Free-roaming dogs in Ushuaia City, Tierra del Fuego, Argentina. How many and why

Arona Emiliano1,2, Schiavini Adrián1,2,3

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Abstract
Free-roaming dogs (FRD) in cities represent an increasing problem. Authorities need numbers of FRD to evaluate policies implemented and to monitor the dog population.

We estimated the number of FRD in Ushuaia city, Argentina, using a photographic capture-recapture methodology. We estimated an abundance index, the power to detect changes in the index, and modeled factors that may explain the spatial distribution of FRD and their welfare status. We also infer whether if they are represented by partially supervised or unsupervised dogs, using a health and welfare index based on body fat coverage and skin condition, as well as on the presence of collars or accessories as a proxy of evidence for tenure.

During three surveys, covering 72 transects along streets (9.9% of the street layout of Ushuaia), we recorded 539 different FRD. A model with individual heterogeneity in capture-recapture probability gave 12,797 FRD (95% CI 10,979—15,323), reflecting a dog:human relation of 1:6, higher than the relation recommended by the World Health Organization (WHO). The abundance index was similar between surveys (8.13 ± 1.36, 8.38 ± 1.46 and 9.55 ± 1.28 dogs/km). The difference needed to detect changes in the index is about twice the standard error of estimates.

The best model explaining dogs’ abundance included only geographical location, although two neighbourhoods with 9 transects stand out with 181 different FRD identified. Together with the good overall dogs’ welfare status, modeling suggests that the behavior of owners is the main driver for the presence of FRD.

We recommend the use of photographic capture-recapture methodologies instead of simple index estimation, due to the small additional effort required and the improved accuracy and precision obtained. We also recommend a permanent systematic design for future surveys, increase the number of survey occasions, and improve the survey process.

Keywords Free-roaming dogs · Abundance estimation · Mark recapture · Modeling · Abundance index

Introduction

The dog population

The domestic dog represents an especially important part of human culture today, and most of the dogs are kept by people as companion animals. Currently, the domestic dog represents the most abundant carnivore on the planet, estimated at 1,000 million individuals, of which 40% live in urban areas (Gompper 2014a). The large number of dogs kept by people as companion animals is not associated with responsible tenure. In well-supervised dog’s populations, the individuals are kept under control so the reproduction rate is low. In contrasts, unrestricted dogs may belong to one or more households, even to none, and the lack of restriction allows them to roam freely, and to breed since humans may provide shelter and protection.

Ushuaia is a city located in the Argentinean portion of the Isla Grande de Tierra del Fuego, at the southernmost tip of South America. Currently it holds about 75,000 inhabitants (Molpeceres 2017). Different industrial promotion policies started by the 1970s led to a fast population growth, mainly caused by internal immigration, and similarly, dog population increased too.
Free-roaming dog (FRD hereafter) abundance varies greatly around the world, but where they exist in high densities can be considered a multi-dimensional issue, in terms of public health, the environment, and the animals’ welfare status.

Reasons for managing free-roaming dog populations

The impacts on public health

FRD are associated with the transmission of more than 300 zoonotic diseases (Boigel et al. 1990; Zanini et al. 2008a; Bonacic and Abarca 2014; Gompper 2014a; Schiavini and Narbaiza 2015), bite injuries (Zanini et al. 2008a), and road traffic accidents (Jackman and Rowan 2007). Dogs are a primary reservoir host of rabies virus and account for 99% of human-rabies transmissions (Knobel et al. 2005). Other notable zoonoses include Giardia spp., the causative agent of zoonotic giardiasis; Echinococcus spp., which causes echinococcosis; and Toxocara canis, agent of toxocariasis (Cociancic et al. 2020).

The impacts on wild and domestic animals

The introduction of exotic carnivorous mammals are considered a threat to biodiversity and constitute an agent of global change that impoverishes and homogenizes the biota, through interactions that frequently result in the extinction, extirpation or range contraction of the native species (Sillero-Zubiri et al. 2004). Although each invaded area differs in susceptibility or resistance to invasive species, islands such as Tierra del Fuego represent, in general, systems susceptible to disturbances due to its limited number of native species, simplified trophic networks and high rates of endemism (Jaksic et al. 2002; Courchamp et al. 2003).

Canids possess a great versatility that allows them to thrive in anthropogenic landscapes, especially in rural areas, and compromise the conservation of wild animals through a combination of pathogens (Knobel et al. 2014), predation (Liljesthröm et al. 2014; Schüttler et al. 2018), competition (Vanak et al. 2014), and hybridization (Leonard et al. 2014). On a global scale, Doherty et al. (2017) reported that dogs endanger of at least 188 threatened species according to the Red List of Threatened Species of the International Union for Conservation of Nature (IUCN) and have played a role in the extinction of 11 vertebrate species, with South America being one of the most affected regions.

FRD also impact on the animal production. One of the most conspicuous effects of FRD in Tierra del Fuego was the reduction in sheep production (Schiavini and Narbaiza 2015). Between 2006 and 2008, 32,725 sheep were lost due to dog attacks. The loss of livestock contributes to substantial economic consequences that amounted to over $4 million Argentine pesos and accounted for 30.8% of net income for rural establishments during this period (Zanini et al. 2008b).

Health and welfare of free-roaming dogs

A well-supervised dog may have an acceptable or even good welfare, due to the possibilities of access to resources every day, such as food and shelter, and medical care. Otherwise, FRD are daily exposed to adverse conditions and are still dependent on human resources, either directly through feeding or indirectly through the provision of food in human waste. Despite this, the prevalence of emaciated body condition state in FRD is probable, may be due to poor quantity or quality of food resources and by the lack of veterinary care (such as vaccination or antiparasitics). Canine transmissible venereal tumors diseases are also a welfare concern in FRD populations (International Companion Animal Management Coalition 2015). Additional health and welfare risks to FRD include injury caused by road traffic accidents. Furthermore, aggression problems are more frequent in dogs with a poor supervision, which constitutes a serious human health risk by increasing the probability of accidents caused by bites to people and even spread diseases to other dogs.

Therefore, FRD population management is necessary to control the population size and to improve dog health and welfare and mitigate against environmental and public health problems. The different policies implemented by the city of Ushuaia, focused in promote responsible tenure by identification, vaccination and spaying of animals, are up to date inefficient to reduce the number of dogs on streets. There are no accurate numbers about the population size of FRD in Ushuaia. Surveys in elementary schools, adjusted for the number of users of the electric service, revealed in 2016 that Ushuaia holds a total of 31,992 owned dogs and that 60% of households let dogs roam some time during the day, either by itself or accompanied by somebody (Dirección Municipal de Zoonosis 2016).

Estimating the dog population

Estimates of numbers and characteristics of FRD is one of the key indicators for planning and monitoring the success of interventions to reduce the amount of dogs on the streets (Hiby et al. 2017), for managing risks linked with them (Dias et al. 2013) and to understand the prevalence of zoonosis. Several methods are being used to estimate the number of FRD (see a complete revision in Belo et al. 2015) and many of them are inspired in methods used for surveying the abundance of natural animal populations (see Sutherland 2006) but adapted to the cities, as direct counts of animals, distance-based methods, and capture-recapture of dogs. An estimation based on direct visual counts of individual dogs
is the simplest method, but its application is very restricted over large geographical areas (Bögel et al. 1990). Also, two especially important points are usually disregarded when estimating the number of FRD in streets: the sampling design and the detection probability of dogs.

The sampling design is the procedure for selecting the number of samples and how to arrange them in the study area so that the results are representative and unbiased. Cochran (1977), Thompson (2002) and Williams et al. (2002), among others, provide technical accounts of this topic. In summary, when surveying part of a city, results from the surveyed portion are extrapolated to the rest of city. Counts (direct counts, distance-based methods or capture-recapture studies) are normally done traversing parts of the street layout of the city and recording the observed animals. Data are later analyzed by several methods as simple averages of counts per distance unit, distance-based analysis or capture recapture techniques. These design-based estimations require that every part of the city has the same coverage probability, that is, that every street has the same probability of being sampled. Otherwise, parts of the city may never be reached by sampling, biasing the results and the conclusions obtained. Many approaches for randomization of designs are used to ensure that these assumptions are met and can be found in the abovementioned references. Besides, when deciding how many streets or pieces of streets to sample, there is a trade-off between spending a large effort to increase accuracy or precision in the estimate or get redundant information that does not adds to neither accuracy nor precision.

When sampling animal populations, random sampling alone do not guarantee reliable sample-based estimators, because not all individuals present at the sampled units may be detected during a survey. Then, to estimate the number of individuals from a survey requires to know the detection probability of individuals. Put in simple terms, the number of individuals detected in a survey is divided by the probability of detection to provide the actual number of individuals. Capture and recapture methodologies, are widely used to study several population parameters and as a way to incorporate the probability of detection in the estimation (Amstrup et al. 2005; Williams et al. 2002; Belo et al. 2015). Direct counts of dogs on streets assume that all dogs present on the streets are detected by observers during the survey, i.e. that the probability of detection equals 1, an assumption rarely tested. Instead, capture-recapture studies allow estimating the detection probability of animals and provide a much accurate estimator of abundance than direct counts. Unlike what happens in nature, the presence of roaming dogs in cities is mainly influenced by decisions of pet owners or holders (Hiby and Hiby 2017) and, possibly, by the history of the neighborhood development and consolidation, as well as other socioeconomic variables (Bögel et al. 1990). In addition, dogs are territorial animals that group in response to the differential availability of resources and may present different behaviors towards people (Horowitz 2014). Also, as dogs move along the streets they may pass undetected by a surveyor on a particular occasion. Therefore, the individual probabilities of being “captured” by sampling methodologies might differ among dogs (Belo et al. 2015). In turn, the spatiotemporal heterogeneity in the density of FRD could affect the detectability and indeed the accuracy of the estimation, and deserve attention if the objective is to estimate the actual numbers. Additionally, taking into account the role that pet owners play, the sampling should be structured towards times of maximum presence of dogs on streets.

When studying FRD in cities, it is necessary to infer whether they are represented by either partially supervised or unsupervised dogs. This information is essential to assess the degree of welfare and life quality of the animals, understand the reasons for this problem, raise public awareness and help to develop standards of responsible ownership to mitigate the presence of dogs in the streets. An approach for this classification may be to assess a health and welfare index, based on body fat coverage and skin condition, as well as on the presence of collars or accessories as a proxy of evidence for tenure. Dogs can suffer skin conditions from several causes, such as fungal pathogens, parasites and allergies. However, when using skin condition as an indicator of welfare at the population level, a diagnosis of the cause of the skin condition is not necessary (ICAM Coalition 2015). These indicators can be scored through observation alone without the need for physical capture and examination of the dog and hence is relatively safe and quick to conduct when surveying.

On the other hand, if the objective is to assess changes in number of FRD, an index of abundance can be enough. This index is a relative measure of the size of the dog population, estimate as the mean densities (± standard error) of FRD for each survey (dogs/km). Indexes do not need to include the detection probability and can be easier to record and estimate because do not require individual identification nor perform several surveys. Hiby and Hiby (2017) advocate for the use of such indexes when the question is if dogs on the streets increase or decrease after an intervention. However, indexes are not excused of the sampling design requirements.

In this paper, first we present an estimation for the FRD population in Ushuaia, defining a proper design aimed to get an even coverage probability, and estimating the abundance of dogs based on a capture recapture methodology. Second, we provide an abundance index and assess the power to detect changes in the index for future surveys. Third, we explore factors that may explain the spatial distribution of dogs along the city. Four, we provide evidence of the degree of supervision of FRD by means of a welfare index and of evidences of tenure. Furthermore, this paper provides tools and recommendations to the city of Ushuaia to assess the abundance of FRD and to monitor their numbers in the future.
Materials and methods

Study area

The study was carried out in the Ushuaia city (54°49' S—68°19' W), located in the Argentine sector of the Isla Grande de Tierra del Fuego, the capital city of the province of Tierra del Fuego, Antártida e Islas del Atlántico Sur (Fig. 1). The city develops along the coast of the Beagle Channel and is bounded by the slopes of the Andean range, covering about 12 km in its main axe and a surface of about 23 km$^2$. The population was estimated at 75,000 inhabitants by 2015 (Molpeceres 2017).

The sampled area corresponded to the road plot available at OpenStreetMap, which excludes some sectors of recent development of about 2.5 km$^2$. This road plot covers 252 km of streets. FRD on the street recorded in this paper comprise dogs with owners who let them roam by themselves and homeless dogs without owners or keepers (partially supervised and unsupervised dogs).

Survey design

The survey was designed with the philosophy of population assessment by distance sampling (Buckland et al. 1993). In a simplification, the survey runs along lines from which objects of interest and their distance from the line are recorded. The analysis models the decay of the detection probability with distance from the line to estimate the probability of sighting an individual over the line, and estimates density combining the number of sightings based on the distance travelled (encounter rate) and the group size (if individuals get together). In our study we used a strip transect, a special case where the probability of detection is constant along the transects over a fixed band, with the transects corresponding to the streets and the bandwidth defined as 14 m, the width of the sidewalks and the street added, which represents the space where FRD can move freely.

The number and length of the transects to survey represents the sampling effort. To assess the effort and its spatial distribution required for uniform coverage, we used the
simulation module of the DISTANCE software (Thomas et al. 2010), which allows to compare the coverage of different designs. The program simulates a grid of points in the study area, over which different designs are applied. The tested designs were limited to what are called “segmented track lines”: parallel streets running from the coast to uphill, segmented in surveyed and not surveyed segments. Two types of designs, available in DISTANCE, were tested: a systematic segmented track line sampling that distributes randomly a systematic set of segments, and a systematic segmented grid sampling that distributes segments based on a set of grid points in a regular pattern.

The use of segmented transects a) increases the number of samples, allowing spatial heterogeneity to be better explored than with continuous transects, b) reduces observer fatigue, allowing rest of the surveyors during non-sampled segments, c) reduces total effort in relation to sample continuous transects and d) traveling complete transects from the coast to the mountains would be difficult because of the layout of the city streets.

The simulated grid models a grid of street intersections separated at a distance of 100 m, which represents the modal distance between intersections in Ushuaia. Simulated transects run in a general direction from the coast to the mountain slopes, to explore the effect of environmental covariates related to height or distance to city borders. At each simulation, transects are laid over the grid and the software records how many points of the grid are “touched” by the transect at every iteration and returns statistics of these so called “hits”, i.e. statistics of the number of times each point is touched by the transects. After a number of simulations, 1000 in this study, it is expected that an even coverage probability is represented by a low variability in the average coverage probability and with all the points of the grid “touched” by a transect. Although there is not an “objective measure of evenness”, designs with points showing minimum numbers of hits equal to zero and larger standard deviations of the average coverage probability should be discarded.

As one of the objectives of this study is to provide managers with a tool for future surveys or monitor efforts, the final selection of the design should also consider logistic criteria, as the total effort needed and the future feasibility of a design to be performed with low need of training. This favors the selection of a set of permanent transects that would be subsequently monitored to detect changes in FRD’ abundance. We simulated designs with different segment length and transect separation (Supplemental Material S1). The selected design was based on the effort to be developed and the lower relative standard deviation of the coverage probability (Supplemental Material S1).

The simulated designs are based on a city with a checkerboard street layout. For a city without this street layout, the selected design must be adapted to the actual street layout. For that, the design was superimposed over the street layout with a Geographical Information System ArcGis 10.7 and street blocks were selected as the segments to survey, based on their length and proximity to the designed segments and on the general direction from the sea uphill for all the segments.

**Abundance estimation**

Many ecological studies and conservation strategies need accurate estimates of population size, which can be obtained only through the identification of single individuals, usually achieved by marking. Artificially marking of animals are invasive techniques that involves capturing and handling, which can stress the captured individuals, alter the behavior or physiology and lead to injury and infections. For the estimation of FRD abundance we used the photographic capture-recapture method first used by Beck (1973), which represents a modification of the classic capture-recapture method of Lincoln (1930), in turn modified by Schnabel (1938) for multiple sampling occasions. This methodology is an easy and inexpensive technique for long-term identification of individuals that does not require the physical capture of dogs to mark them. In its original development, the methodology assumes that (1) the capture of the animal does not affect its subsequent probability of recapture, (2) all animals have the same probability of being captured on an occasion, (3) the population is closed during the sampling period and (4) the marks are not lost during the study. Further developments replaced the first two assumptions by models that account for variation in capture probabilities due to capture, occasions or individual behavior (Otis et al. 1978), some of them used in this study.

Street segments were travelled by car at a speed of 10 km/h with two surveyors with a photographic camera, one at each side. A third surveyor recorded the dogs seen to have a direct count of FRD. The same team collected data throughout the study, to reduce variability in the observation process. All dogs seen on the street, or inside a house parcel but free to move to the street were counted and photographed. The dogs were not classified by sex or age because dogs were not always standing or showing evidence of their sex. Since one of the objectives was to generate a FRD detection tool that could be easily applied by the Municipality personnel, we decided to minimize the number of surveys. Three surveys were performed, between 10 AM to 7 PM, during three consecutive Saturdays (October 12th, 19th and 26th of 2019). Due the bad weather conditions on the second Saturday, the survey was completed in Sunday. The day of the week and time of the day was chosen after free interviews with people that interact with dogs during their work as postmen, garbage collectors and a member of
a dog protection organization. These people suggested that during the weekends there would be a greater influx of FRD because more people are at their homes, and owners would know that dog catchers are not active, so they let them roam the streets. Moreover, the people interviewed referred that dogs usually accompany children to school on weekdays, so this would have generated statistical noise. The surveys were also conducted on Saturdays because on weekdays there is usually more traffic, which would hinder the survey. The starting point was different in each survey, so we did not follow the same route throughout the study. We consider that the incidence of sunlight, mainly in a city where temperatures drop considerably at twilight, could influence the presence of dogs roaming the streets. For this reason we decided to vary the catch hour for each transect in the three efforts. The chosen time period also ensured sufficient light for a better quality of the photographs. After the surveys, we manually analyzed the pictures to identify individual dogs on each occasion and segment surveyed, based on phenotypic characters like color, patches or size (Supplemental Material). Each photo was compared between occasions to determine if it was a recaptured dog or a new “capture”. The first author carried out all the identification process to reduce variation in identification. Given the amount of different dogs recorded at each segment, there were no identification doubts among survey occasions. The “history of capture/recapture” of each identified dog was built, using a standard matrix format (Otis et al. 1978), like dogs seen on the three surveys, dogs seen only in one of the surveys, and all the possible combinations among the three surveys. Due to the short time between surveys we assumed that the sampled population was demographically closed.

Usually, the major challenge involved in using photographic capture-recapture methodology is the misidentification of individuals. Yoshizaki (2007) developed an alternative method to the typical multinomial approach used to building likelihood for capture histories. He proposed an unweighted least square for estimate abundance, for situations where misidentification occurs at any capture occasion. He compared estimations using models $M_0$ and $M_r$ with his statistical approach and modeled the bias in estimation in relation to known abundances. Another option for dealing with not identified animals would be to discard these observations from the capture-recapture histories, based on their low frequency. A third approach would be to assign unidentified dogs to the possible detection histories in a random way, and then compute the detection histories to estimate abundance. All these options were considered in the analysis.

The capture-recapture history was analyzed using maximum likelihood estimators for closed populations to assess the probability of capture and recapture with the MARK software (White and Burnham 1999), including models from the CAPTURE software (White et al. 1978), a program with a long history of use in wildlife demography studies. Detectability is equivalent to the probability of capture and the probability of recapture in this study, since the photographed dogs were “captured” and "recaptured” without being physically trapped. From this information the probability of detection of dogs was assessed, from the comparison of some models that are likely to have generated the observed capture histories.

Four models that account for the heterogeneity in detectability (Otis et al. 1978) were tested:

- Null model ($M_0$): detectability remains constant between sampling occasions and individuals.
- Temporal heterogeneity ($M_t$ model): detectability varies between sampling occasions, but is constant among animals at each sampling occasion.
- Behavior heterogeneity ($M_b$ model): detectability differ between previously caught and uncaught dogs due to trap-response behavior, either by avoiding or by being attracted to the subsequent recaptures situations.
- Individual heterogeneity ($M_i$ model): each animal has a unique detectability throughout the capture occasions.

For each analysis, the program CAPTURE estimated capture probabilities per sample and the dog population size in the sampled area, inclusive of animals that were not photographed at all. Models were compared using a theoretic information approach, by means of the Akaike Information Criterion corrected for small samples ($\text{AIC}_c$, Akaike 1973). Estimations based on the best model were extrapolated to the whole street layout of the city.

**Abundance index**

The three surveys provided by themselves an index of abundance, as the number of animals seen at each occasion, averaged over the street segments of each survey. An index is worth if it allows to detect changes in numbers and, obviously, assumes perfect detectability of dogs seen on the streets during a survey. Following Hiby and Hiby (2017), the differences between the densities recorded in each transect for two surveys done using the same transects, averaged over the transects and then divided by their standard error, follows a Student’s $t$ distribution with $n-1$ degrees of freedom, where $n$ equals the number of transects. If this quotient presents a probability less than 0.05 in a Student’s $t$ distribution, then the average density between surveys is significantly different at the 95%. Therefore, using the Solver tool of Microsoft Excel, we can estimate how much the average density should differ in a future survey to detect a significant change in density for different levels of standard error.
Factors affecting dog abundance

Dog populations inhabit a great variety of habitats over a city and therefore their density can be determined by several factors. An analysis of these habitats should reveal the abundance, distribution and predictability of resources for dogs. The total number of different dogs identified at each transect (the sum of different dogs identified in the 3 surveys for each transect) was used as a response variable to model the factors that would affect the presence of roaming dogs in streets. This number represents the “minimum” number of dogs present in the transect, and is more representative of the average behavior of dog owners (who let dogs roam freely during some time of the day) than the counts for each one of the three surveys.

The covariates considered were:

- Number of houses in each transects. At apartment buildings the main entrance door to the building was recorded and the number of dwellings was estimated accounting for an average of three households per floor.
- Availability of food resources, using as a proxy the number of waste containers in each transect.
- Number of properties in each transect with effective fences against the free movement of dogs to the street.
- Presence of “shelters”, using as a proxy the distance from the midpoint of the transect to the city limit.
- Geographic location at the midpoint of the transect.
- Height above sea level at the midpoint of the transect (taken from the Digital Elevation product, Shuttle Radar Topography Mission, 1 Arc-Second Global, 30 m resolution, from the page https://earthexplorer.usgs.gov).

Collinearity of covariates was checked examining the Variance Inflation Factor (VIF) of each covariate, using the package car (v.3.0–6; Fox and Weisberg 2019) for R software. Covariates whose VIF was > 3 should be removed from modelling (Zuur et al. 2010).

The relationship between the dog counts and the covariates was explored by means a Generalized Additive Model (Wood 2017) with a Poisson family of errors. As transects differed in length, the logarithm of the length of each transect was added as an offset variable in all the models analyzed. The degree of support to the different models was assessed using a multimodel inference approach (Anderson and Burnham 2017) with a Poisson family of errors. As transects differed, these individuals were considered “new” dogs (not previously or subsequently identified) for analytical purposes, since having withdrawn those from the analysis would have underestimated the results. Consequently, 539 different dogs were registered for the analysis.

Welfare and tenure

A body condition index and a skin condition index for each dog were recorded. There are several scoring systems available, but we used a scale from 1 to 3, based on body fat coverage as “underweight”, “ideal weight”, and “overweight”, respectively, a modification of the categories described by WSAVA (2011) and ICAM Coalition (2015) allowing robust remote registration. In this study, we scored only the adult dogs and excluded puppies. Body condition score systems for puppies are different to adults, as puppies are difficult to observe when surveying, and this leads to bias, thus providing less reliable data than adults. The skin condition scoring system recorded the presence or absence of a visible injury, including any sign of hair loss or scaly and skin tumors. We also recorded the presence of collars or other kind of accessory, as a proxy of evidence for direct tenure (Supplemental Material).

Results

Record of data

Each survey comprised a total of 25 km covered in 72 transects. From the 996 photographs taken, a total of 211 dogs were photographed in the first survey, 221 in the second and 240 in the last (Fig. 2). The number of pictures taken of each dog varied between 1 and 4 photos, depending on the possibilities of visibility in each case. A total of 511 different dogs were identified from all the pictures. Apart from this, 28 specimens were recorded but could not be photographed and identified (15, 9 and 4 for the first, second and third survey respectively). As their proportion was 5.2% of the total, these individuals were considered “new” dogs (not previously or subsequently identified) for analytical purposes, since having withdrawn those from the analysis would have underestimated the results. Consequently, 539 different dogs were registered for the analysis.

Abundance estimation and abundance index

Program MARK returned model \( M_h \) as the best model, far apart from the rest of the models based on the \( \Delta AIC_c \) (Supplemental Material S2). Thus, the abundance of FRD
The abundance index presented considerable standard errors, due to the heterogeneity in encounter rates of dogs between transects on each occasion (8.13 ± 1.36, 8.38 ± 1.46 and 9.55 ± 1.28 for the first, second and third survey respectively). Mean densities between sampling occasions were not significantly different at the 95% (two tailed paired t-test:
The level of difference in the abundance index needed to detect changes in them among two surveys depends on the standard errors of the differences between surveys. Using the same 72 transects, the difference in density of dogs from which a significant change in the population could be detected varies between 0.8 and 4 individuals per linear kilometer (Table 1), representing approximately twice the standard error between surveys.

**Factors affecting dog abundance**

The magnitudes of the covariates considered in each model are shown in Table 2. The analysis of covariates revealed a high correlation among the number of houses, waste containers and fences. Despite that, as the multicollinearity analysis revealed that none of the covariates exceeded the 3 units of the Variance Inflation Factor, all of them were included in the models. A total of 16 models were tested (Supplemental Material S3) and ranked according to the \( \Delta \text{AIC}_c \) value. The best model included only the geographic location, with an Akaike weight of 0.91. The remaining models presented a \( \Delta \text{AIC}_c > 2 \) and therefore little support with respect to the best model.

**Spatial distribution of free-roaming dogs**

The city presented spatial heterogeneity in the number of FRD, both for each survey as well as for the sum of different dogs from the three surveys (Fig. 3), although the areas with the largest numbers were the same along the three surveys. The smoothing of the geographical position in the GAM (Fig. 4) also reveals areas of large numbers of FRD, with the smallest number of dogs in downtown. There was not evident spatial heterogeneity in the number of houses, but the number of containers and fences are lower in the most peripheral neighborhoods (Supplemental Material S4).

**Welfare and tenure**

The visible welfare records for the three surveys revealed that most of the dogs presented ideal weight (60%, 76% and 86% respectively), followed by individuals showing overweight (7%, 14 and 9% respectively) and underweight (4%, 5% and 1% respectively). The number of unrated dogs (29%, 5% and 4% respectively) came from animal that escaped prior to record or were lying down or in a position that made it difficult to classify. Injuries were infrequent (2%, 4% and 1% respectively), and dogs presented a collar or other accessory as a sign of tenure in 12%, 24% and 17% of the cases respectively.

**Discussion**

The non-identification of dogs, because no photographs could be taken or because the quality of the pictures is low, may leads to uncertain identifications (Belo et al. 2015). Nevertheless, in this work, multiple photographs of each animal were available, and also dogs had widely differentiable phenotypes, which greatly allowed the individual recognition. The non-identification of dogs occurred only due to running of the individuals that made photographic capture impossible.

Previous works using the same methodology do not present details on the building of the capture history (Daniels and Bekoff 1989; Özen et al. 2016; Hu et al. 2019), the success in reidentification, the uncertain identification, or the impact of this uncertainty on abundance estimates (Beck 1973; Kato et al. 2003; Hiby et al. 2011; Belsare et al. 2014; Gompper 2014b; Tenzin et al. 2015). Then, we interpret that these studies assumed that animals were identified without error and we cannot make comparisons regarding this.

| Change in index required in relation to a previous survey (dogs/km) | 72 transects | 100 transects | 150 transects |
|---------------------------------------------------------------|-------------|---------------|---------------|
| **Standard Error**                                            |             |               |               |
| 0.4                                                           | 0.798       | 0.794         | 0.790         |
| 0.6                                                           | 1.196       | 1.191         | 1.186         |
| 0.8                                                           | 1.595       | 1.587         | 1.581         |
| 1                                                             | 1.994       | 1.984         | 1.976         |
| 1.2                                                           | 2.393       | 2.381         | 2.371         |
| 1.4                                                           | 2.792       | 2.778         | 2.766         |
| 1.6                                                           | 3.190       | 3.175         | 3.162         |
| 1.8                                                           | 3.589       | 3.572         | 3.557         |
| 2                                                             | 3.988       | 3.968         | 3.952         |

**Table 2** Magnitudes of the covariates used to fit the models. Covariate: 1 = number of houses; 2 = number of fences; 3 = number of waste containers; 4 = distance from the midpoint of the transect to the edge of the city; and 5 = altitude above sea level

| Covariate | Min  | Max  | Mean | Standard Deviation |
|-----------|------|------|------|--------------------|
| 1         | 0.00 | 81.00| 25.06| 18.49              |
| 2         | 0.00 | 44.00| 11.69| 10.80              |
| 3         | 0.00 | 38.00| 11.72| 11.53              |
| 4         | 11.36| 713.90|220.10|169.07              |
| 5         | 5.00 | 205.00|58.99 |44.08               |
Some capture-recapture studies tried to tackle the problem of misidentification but, at the present time, these approaches do not apply to our study. Most of them deals to DNA analysis applied to capture-recapture studies, when an error in genetic identification produces a “ghost” animal that does not exist (see Lukacs and Burnham 2005a; Link et al. 2010). What makes different natural mark capture-recapture studies show that individuals not identified in one occasion can be accurately identified in another. In our case, a dog not identified on the first occasion should belong to any of the histories of dogs identified on the first occasion (100, 110, 101 and 111). Worst, dogs may not be identified in two or three sampling occasions, increasing the number of possible combinations of true detection histories for unidentified dogs. Lukacs and Burnham (2005b) consider that two identification errors made at different genetic capturing occasions are assumed to never produce identical genotypes. In our case, we cannot assure if dogs not identified on two or three occasions are the same dog.

The spatial heterogeneity in the number of FRD observed would call for applying a stratified sampling in the design to account for such variability, instead of applying a systematic sampling. However, as one of the outcomes of this work is to give a cognitive product to the city authorities to be applied in future evaluations, we selected and recommend a systematic sampling of permanent transects. These transects can be easily repeatable in the future and can be used as “permanent” stations. On the other hand, covariate-based modeling approaches are progressively replacing stratified sampling approaches, because of the explanatory improvement of modeling in relation to a simple stratification approach (Buckland et al. 2015). Therefore, it is expected that estimates of the abundance of FRD in the future should be based on spatial models. These models enable the investigation of interactions between environmental/social covariates and population densities and mapping the spatial distribution of a population help to communicate results to non-experts (Miller et al. 2013). Also, covariates can vary along space
and time over a city, together with changes in the population of the city and/or in the welfare of inhabitants.

**Abundance estimation**

This study used coloration patterns of dogs for identification, a type of permanent and non-invasive mark, so estimations cannot be affected by loss or retention of marks (Hiby et al. 2013; Nery and Simão 2012). The assumption of a constant probability of capture and recapture of individuals among surveys is unlikely, due to several factors affecting capture probabilities. If most dogs are owned, their photographic capture/recapture probability depends largely on human behavior, as people let dogs out. This heterogeneity must be considered in the models; in fact, a recurring criticism of FRD abundance estimates is not to consider dogs’ probability of detection (Belo et al. 2017). Then, it was pertinent to include a model that accounted for individual heterogeneity of the probability of detection ($M_h$ model). This model was also used by Belsare and Gompper (2013) meanwhile Hu et al. (2019) used models $M_r$, $M_h$ and $M_{rh}$ (being $M_{rh}$ a model that combines heterogeneity in time and individuals).

In turn, Hiby et al. (2011) used $M_r$ as their first and unique choice.

The size of the FRD population in Ushuaia was estimated at 12,797 individuals (95% CI 10,979—15,323). The estimate does not correspond to the whole city since about 12.5% of the surface was excluded from sampling as this area presents a very lower density of houses, expecting a lower FRD density. The estimation must be taken as a minimum estimate and represents the number of dogs that could be roaming at some time of the day. This estimation is lower than the one reported by Dirección Municipal de Zoonosis (2016), when 60% of the 31,922 estimated dogs are roaming at some time of the day (19,152), but taking in mind the non-surveyed part of the city, the final numbers could come closer. Given that Ushuaia had around 75,000 inhabitants by 2015 (Molpeceres 2017), the relative dog population is around 170 dogs per 1,000 people. Dogs are not spread out evenly across the landscape so the range of roaming dog populations varies widely in different communities around the world (Gompper 2014b; Kartal and Rowan 2018). If we compare our estimation with other countries of South America or the United States, where the relative number of FRD exceeds 200 per 1,000 people (Kartal and Rowan 2018; Herzog 2019), we could consider our estimation a relatively low figure. However, our results contrast considerably with countries like India, which is estimated to have only about

![Fig. 4 Smooth of geographical location for the sum of different dogs. Lighter areas correspond to lower number of dogs.](image-url)
30 dogs per 1,000 people (Kartal and Rowan 2018), Saudi Arabia with less than 2 dogs per 1,000 people (Herzog 2019), or even United Kingdom with almost 1 dog per 1,000 people (Dogs Trust 2019), to mention some examples. Our results are equivalent to a FRD:inhabitants ratio of 1:6 (taking the limits of the confidence interval, 1:7 and 1:5). This ratio exceeds the 1:10 dog:inhabitants ratio recommended by the World Health Organization (Bögel et al. 1990). Moreover, the WHO value refers to the total number of dogs, which would include supervised, partially supervised and unsupervised dogs. The ratio for Ushuaia is similar to that observed in other areas of the country and the world (Table 3) but as we excluded completely supervised dogs for the survey, the final dog:inhabitant ratio should be greater in favor of dogs, which is consistent with the ratio of dog:inhabitants of 1:2.05 provided by Dirección Municipal de Zoonosis (2016).

**Abundance index**

As stated by Hiby and Hiby (2017), the number of FRD per kilometer of street should be a useful tool to detect dog population changes over time, changes in citizen behavior regarding the tenure of pets and expose differences between sites in a city. Given our sampling, the difference in density needed between two surveys to detect a significant change in the dog population (with a confidence level of 95%) is approximately twice the standard error. Then, the smaller the standard error between surveys, the lower the level of change required to detect changes in the index. To reduce the standard error, the alternatives would be to increase the number of transects to survey and/or reduce the variability of the count between transects (encounter rate). However, we observed that increasing the number of transects from 72 to even 150 does not have an impact in reducing the level of change in density required with constant levels of standard error (Table 1), so the greatest effort should be put in reducing the variability in encounter rate between transects.

As the abundance index was not significantly different between surveys, the count from any of the three days could be used as an indicator of the abundance. However, there were differences between transects among surveys, so carrying out a single count could lead to results that do not adequately describe the spatial variability of dogs. Also, as the number of recorded dogs increased with the survey occasion, it is possible that surveyors became more experienced with time for looking for dogs.

**Factors affecting dog abundance**

The demographic, socioeconomic, environmental and cultural factors that explain the differences in the abundance of FRD have not been sufficiently explored so far (Belo et al. 2017). The population of FRD varies between areas in a city and depends on the attitudes of owners and neighbors towards dogs, and on the structure of homes and fencing which in turn are influenced by cultural and economic drivers (Hiby and Hiby 2017). However, our best model included only geographical location, revealing several hotspots in the Ushuaia city. Despite that, the presence of outliers in the data could be forcing the inferences made with this covariate. Two areas named Valle de Andorra and Escondido, yielded 181 different dogs identified in 9 of the 72 transects surveyed, equivalent to 33.6% of the total number of different dogs identified in 12.5% of the samples. The geographical location may be the expression of some covariate not measured and merits further studies. Contrary of what was expected, the number of houses did not receive support as a factor. Some authors propose that areas with a lower socioeconomic level and/or with a higher density of houses may have a larger density of dogs and less care for their pets, compared to areas with a higher socioeconomic level (Font 1987; Ochoa et al. 2014; Belo et al. 2015). Likewise, some authors suggest that apartments are the type of residence with lower frequency of roaming dogs (Jensen 2007). The number of waste containers was neither a significant factor, so the availability of food resources in the way of garbage without proper disposal does not seem to favor the number of roaming dogs. The distance to the city limit was neither a significant factor, so the availability of shelters outside the city does not seem to affect the presence of FRD. However, the city can provide multiple shelters and in less severe conditions than the forest out of the city. For example, during the surveys we observed dogs resting under vehicles, at the entrance doors of buildings or even in shelters on the streets expressly built by people. Finally, the number of perimeter fences did not influence the abundance of FRD, so we reject the idea that the lack of perimeter fences favors the presence of dogs.

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**Table 3** Estimated number of people per dog for different cities and countries of the world (Brusoni et al. 2007)

| Place                                      | People per dog |
|--------------------------------------------|----------------|
| Santa Fe de Bogotá, Colombia               | 10.9           |
| Belo Horizonte, Brazil                     | 8.6            |
| Santiago de Chile, Chile                   | 7.4            |
| Asunción, Paraguay                         | 6.8            |
| Maracaibo, Venezuela                       | 6.7            |
| Morón, Argentina                           | 5.7            |
| Rosario, Argentina                         | 5.1            |
| Buenos Aires, Argentina                    | 5.0            |
| Neuquén, Argentina                         | 5.0            |
| San Martín de los Andes, Argentina         | 5.0            |
| General Pico, Argentina                    | 4.6            |
| Costa Rica                                 | 4.0            |
| United Kingdom                             | 3.1            |
Welfare and tenure

The number of dogs in good body condition, the scarcity of dogs with skin conditions or injuries, and the number of dogs carrying collars or other accessories suggest that the FRD in the streets of Ushuaia are mostly represented by owned dogs totally or partially unsupervised. This is consistent with the weakness in the explanation power of the factors to explain dog distribution and abundance as it is explained further in the text. All this evidence, strongly suggests that the main driver for the presence of FRD on the streets is just the behavior of their owners or holders. This is a consequence of a lack of awareness on the part of dog owners (Zumpano et al. 2011), who leave their pets roaming free during some time of the day or the whole day, allowing them to defecate in the streets instead than at home, let them look for food or amusement, make them serve as guardians or simply because their holders are absent from the home for several hours. We suggest carrying out social studies to assess the number of households with dogs and the behavior of owners, including their motivations for the possession, adoption or abandonment of these animals, as well as the motivations for letting their pets roaming in public spaces.

Recommendations

We present some recommendations for future surveys. First, we recommend adopting a systematic design that allows establish a series of permanent stations for monitoring numbers in the future and adding transects according to the expansion process of the city. Secondly, we recommend testing the improvement in estimations by increasing the number of occasions of recapture, from three to five for example, as suggested by Pollock (1982). Third, we recommend improving the observation process by increasing the number of observers and/or reduce the speed of the vehicle or carrying out the search for dogs on foot (for example with one person walking on each sidewalk of a street section). These improvements in the observation process should reduce the non-identification of dogs, enhance the detection histories, reduce the variability between transects and the standard error between surveys and, therefore, reduce the difference in density need to detect a significative change in the index, improving finally both the abundance estimation and the estimation of the index.

The abundance estimation differs from the index estimation in the extra labor of taking pictures, identify dogs from pictures, the making of the detection history, and the use of the program MARK. In this study, this extra labor demanded less than three days of work in relation of the estimation of the index, which can be done few minutes after the end of a survey. However, in view of the more accurate and precise results, we advocate for the estimation of abundance instead of an index because it delivers a more accurate product at a not very extra expense of effort. For the future we recommend making the estimation every four years, as this frequency ensures that every municipal Major performs an estimation during their term of four years.

Conclusions

The simulation of survey designs allows drawing samples that accomplish design-based surveys prescriptions. Systematic segmented grid sampling allows establishing permanent transects as sampling stations to monitor numbers along the time.

We estimated a population of FRD at Ushuaia of at least 12,797 dogs (95% CI 10,979—15,323), giving a relationship of dog:humans of 1:6, higher than the 1:10 relationships recommended by the WHO. Dogs exhibit strong spatial heterogeneity in their distribution, with two neighbourhoods standing out, with 33.6% of the different dogs identified in the 12.5% of samples.

The abundance index presents large uncertainty due to the spatial heterogeneity in the encounter rate. This affects the difference in the index needed to detect changes, which reaches twice the standard error of estimates.

The visible welfare records revealed that most of the dogs presented ideal weight, injuries were infrequent and numerous dogs presented a collar or other accessory as a sign of tenure. Giving this welfare status of dogs and the weak relationship with covariates to explain numbers and distribution of dogs (apart from the geographical location), we suggest that the FRD in the streets of Ushuaia are mostly represented by owned dogs partially supervised, and that the behavior of owners is the main driver for the presence of FRD in the streets.

The capture-recapture methodology requires a slightly larger effort than the estimation of the abundance index but gives a much more precise estimation than the last. Then, we advocate for the use of a photographic capture-recapture methodology, at least for cities of similar scale to Ushuaia.

This work aims to provide an initial baseline on the number of FRD in Ushuaia and provide information for future evaluations and monitoring of the canine population conducted by any local government. Furthermore, we hope this information will contribute to the planning and assessment of the effects of interventions, in order to reduce the presence of FRD in public spaces.

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Author contributions Both authors contributed equally to the conception and design of the study, the acquisition of data, the analysis and interpretation of data, the drafting of the article, the critical review and the final approval of the version to be submitted.

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Data availability Data are available upon reasonable request. Data include individual dog data identification, DISTANCE projects used for the survey design selection, and data used for modeling dog abundance. Data will be available beginning 9 months and ending 18 months following article publication. Researchers which provide a methodologically sound proposal and are approved by the researches from this study are allowed to reuse this data. Proposals should be directed to aschiavini@wcs.org.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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