6	484	14.2	1884	9.8

Respondents' level of agreement.

	Bulgaria	%	Italy	%	Ukraine	%
I do not like stray dogs being present in the streets around my home or work.						
Strongly agree	1039	19.1	310	8.9	4052	21.0
Agree	715	13.2	364	10.5	2781	14.4
Neither agree nor disagree	1158	21.3	713	20.6	4669	24.2
Disagree	763	14.0	538	15.5	2959	15.3
Strongly disagree	938	17.3	1242	35.8	3114	16.1
No answer	821	15.1	301	8.7	1748	9.0
It is a good thing for the public to provide shelter for stray dogs.						
Strongly agree	3855	70.9	2558	73.8	15145	78.4
Agree	1034	19.0	584	16.8	2800	14.5
Neither agree nor disagree	256	4.7	175	5.0	630	3.3
Disagree	71	1.3	61	1.8	216	1.1
Strongly disagree	71	1.3	65	1.9	272	1.4

	Bulgaria	%	Italy	%	Ukraine	%
No answer	147	2.7	25	0.7	260	1.3
It is unacceptable for the public to feed stray dogs.						
Strongly agree	242	4.5	110	3.2	887	4.6
Agree	120	2.2	69	2.0	670	3.5
Neither agree nor disagree	272	5.0	174	5.0	1183	6.1
Disagree	1026	18.9	468	13.5	4536	23.5
Strongly disagree	3062	56.3	2383	68.7	10664	55.2
No answer	712	13.1	264	7.6	1383	7.2
It is unacceptable for the public to provide water for stray dogs.						
Strongly agree	182	3.3	68	2.0	621	3.2
Agree	89	1.6	32	0.9	471	2.4
Neither agree nor disagree	159	2.9	112	3.2	1113	5.8
Disagree	789	14.5	351	10.1	4079	21.1
Strongly disagree	3410	62.8	2550	73.5	11083	57.4

	Bulgaria	%	Italy	%	Ukraine	%
No answer	805	14.8	355	10.2	1956	10.1
I feel physically threatened by stray dogs						
Strongly agree	355	6.5	63	1.8	1957	10.1
Agree	328	6.0	125	3.6	2172	11.2
Neither agree nor disagree	612	11.3	369	10.6	2885	14.9
Disagree	1130	20.8	671	19.3	4890	25.3
Strongly disagree	2295	42.2	1956	56.4	6097	31.6
No answer	714	13.1	284	8.2	1322	6.8
Stray dogs are a threat to the safety of children.						
Strongly agree	513	9.4	125	3.6	2867	14.8
Agree	653	12.0	389	11.2	4161	21.5
Neither agree nor disagree	1003	18.5	746	21.5	2871	14.9
Disagree	1101	20.3	730	21.0	4301	22.3
Strongly disagree	1478	27.2	1243	35.8	3762	19.5
No answer	686	12.6	235	6.8	1361	7.0

	Bulgaria	%	Italy	%	Ukraine	%
Stray dogs spread diseases.						
Strongly agree	536	9.9	102	2.9	1941	10.0
Agree	974	17.9	373	10.8	3447	17.8
Neither agree nor disagree	1100	20.2	762	22.0	3470	18.0
Disagree	947	17.4	675	19.5	4818	24.9
Strongly disagree	1151	21.2	1282	37.0	4037	20.9
No answer	726	13.4	274	7.9	1610	8.3
Stray dogs spread rubbish and faeces.						
Strongly agree	608	11.2	157	4.5	1106	5.7
Agree	1114	20.5	645	18.6	946	4.9
Neither agree nor disagree	866	15.9	743	21.4	1902	9.8
Disagree	946	17.4	624	18.0	5436	28.1
Strongly disagree	1196	22.0	1038	29.9	8384	43.4
No answer	704	13.0	261	7.5	1549	8.0

	Bulgaria	%	Italy	%	Ukraine	%
Who should be responsible for managing stray dogs (such as by providing care and/or preventing an increase in stray dogs: **						
National government	2425	44.7	1775	51.2	12475	64.6
Municipality government	4776	88.1	3201	92.4	14998	77.6
Public veterinarians	2639	48.7	2057	59.4	9052	46.8
Private veterinarians	412	7.6	249	7.2	1588	8.2
Police	596	11.0	240	6.9	1387	7.2
Volunteer organisations	2825	52.1	1517	43.8	9380	48.5
Garbage control	25	0.5	36	1.0	219	1.1
Nobody	22	0.4	7	0.2	31	0.2
Other	277	5.1	37	1.1	537	2.8
No answer	47	0.9	11	0.3	71	0.4
An increase in stray dogs should be prevented						
Yes	5177	95.3	3319	95.7	18414	95.3

	Bulgaria	%	Italy	%	Ukraine	%
No	111	2.0	81	2.3	461	2.4
No answer	146	2.7	68	2.0	448	2.3
If yes, how should stray dogs be prevented: *						
Public education campaigns for responsible dog ownership	4268	78.5	2879	83.0	12763	66.1
School education campaigns	3513	64.6	2356	67.9	9915	51.3
Sanctions for abandoning dogs	5069	93.3	3115	89.8	18027	93.3
No answer	94	1.7	44	1.3	417	2.2
Other	243	4.5	346	10.0	1029	5.3
Respondent prefer to see:						
No stray dogs	2848	52.4	2435	70.2	8740	45.2
Fewer stray dogs	1780	32.8	841	24.3	7846	40.6
You do not mind stray dogs	726	13.4	63	1.8	2552	13.2
More stray dogs	4	0.1	40	1.2	21	0.1
No answer	76	1.4	89	2.6	164	0.8

	Bulgaria	%	Italy	%	Ukraine	%
If respondent prefer to see no dogs or fewer dogs on the street, how should stray dogs be reduced *						
Remove dogs and put in shelters	3643	67.2	1236	36.4	13349	69.1
Catch-neuter-return of strays	3644	67.2	2088	61.4	11085	57.4
Controlling the birth rate of owned dogs	3811	70.3	2320	68.3	11481	59.4
Culling	92	1.7	56	1.6	1216	6.3
I do not mind dogs on the street	721	13.3	21	0.6	2388	12.4
Other	170	3.1	293	8.6	446	2.3
No answer	15	0.3	69	2.0	97	0.5

* Multi answer question: Percentage of respondents who selected each answer option (i.e. 100% would indicate that all respondents chose this option)

** Respondents allowed to choose three options for list. Percentage illustrate the percentage of respondents who selected that option.

Table B7. Number of "No responses" to outcome and predictor variables in statistical analysis.

Dataset	Variable	No. NA's	Total length	%
Dog owners	Sterilisation	0	16906	0.0%
	Roaming status	168		1.0%
	Gender	71		0.4%
	Age	120		0.7%
	Education	843		5.0%
	Religious	2256		13.3%
	Practical	0		0.0%
	Country	0		0.0%
All	Do not like stray presence	2870	28225	10.2%
	Prevent stray increase	662		2.3%
	Prefer see	329		1.2%
	Child household	549		1.9%
	Feel threatened	2320		8.2%
	Attacked	303		1.1%
	Bitten	364		1.3%
	Country	0		0.0%

Table B8. The posterior mean values, error estimates, the 2.5 and 97.5 percentiles of the posterior distribution (CI), Rhat values and bulk and tail effective sample sizes (ESS) for Model 1.

	Posterior mean	**Posterior standard deviation**	**2.5% CI**	**97.5% CI**	**Rhat**	**Bulk ESS**	**Tail ESS**
Intercept	-0.14	0.02	-0.18	-0.10	1.00	5738	3381
Gender	0.39	0.06	0.26	0.51	1.00	5341	2871
Age	0.14	0.01	0.11	0.16	1.00	6069	2736
Education status	0.25	0.05	0.16	0.35	1.00	5061	2943
Religious beliefs	-0.41	0.04	-0.50	-0.32	1.00	5769	3458
Reason for dog ownership practical	-0.72	0.06	-0.84	-0.61	1.00	5252	3130
Country 1	-0.22	0.03	-0.29	-0.16	1.00	3136	2917
Country 2	0.61	0.04	0.54	0.68	1.00	3399	3354

Table B9. The posterior mean values, error estimates, the 2.5 and 97.5 percentiles of the posterior distribution (CI), Rhat values and bulk and tail effective sample sizes (ESS) for Model 2.

	Posterior mean	**Posterior standard deviation**	**2.5% CI**	**97.5% CI**	**Rhat**	**Bulk ESS**	**Tail ESS**
Threshold 1	0.85	0.02	0.82	0.88	1.00	3720	3284
Threshold 2	1.86	0.02	1.81	1.90	1.00	4607	3411
Gender	-0.05	0.01	-0.06	-0.03	1.00	5880	2624
Age	-0.09	0.03	-0.14	-0.03	1.00	4525	2855
Education status	0.16	0.03	0.10	0.23	1.00	4052	3016
Religious beliefs	0.32	0.03	0.25	0.39	1.00	4295	2892
Reason for dog ownership practical	0.58	0.02	0.54	0.63	1.00	2289	2679
Country 1	-0.54	0.03	-0.60	-0.48	1.00	2238	2655

Country 2	0.85	0.02	0.82	0.88	1.00	3720	3284

Table B10. The posterior mean values, error estimates, the 2.5 and 97.5 percentiles of the posterior distribution (CI), Rhat values and bulk and tail effective sample sizes (ESS) for Model 3.

	Posterior mean	**Posterior standard deviation**	**2.5% CI**	**97.5% CI**	**Rhat**	**Bulk ESS**	**Tail ESS**
Threshold 1	-0.94	0.01	-0.97	-0.92	1.00	4049	3359
Threshold 2	-0.36	0.01	-0.38	-0.33	1.00	4904	3421
Threshold 3	0.45	0.01	0.43	0.47	1.00	4891	3234
Threshold 4	1.03	0.01	1.01	1.05	1.00	5290	3616
Dog ownership	0.00	0.02	-0.03	0.03	1.00	5292.00	2625.00
Gender	-0.08	0.02	-0.13	-0.04	1.00	5752.00	3063.00
Age	0.02	0.01	0.01	0.03	1.00	5894.00	3131.00
Education status	0.02	0.02	-0.02	0.06	1.00	4727.00	3375.00

	Posterior mean	Posterior standard deviation	2.5% CI	97.5% CI	Rhat	Bulk ESS	Tail ESS
Children in household	0.03	0.02	-0.01	0.06	1.00	4924	3458
Threatened by dogs on the street	0.50	0.01	0.48	0.51	1.00	5102	3515
Been attacked by dogs on the street	0.05	0.02	0.01	0.09	1.00	4493	3358
Respondent or family members have been bitten by dogs on the street in last 12 months	0.18	0.03	0.13	0.23	1.00	4518	3180
Country1	0.17	0.01	0.14	0.20	1.00	3388	2792
Country2	-0.23	0.02	-0.26	-0.20	1.00	3417	3051

Table B11. The posterior mean values, error estimates, the 2.5 and 97.5 percentiles of the posterior distribution (CI), Rhat values and bulk and tail effective sample sizes (ESS) for Model 4.

	Posterior mean	**Posterior standard deviation**	**2.5% CI**	**97.5% CI**	**Rhat**	**Bulk ESS**	**Tail ESS**
Intercept	4.09	0.07	3.96	4.23	1.00	4661	3629
Dog ownership	0.02	0.09	-0.17	0.20	1.00	5643.00	3333.00
Gender	0.76	0.12	0.52	0.98	1.00	5277.00	3050.00
Age	0.10	0.04	0.03	0.17	1.00	4387.00	2945.00
Education status	0.43	0.10	0.23	0.62	1.00	4573.00	3209.00
Children in household	-0.14	0.10	-0.33	0.05	1.00	5149	2980
Threatened by dogs on the street	0.42	0.05	0.32	0.52	1.00	3860	3272

	Posterior mean	Posterior standard deviation	2.5% CI	97.5% CI	Rhat	Bulk ESS	Tail ESS
Been attacked by dogs on the street	0.07	0.15	-0.21	0.35	1.00	4165	2920
Respondent or family members have been bitten by dogs on the street in last 12 months	0.06	0.20	-0.31	0.45	1.00	5075	3416
Country1	0.21	0.09	0.03	0.40	1.00	2408	2787
Country2	-0.02	0.10	-0.21	0.17	1.00	2435	3022

Table B12. The posterior mean values, error estimates, the 2.5 and 97.5 percentiles of the posterior distribution (CI), Rhat values and bulk and tail effective sample sizes (ESS) for Model 5.

	Posterior mean	**Posterior standard deviation**	**2.5% CI**	**97.5% CI**	**Rhat**	**Bulk ESS**	**Tail ESS**
Threshold 1	0.23	0.01	0.21	0.25	1.00	5604	3595
Threshold 2	1.47	0.01	1.44	1.50	1.00	6718	3479
Threshold 3	3.18	0.04	3.10	3.27	1.00	5042	3108
Dog ownership	-0.09	0.02	-0.12	-0.05	1.00	5546.00	3143.00
Gender	-0.17	0.02	-0.22	-0.13	1.00	5233.00	3290.00
Age	-0.03	0.01	-0.04	-0.02	1.00	6402.00	3121.00
Education status	-0.03	0.02	-0.07	0.01	1.00	4706.00	3332.00
Children in household	-0.02	0.02	-0.05	0.01	1.00	5157	2954

	Posterior mean	Posterior standard deviation	2.5% CI	97.5% CI	Rhat	Bulk ESS	Tail ESS
Threatened by dogs on the street	-0.21	0.01	-0.23	-0.20	1.00	4288	3245
Been attacked by dogs on the street	-0.05	0.02	-0.09	-0.01	1.00	4156	3166
Respondent or family members have been bitten by dogs on the street in last 12 months	-0.17	0.03	-0.23	-0.12	1.00	4189	3238
Country1	0.11	0.02	0.08	0.14	1.00	2576	3108
Country2	-0.47	0.02	-0.50	-0.43	1.00	2686	3063

Appendix C

Supporting material related to Chapter Four.

1. Survey timings

All surveys took place between 06:00 and 10:00. In Ukraine, out of 60 surveys, 58 (97%) surveys took place between 06:30 and 09:30, one survey (2%) was missed due to illness, and one survey (2%) began at 06:00 due to logistical constraints. In Italy, out of the 60 surveys, 59 (98%) took place between 06:30 and 09:30, and one survey began at 06:00 due to logistical constraints. For the survey that was missed due to illness, NA's were included in the array of capture histories ($\gamma^{(i \times t \times s)}$) for study site one in Lviv for primary period three, secondary sampling period two. For the predictor variables, temperature and rainfall (no rainfall) was recorded using records in weather.com, the missed survey day was a weekday and market event was recorded as NA.

Table C1. Survey timings, distance and length (minimum, maximum and mean) in study sites in Italy and Ukraine.

Focal Country	Study site	Distance (km)	Survey time (minutes)			Start time			End time		
			Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Italy	One	3.38	49	97	63	06:53	07:08	06:59	07:44	08:30	08:01
	Two	6.20	49	81	67	06:55	07:09	07:00	07:49	08:17	08:07
	Three	8.79	76	128	92	06:52	07:15	07:01	08:16	09:00	08:33
	Four	6.50	77	106	87	06:00*	07:21	06:57	07:18	08:45	08:24
Ukraine	One	8.44	77	153	99	06:50	07:13**	07:00	08:14	08:57	08:32
	Two	7.20	86	112	95	06:45	07:30**	07:01	08:13	09:01	08:36
	Three	9.43	74	121	101	05:58*	07:40**	07:01	07:53	09:14	08:48
	Four	7.64	86	135	107	06:50	07:31**	07:05	08:26	09:27	08:51

* Survey began earlier due to logistical constraints.

** Survey began later due to daylight hours (sunrise at later time).

2. Survey weather

Table C2. Primary and secondary sampling period timings, temperature and weather conditions in Italy.

Primary sampling period	**Study site**	**Secondary sampling period**	**Date**	**Start Temp**	**Finish Temp**	**Mean temperature (ºC)**	**Rain**	**Market event**	**Start time**	**Finish time**	**Survey length (minutes)**
One (April 2018)	One	1	11/04/2018	11	11	11	Yes	No	07:00	07:57	57
		2	12/04/2018	13	13	13	No	No	07:00	08:01	61
		3	13/04/2018	11	12	11.5	No	No	06:53	08:30	97
	Two	1	14/04/2018	11	12	11.5	No	No	06:55	08:16	81
		2	15/04/2018	13	13	13	No	No	06:55	08:16	81
		3	16/04/2018	14	14	14	No	No	07:00	08:09	69
	Three	1	17/04/2018	12	13	12.5	No	No	06:52	08:26	94

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	18/04/2018	14	14	14	No	No	06:58	08:42	105
		3	19/04/2018	13	16	14.5	No	No	06:52	09:00	128
	Four	1	20/04/2018	14	17	15.5	No	No	06:55	08:41	106
		2	21/04/2018	14	14	14	No	No	06:49	08:23	94
		3	22/04/2018	12	14	13	No	No	06:50	08:16	86
Two (July 2018)	One	1	06/07/2018	22	23	22.5	No	No	06:55	08:03	68
		2	07/07/2018	20	22	21	No	No	07:00	08:20	80
		3	08/07/2018	20	22	21	No	No	06:55	08:10	75
	Two	1	09/07/2018	21	24	22.5	No	No	07:03	08:10	67

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	10/07/2018	19	22	20.5	No	No	06:55	08:12	77
		3	11/07/2018	24	24	24	No	No	07:00	08:00	60
		1	12/07/2018	20	23	21.5	No	No	07:09	08:57	108
	Three	2	13/07/2018	22	24	23	No	No	07:00	08:34	94
		3	14/07/2018	21	24	22.5	No	Yes	07:06	08:36	90
		1	15/07/2018	23	26	24.5	No	No	07:05	08:39	94
	Four	2	16/07/2018	23	26	24.5	No	No	07:05	08:33	88
		3	17/07/2018	19	19	19	Yes	No	07:01	08:20	79
	One	1	02/10/2018	12	13	12.5	No	No	07:00	08:00	60

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	03/10/2018	12	13	12.5	No	No	07:00	08:00	60
		3	04/10/2018	13	14	13.5	No	No	06:55	08:02	67
		1	05/10/2018	16	15	15.5	Yes	Yes	07:06	08:09	63
	Two	2	06/10/2018	14	16	15	Yes	No	07:01	08:17	76
Three (October 2018)		3	07/10/2018	14	16	15	No	No	06:58	08:10	72
		1	08/10/2018	13	14.5	13.75	No	No	07:00	08:32	92
	Three	2	09/10/2018	14	15	14.5	No	No	07:02	08:34	92
		3	10/10/2018	14	15	14.5	No	No	07:15	08:45	90
	Four	1	11/10/2018	14	16	15	No	No	07:15	08:45	90

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	12/10/2018	17	17	17	No	No	06:56	08:22	86
		3	13/10/2018	13	14	13.5	No	No	07:21	08:43	82
Four (April 2019)	One	1	07/04/2019	8	9	8.5	Yes	No	07:00	07:51	51
		2	08/04/2019	10	9	9.5	No	No	07:08	08:04	56
		3	09/04/2019	12	12	12	No	No	06:55	07:44	49
	Two	1	10/04/2019	9	10	9.5	No	No	07:00	08:03	63
		2	11/04/2019	7	9	8	No	No	07:09	08:07	58
		3	12/04/2019	7	9	8	No	No	07:00	07:49	49
	Three	1	13/04/2019	7	7	7	No	Yes	07:00	08:23	83

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	14/04/2019	7	8	7.5	No	No	07:00	08:23	83
		3	15/04/2019	7	7	7	Yes	No	07:00	08:22	82
	Four	1	16/04/2019	9	10	9.5	No	No	07:00	08:20	80
		2	17/04/2019	9	12	10.5	No	Yes	07:00	08:23	83
		3	18/04/2019	11	12	11.5	No	No	07:00	08:44	104
Five (July 2019)	One	1	09/07/2019	25	26	25.5	No	No	07:05	08:04	59
		2	10/07/2019	23	23	23	No	No	07:00	07:52	52
		3	11/07/2019	19	21	20	No	Yes	07:00	07:50	50
	Two	1	12/07/2019	19	22	20.5	No	Yes	06:57	08:06	69

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	13/07/2019	20	22	21	No	No	07:03	08:00	57
		3	14/07/2019	18	19	18.5	No	No	07:05	08:02	57
		1	15/07/2019	17	19	18	No	No	07:14	08:33	79
	Three	2	16/07/2019	17	18	17.5	No	No	07:00	08:16	76
		3	17/07/2019	17	19	18	No	No	07:01	08:26	85
		1	18/07/2019	18	22	20	No	No	07:00	08:20	80
	Four	2	19/07/2019	19	21	20	No	No	07:00	08:17	77
		3	20/07/2019	19	22	20.5	No	No	06:00	07:18	78

Table C3. Primary and secondary sampling period timings, temperature and weather conditions in Lviv.

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
One (April 2018)	One	1	01/05/2018	12	19	15.5	No	No	07:00	08:57	117
		2	02/05/2018	11	17	14	No	No	06:55	08:53	118
		3	03/05/2018	14	17	15.5	No	No	06:50	08:29	99
	Two	1	04/05/2018	10	17	13.5	No	No	06:50	08:42	112
		2	05/05/2018	13	14	13.5	No	No	06:45	08:21	96
		3	06/05/2018	11	11	11	No	No	06:45	08:13	88
	Three	1	07/05/2018	6	24	15	No	No	06:55	08:55	120
		2	08/05/2018	11	13	12	No	No	06:55	08:50	115

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		3	09/05/2018	14	17	15.5	No	No	06:50	08:45	85
		1	10/05/2018	12	17	14.5	No	No	06:55	08:50	115
	Four	2	11/05/2018	10	16	13	No	No	06:55	08:26	91
		3	12/05/2018	9	13	11	No	No	06:50	08:34	104
		1	20/07/2018	18	19	18.5	No	No	07:00	08:28	88
	One	2	21/07/2018	17	19	18	No	Yes	07:00	08:47	107
Two (July 2018)		3	22/07/2018	14	18	16	No	No	07:00	08:24	84
		1	23/07/2018	18	19	18.5	No	No	07:00	08:41	101
	Two	2	24/07/2018	18	19	18.5	Yes	No	07:00	08:36	96
		3	25/07/2018	18	18	18	No	No	07:00	08:42	102

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		1	30/07/2018	17	21	19	No	No	07:00	09:14	74
	Three	2	31/07/2018	18	19	18.5	Yes	No	07:00	08:48	108
		3	01/08/2018	18	19	18.5	No	No	05:58	07:53	115
		1	27/07/2018	17	21	19	No	No	06:50	09:05	135
	Four	2	28/07/2018	17	21	19	No	No	06:55	08:58	124
		3	29/07/2018	20	21	20.5	No	No	07:00	09:07	127
Three (October 2018)		1	16/10/2018	6	7	6.5	No	No	06:55	08:28	94
	One	2	17/10/2018*	5	7	6	NA	NA	NA	NA	NA
		3	18/10/2018	7	7	7	No	No	07:13	08:46	153
	Two	1	19/10/2018	7	9	8	No	No	07:20	08:50	90

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	20/10/2018	8	9	8.5	No	No	07:30	09:01	91
		3	21/10/2018	7	7	7	Yes	No	07:28	09:00	92
		1	22/10/2018	0	1	0.5	No	No	07:27	09:07	100
	Three	2	23/10/2018	6	6	6	Yes	No	07:30	09:07	97
		3	24/10/2018	6	6	6	Yes	No	07:40	09:11	91
		1	25/10/2018	3	3	3	No	No	07:31	09:27	122
	Four	2	26/10/2018	6	6	6	No	No	07:30	09:08	98
		3	27/10/2018	8	8	8	No	Yes	07:30	09:13	103
	One	1	26/04/2019	9	15	12	No	Yes	07:00	08:36	94
		2	27/04/2019	16	17	16.5	No	No	07:00	08:25	85

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		3	28/04/2019	12	12	12	No	No	06:57	08:14	77
		1	29/04/2019	9	10	9.5	Yes	No	07:00	08:26	86
	Two	2	30/04/2019	9	10	9.5	Yes	No	06:50	08:21	91
		3	01/05/2019	8	8	8	Yes	No	06:55	08:24	89
Four (April 2019)		1	02/05/2019	7	10	8.5	No	No	06:57	08:58	121
	Three	2	03/05/2019	9	12	10.5	No	No	07:08	08:50	102
		3	04/05/2019	8	8	8	No	No	07:02	08:49	107
		1	05/05/2019	9	9	9	Yes	No	07:06	08:49	103
	Four	2	06/05/2019	5	5	5	Yes	No	07:02	08:51	109
		3	07/05/2019	5	6	5.5	No	No	07:04	08:51	107

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
Five (July 2019)	One	1	21/07/2019	15	19	17	No	No	07:02	08:20	78
		2	22/07/2019	16	17	16.5	No	No	07:05	08:28	83
		3	23/07/2019	16	18	17	No	No	07:00	08:18	78
	Two	1	24/07/2019	16	17	16.5	No	No	07:00	08:32	92
		2	25/07/2019	16	17	16.5	No	No	07:00	08:36	96
		3	26/07/2019	16	18	17	No	No	07:02	08:44	102
	Three	1	27/07/2019	14	17	15.5	No	No	07:01	08:38	97
		2	28/07/2019	20	21	20.5	No	No	07:00	08:27	87
		3	29/07/2019	19	23	21	No	No	07:00	08:35	95
	Four	1	30/07/2019	18	19	18.5	No	No	07:03	08:32	89

Primary sampling period	Study site	Secondary sampling period	Date	Start Temp	Finish Temp	Mean Temperature (ºC)	Rain	Market event	Start time	Finish time	Survey length (minutes)
		2	31/07/2019	18	19	18.5	No	No	07:00	08:26	86
		3	01/08/2019	16	18	17	No	No	07:07	08:33	86

***** Primary sampling period three, secondary sampling period two was missed due to fieldworker illness

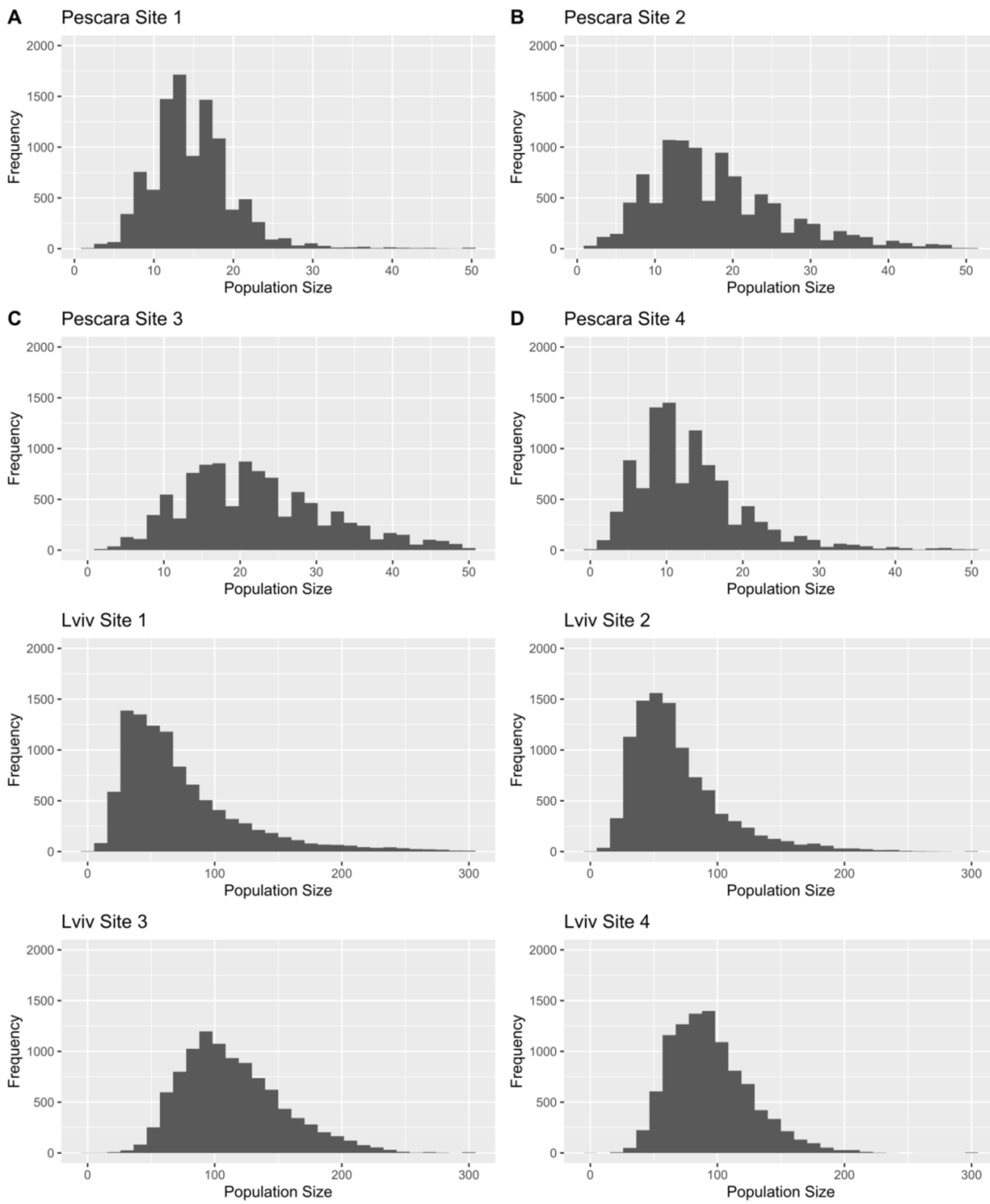

Figure C1. Posterior distribution of estimated population size (N) at primary sampling period 1 in study sites in Pescara and Lviv.

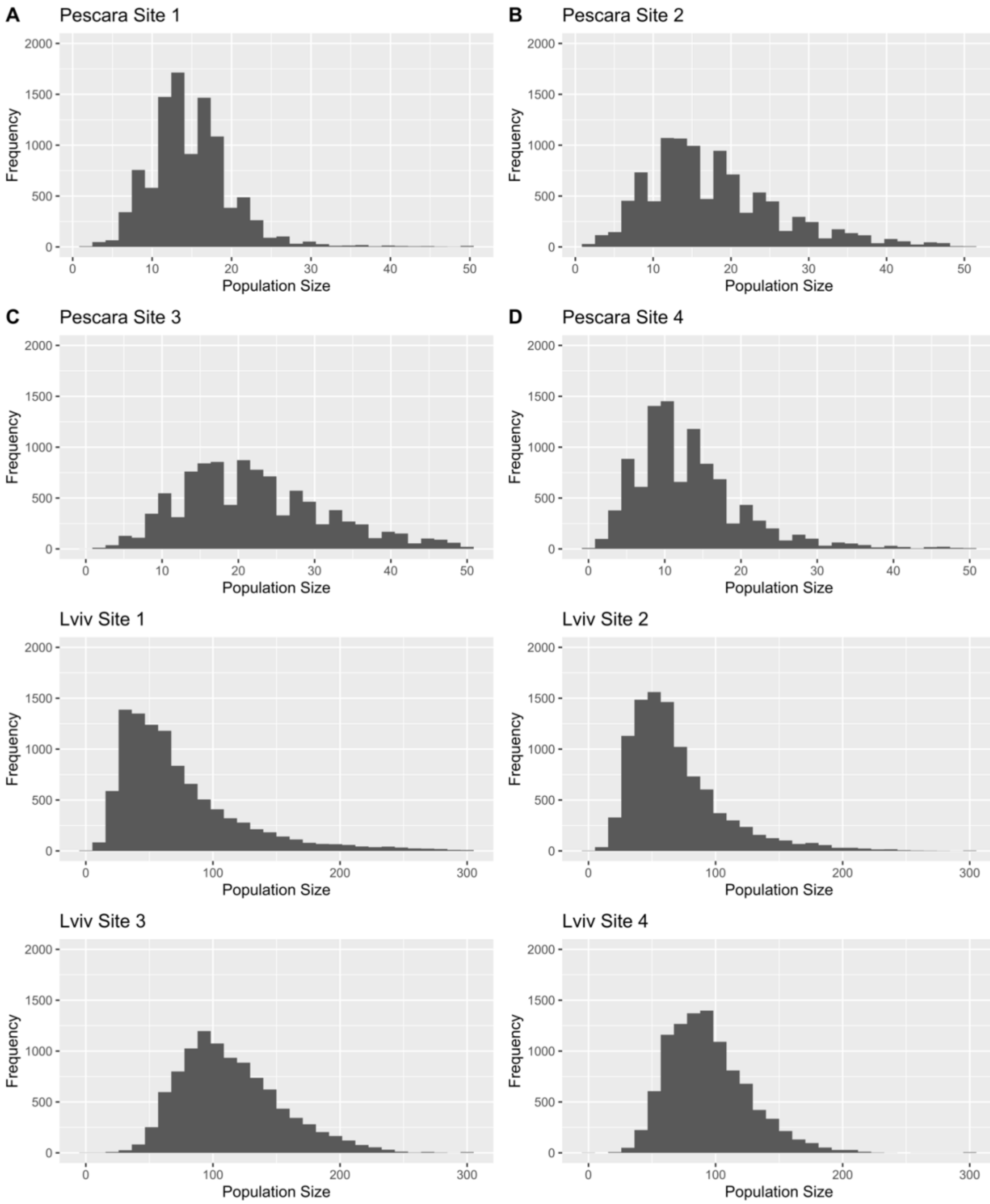

Figure C2. Posterior distribution of estimated population size (N) at primary sampling period 2 in study sites in Pescara and Lviv.

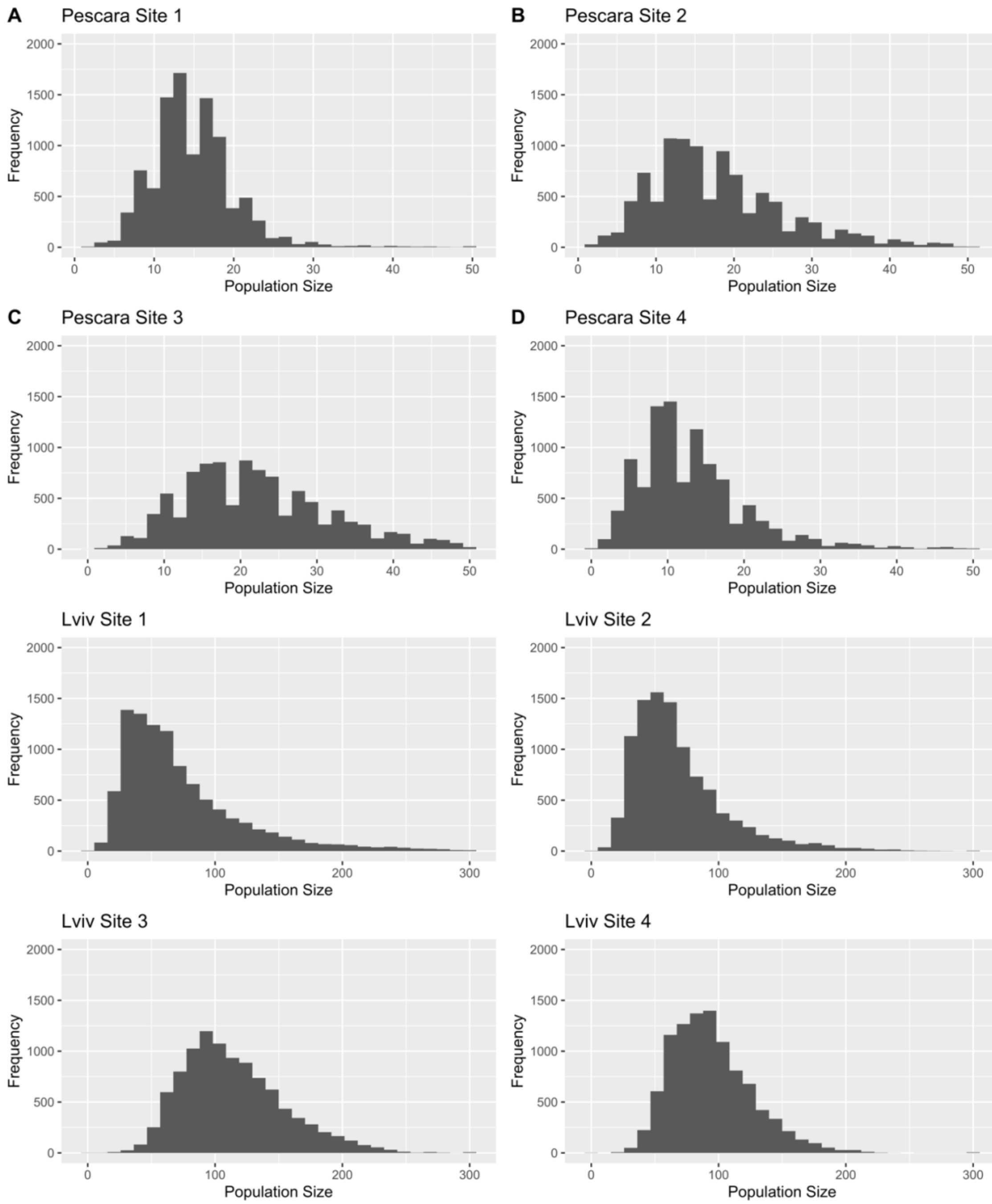

Figure C3. Posterior distribution of estimated population size (N) at primary sampling period 3 in study sites in Pescara and Lviv.

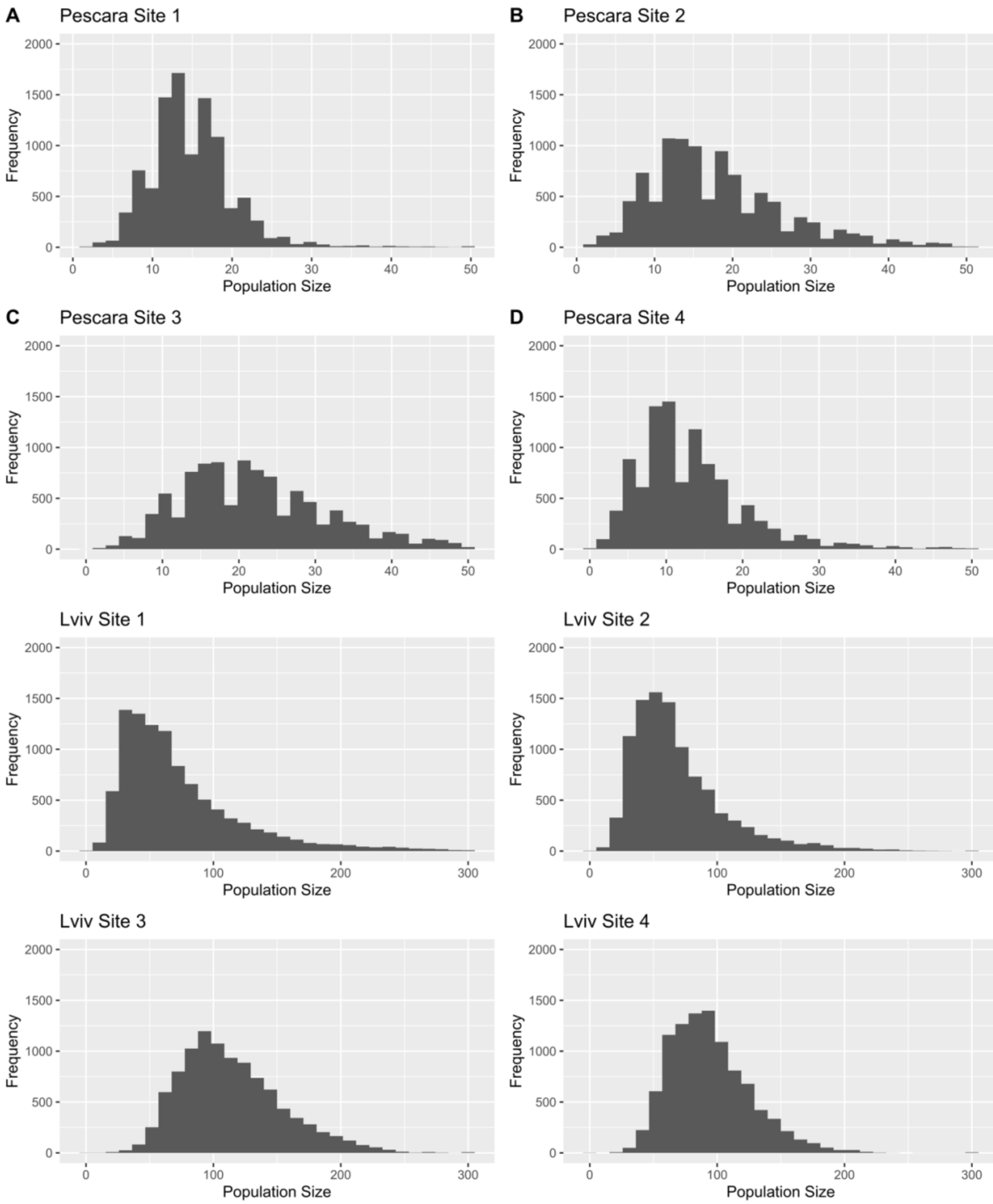

Figure C4. Posterior distribution of estimated population size (N) at primary sampling period 4 in study sites in Pescara and Lviv.

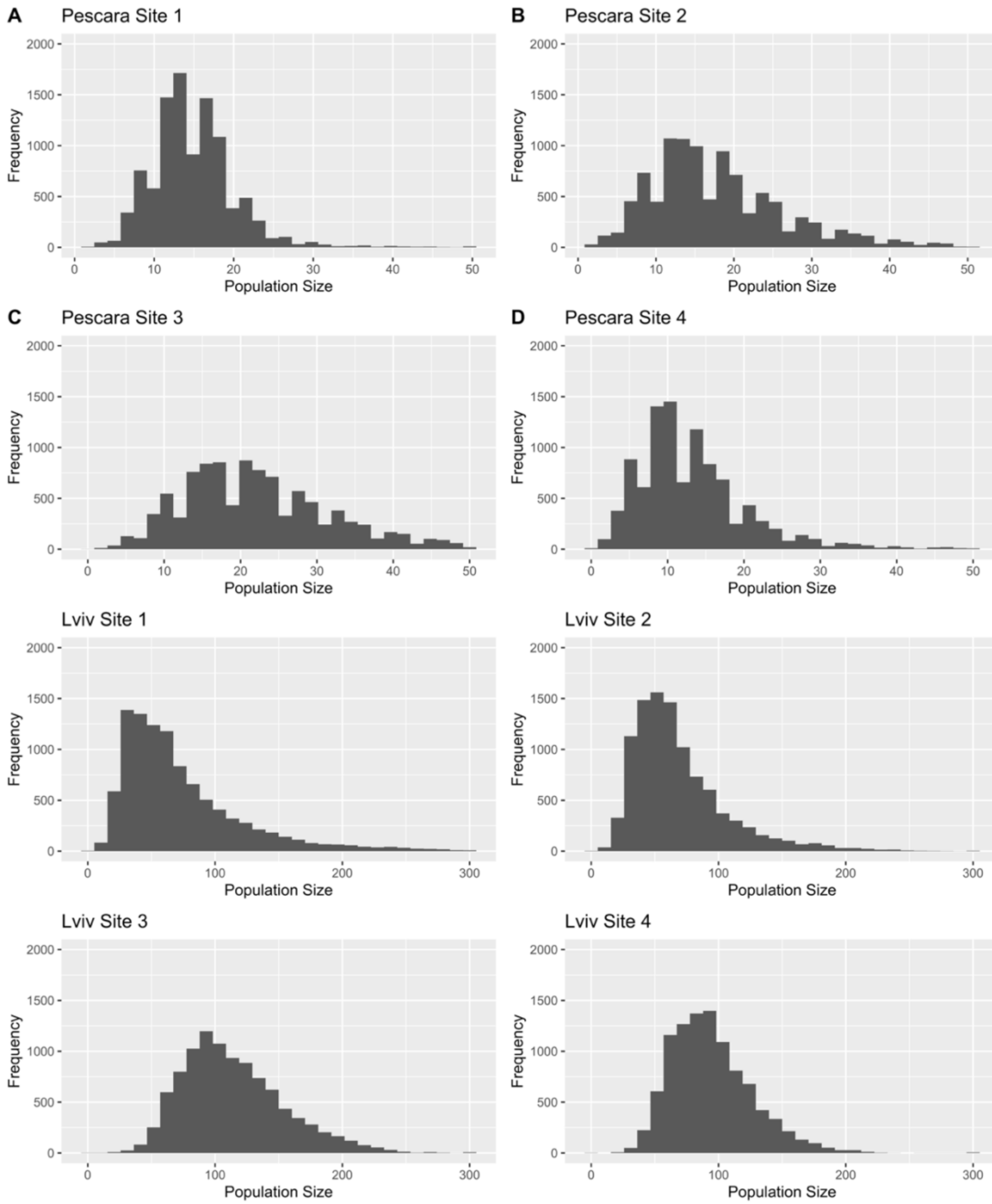

Figure C5. Posterior distribution of estimated population size (N) at primary sampling period 5 in study sites in Pescara and Lviv.

Table C4. Probability of apparent survival and detection for primary sampling periods (averaged across individuals and study sites) and study sites (averaged across individuals and primary periods) in Pescara, Italy.

		Mean	**2.5% CI**	**97.5% CI**
Average probability of apparent survival	Primary Period 1 to 2 (3-month interval)	0.82	0.58	1.00
	Primary Period 2 to 3 (3-month interval)	0.74	0.44	0.99
	Primary Period 3 to 4 (6-month interval)	0.74	0.43	1.00
	Primary Period 4 to 5 (3-month interval)	0.79	0.47	1.00
	study site 1	0.77	0.48	0.98
	study site 2	0.71	0.36	0.99
	study site 3	0.71	0.33	1.00
	study site 4	0.77	0.45	1.00
Average probability of detecting a dog	Primary Period 1	0.23	0.04	0.47
	Primary Period 2	0.18	0.02	0.40
	Primary Period 3	0.20	0.03	0.42
	Primary Period 4	0.18	0.02	0.40
	Primary Period 5	0.25	0.04	0.52
	study site 1	0.41	0.14	0.74
	study site 2	0.18	0.01	0.46
	study site 3	0.11	0.01	0.27

		Mean	2.5% CI	97.5% CI
	study site 4	0.22	0.01	0.51

Table C5. Probability of apparent survival and detection for primary sampling periods (averaged across individuals and study sites) and study sites (averaged across individuals and primary periods) in Lviv, Ukraine.

		Mean	2.5% CI	97.5% CI
Average probability of apparent survival	Primary Period 1 to 2 (3-month interval)	0.83	0.61	1.00
	Primary Period 2 to 3(3-month interval)	0.76	0.50	0.97
	Primary Period 3 to 4 (6-month interval)	0.90	0.73	1.00
	Primary Period 4 to 5(3-month interval)	0.73	0.44	0.97
	study site 1	0.83	0.56	1.00
	study site 2	0.82	0.57	1.00
	study site 3	0.75	0.46	0.98
	study site 4	0.67	0.35	0.93
Average probability of detecting a dog	Primary Period 1	0.08	0.00	0.21
	Primary Period 2	0.12	0.01	0.30
	Primary Period 3	0.14	0.01	0.34
	Primary Period 4	0.10	0.01	0.26

		Mean	**2.5% CI**	**97.5% CI**
	Primary Period 5	0.10	0.01	0.25
	study site 1	0.07	0.00	0.22
	study site 2	0.11	0.00	0.31
	study site 3	0.10	0.00	0.28
	study site 4	0.16	0.01	0.41

Table C6. Standard deviations for between-dog effects on survival and detection on log odds scale.

	Study site	**Pescara**			**Lviv**		
		Mean	**2.5% CI**	**97.5% CI**	**Mean**	**2.5% CI**	**97.5% CI**
Survival (φ)	1	0.95	0.00	2.14	1.02	0.00	2.31
	2	1.01	0.00	2.30	0.77	0.00	1.87
	3	0.85	0.00	2.06	1.22	0.00	2.47
	4	0.78	0.00	1.92	0.63	0.00	1.54
Detection (δ)	1	0.55	0.00	1.37	1.58	0.81	2.34
	2	1.47	0.45	2.44	1.54	0.81	2.31
	3	0.48	0.00	1.17	1.85	1.20	2.49
	4	1.05	0.04	2.00	1.67	1.01	2.31

Appendix D

Supporting material related to Chapter Five.

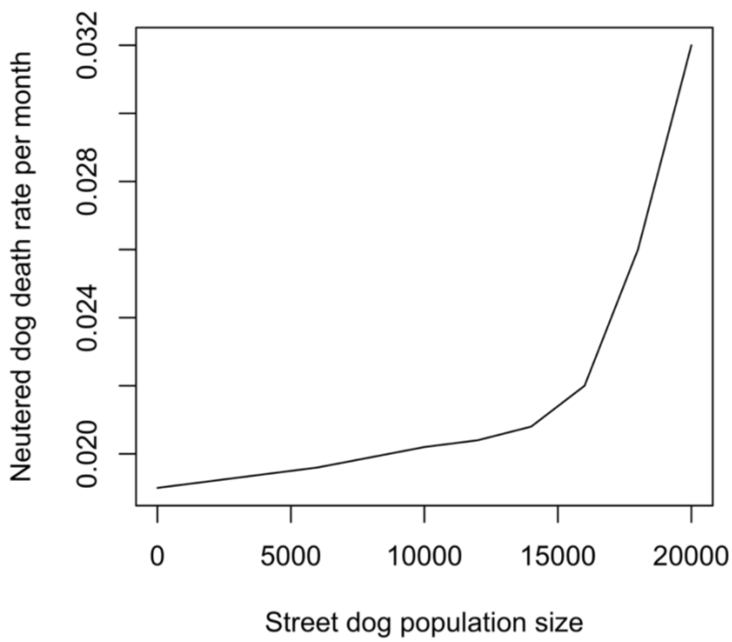

Figure D1. Neutered dog death rate lookup function.

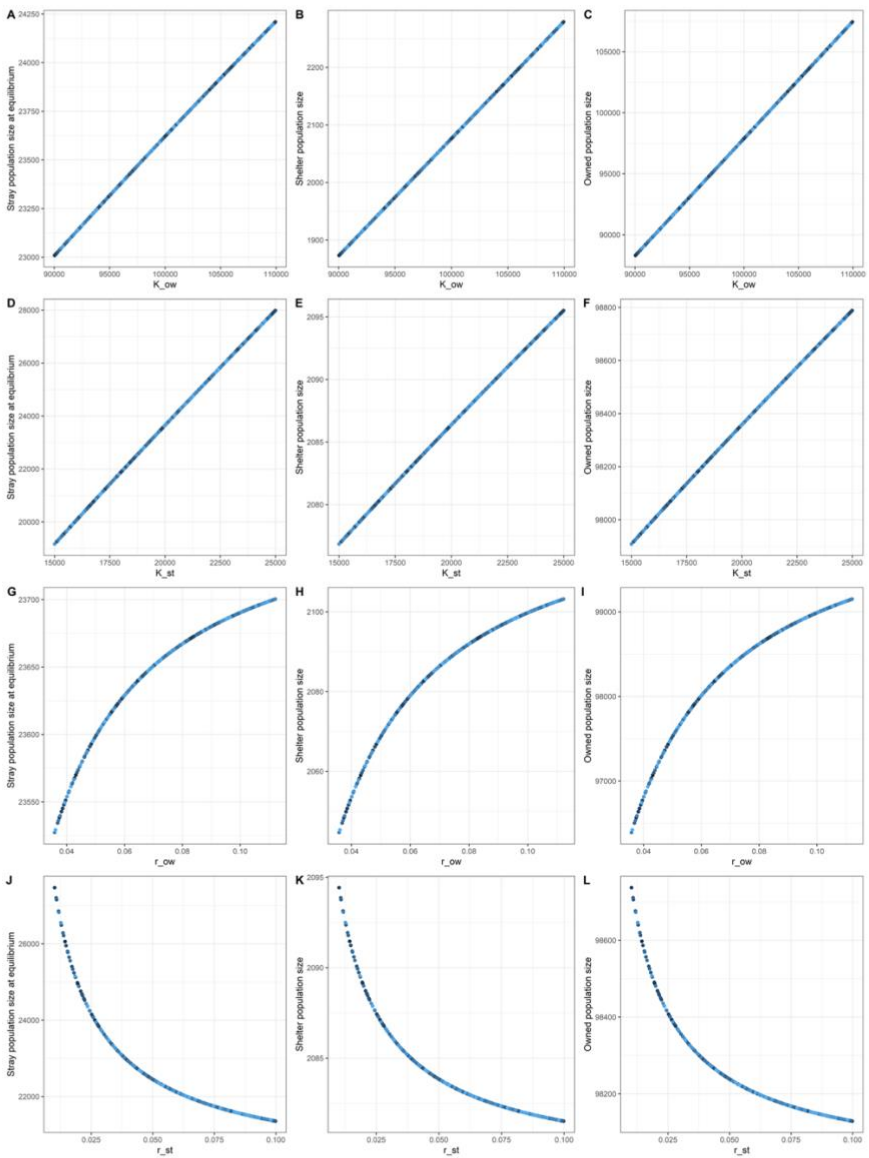

Figure D2. Local sensitivity analysis assessing the effect of parameters on the street, shelter and owned dog population equilibrium size. Parameters include: (i) carrying capacity of owned dogs (K_o) on (A) street dog population, (B) shelter dog population, and (C) on owned dog population; (ii) carrying capacity of street dogs (r_s) on (D) street dog population, (E) shelter dog population, and (F) on owned dog population; (iii) growth rate of owned dogs (r_o) on (G) street dog population, (H) shelter dog population, and (I) on owned dog population; and (iv) growth rate of street dogs (r_s) on (J) street dog population, (K) shelter dog population, and (L) on owned dog population.

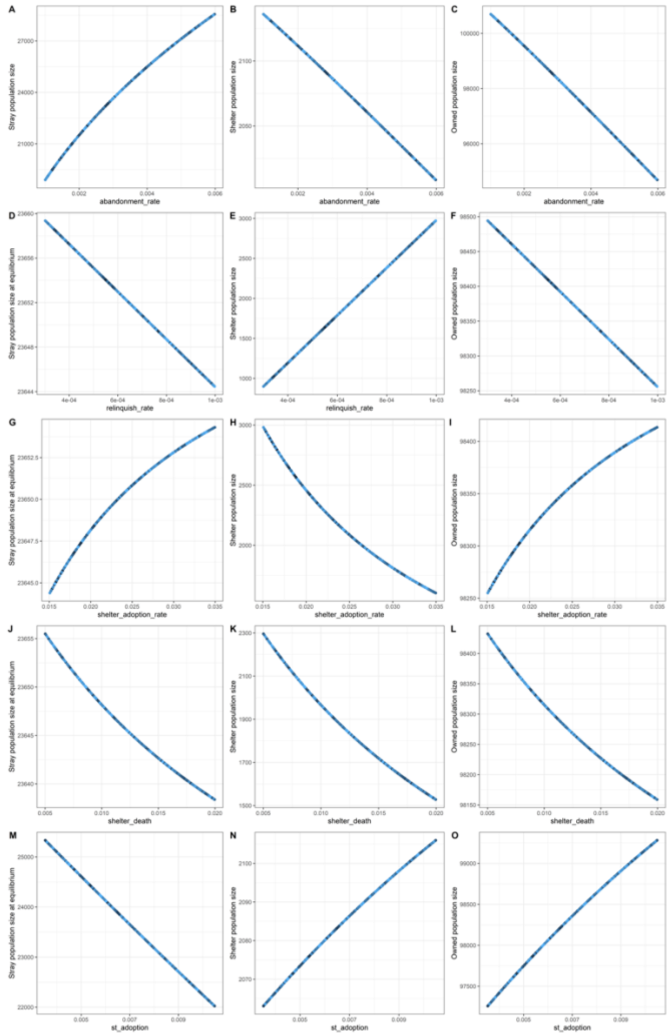

Figure D3. Local sensitivity analysis assessing the effect of parameters on the street, shelter and owned dog population equilibrium size. Parameters include: (i) abandonment rate (α) on (A) street dog population, (B) shelter dog population, and (C) on owned dog population; (ii) relinquishment rate (γ) on (D) street dog population, (E) shelter dog population, and (F) on owned dog population; (iii) shelter adoption rate (β) on (G) street dog population, (H) shelter dog population, and (I) on owned dog population; (iv) shelter death rate (μ_h)on (J) street dog population, (K) shelter dog population, and (L) on owned dog population; and (v) street dog adoption rate (δ) on (M) street dog population, (N) shelter dog population, and (O) on owned dog population.

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