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On the causes and consequences of the free-roaming dog problem in southern Chile

Eduardo A. Silva-Rodríguez [a,b,*], Esteban I. Cortés [a,b,c], Brayan Zambrano [a,d,e], Lisa Naughton-Treves [f], Ariel A. Farías [g,h]

[a] Laboratorio de Fauna Silvestre & Laboratorio de Biodiversidad y Ecología del Dosel, Instituto de Conservación, Biodiversidad y Territorio, Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile, Casilla 567, Valdivia, Chile
[b] Programa Austral Patagonia, Universidad Austral de Chile, Valdivia, Chile
[c] Programa de Magíster en Ciencias mención Bosques y Medio Ambiente, Escuela de Graduados, Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile, Casilla 567, Valdivia, Chile
[d] Centro de Investigación para la Sustentabilidad & Programa de Doctorado en Medicina de la Conservación, Facultad de Ciencias de la Vida, Universidad Andrés Bello, Chile
[e] ONG, Unidad por la Conservación de los Ecosistemas, Valdivia, Chile
[f] Department of Geography, University of Wisconsin-Madison, United States of America
[g] Departamento de Ecología & Gestión Ambiental, Centro Universitario Regional del Este (CURE-Maldonado), Universidad de la República, Maldonado, Uruguay
[h] Center of Applied Ecology and Sustainability (CAPES), P. Universidad Católica de Chile, Santiago, Chile

HIGHLIGHTS

- Free-roaming dog abundance is linked to the number of owned dogs with outdoor access.
- Free-roaming dogs are more abundant in lower-income neighborhoods.
- Dog owners who allow pets to roam or abandon them explain most of the dog problem.
- Several, but not all, problems caused by dogs are associated with dog abundance.
- Dog management programs should focus on keeping owned dogs inside properties.

GRAPHICAL ABSTRACT

Free-roaming dog abundance is correlated to the number of owned dogs with outdoor access in the neighborhood

Graphical abstract by Carla Ulloa Vera (carla.ulloa@uach.cl)

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ABSTRACT

Free-roaming dogs are an important concern for public health, livestock production and the environment. Human behaviors—such as allowing pets to roam, abandoning dogs, or feeding stray animals—could influence free-roaming dog abundance and the frequency of occurrence of dog-caused problems. Here we aim to determine patterns of free-roaming dog abundance in urban and rural areas, to reveal spatial variation in human behaviors underlying the free-roaming dog problem, and to test for associations between free-roaming dog abundance and related problems. We conducted our study in Chile, where dogs are a major environmental issue. In Chile, as in many other Global South countries, many people leave their dogs to roam, partly due to norms and to lax enforcement of dog control laws. To address our objectives, we counted dogs in 213 transects in urban and rural areas to model dog abundance using N-mixture models. Then we conducted interviews in 553 properties around the transects to determine people's dog management, their behavior towards free-roaming dogs and the prevalence of dog-caused problems. Dog abundance was higher in transects where a higher number of owned dogs was allowed to roam, as well as in lower-income neighborhoods (based on property tax valuation). Meanwhile, rural citizens were more likely to let their dogs' roam. Dog abandonment was reported more frequently in lower-income urban neighborhoods and rural areas.

* Corresponding author at: Laboratorio de Fauna Silvestre & Laboratorio de Biodiversidad y Ecología del Dosel, Instituto de Conservación, Biodiversidad y Territorio, Facultad de Ciencias Forestales y Recursos Naturales, Universidad Austral de Chile, Casilla 567, Valdivia, Chile.
E-mail address: eduardo.silva@uach.cl (E.A. Silva-Rodríguez).

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Not surprisingly, we found that several problems—such as dog bites—were more frequent where we detected more free-roaming dogs. Our results highlight that the owned dog population is a central component of the free-roaming dog problem, and that human behavior is the key driver underlying the problem. Dog management programs should promote responsible dog-ownership, with a strong message focused on keeping dogs inside properties and preventing abandonment.

1. Introduction

Dogs and humans share an ancient bond. Dogs in current human societies fulfill numerous roles, including companionship, guarding and livestock protection (Serpell, 2017). However, dogs are also associated with many problems that affect human welfare and the environment. The most obvious examples are linked to public health. Canine rabies alone is the cause of death of over 59,000 people worldwide per year (Hampson et al., 2015) and by some estimates, over 1 % of citizens suffer dog bites every year, whether in the U.S. or Chile (Gilchrist et al., 2008, Ibarra et al., 2003, respectively). Dogs can also prey on livestock (e.g., Home et al., 2017; Montecino-Latorre and San Martín, 2019) and transmit cystic echinococcosis a parasitic disease that—in addition to being a public health concern—causes economic losses to livestock production (Budke et al., 2006). Finally, roaming dogs threaten biodiversity (Doherty et al., 2017). In fact, dogs are—among invasive predators—the third worst species causing damage to vertebrates worldwide, only surpassed by cats and rats (Doherty et al., 2016).

When it comes to their environmental impacts, not all dogs are equally important. Dogs whose movement are fully restricted (e.g., to the household) are unlikely to be an issue, although they could still produce problems (e.g., to backyard wildlife, Kays and Parsons, 2014, Rodrigues and Martinez, 2014). Here we focus on dogs that are allowed to roam unsupervised, outside of the confines of the owner's property. We use the term 'free-roaming dog' to refer to "any dog not under direct control or not prevented from roaming" (OIE, 2019, p. 17), including free-roaming owned dogs, free-roaming dogs without owners, as well as feral dogs, defined as "domestic dog that has reverted to the wild state and is no longer directly dependent upon humans" (OIE, 2019, p. 17). Owned dogs may be an important source of free-roaming dogs (Makenov and Bekova, 2016), and in some cases, may comprise the majority of them (e.g., Ibarra et al., 2006; Morters et al., 2014; Astorga et al., 2015). Unowned dogs may include pets that are lost (and not reunited) or abandoned, animals born in the streets, and dogs fed by people but for whom nobody takes responsibility (often called "community dogs", Rojas et al., 2018, ICAM, 2019). Therefore, a combination of human behaviors—owning dogs and allowing them to roam (e.g., Ibarra et al., 2006; Morters et al., 2014; Astorga et al., 2015), abandoning owned dogs (Hsu et al., 2003; Fatjó et al., 2015; Santos Baquero et al., 2016), and feeding free-roaming dogs (e.g., Tiwari et al., 2019; Bhalla et al., 2021)—could be among the most important factors explaining free-roaming dog abundance.

Two key differentiating factors could lead to spatial variation in free-roaming dog abundance: the degree of rurality and social inequality. Dog ownership patterns vary strongly between urban and rural areas. People in rural areas tend to have more dogs (Gompper, 2014), but since human densities are much lower, so is the density of dogs (e.g., Acosta-Jamett et al., 2010). Movement restrictions complicate this association. In rural areas, dogs fulfill fundamental functions such as guarding the property and the livestock (e.g., Sepúlveda et al., 2014). To protect livestock and property, dogs need to move freely, and the large size of properties makes it costly and difficult to fence. Thus, rural dogs that are owned often roam (e.g., Sepúlveda et al., 2014; Astorga et al., 2022). The second fundamental factor related to dog abundance is poverty and economic hardship. At a macroscale, dog problems are more pronounced in poorer countries (Dalla Villa et al., 2010). The same pattern seems to be replicated within countries; free-roaming dogs appear to be more abundant in lower-income neighborhoods (Rubel and Carbajo, 2019; Bhalla et al., 2021; Flores et al., 2022). One explanation is that wealthier areas tend to have lower human density (Livert Aquino and Gainza, 2014), thus the density of owned dogs is expected to be lower (dog and human densities are correlated, see Butler and Bingham, 2000; Gompper, 2014, 2021). Furthermore, people suffering economic hardship simply may not be able to afford dog-proof fences (especially in larger rural properties, Astorga et al., 2022). Beyond economic factors, norms and attitudes about dog care may vary across socioeconomic groups. For example, certain forms of compassionate behavior, namely feeding free-roaming dogs appears to be more frequent in lower-income neighborhoods (Bhalla et al., 2021).

In this study, we analyzed free-roaming dog populations starting with the patterns of abundance, then turning to subjacent mechanisms, particularly the human behaviors related to dog roaming. We then test for associations between free-roaming dog abundance and related problems. We conducted our study in southern Chile, where dogs are a major environmental issue. Free-roaming dogs in southern Chile are a public-health concern due to parasitic diseases (Venegas et al., 2014) and bites (Barrios et al., 2019, 2021) and they also contribute to fouling local environments (MINSAL, 2017). Furthermore, free-roaming dogs prey on sheep (Montecino-Latorre and San Martín, 2019) and are a major threat to the conservation of several native vertebrates (e.g., Silva-Rodríguez and Sieving, 2012; Moreira-Arce et al., 2015). A priori, we hypothesized that in urban areas the density of free-roaming dogs depends on the socioeconomic level of the neighborhood, whereas in rural areas this parameter was expected to be strongly and positively associated to the number of dogs owned in surrounding properties. Our hypothesis is phenomenological, however we also addressed some of the mechanisms that underlie the predicted patterns. In particular, the design of our study allowed us to compare some human behaviors towards dogs in areas that differed in term of free-roaming dog numbers. Finally, we hypothesized that the level of dog-caused problems (e.g., bites, harassment to pedestrians, etc.) was correlated with the abundance of free-roaming dogs.

2. Methods

2.1. Study area

The study was conducted between July 2018 and January 2019 in the Los Ríos region, Southern Chile. The c. 542.000 ha study area was delimited by a major highway to the east, the Pacific Ocean to the west and political boundaries to the north and south (Fig. 1). The study area overlaps with—in some cases partially and in others completely—nine municipalities—note that municipalities include rural and urban areas—and contains nine urban areas. As per the National Institute of Statistics census data (INE, 2019) the urban areas include five cities (>5000 inhabitants) and four towns (1001–5000 inhabitants). Cities include San José de la Mariquina (9276), Los Lagos (9746), Valdivia (150,048), Paillaco (11,296), and La Unión (26,517), whereas towns include Mafil (4239), Niebla (3989), Corral (3469) and Reumén (1001, but not sampled). Free-roaming dogs have been observed in all of these urban areas (E. Silva-Rodríguez, pers. Obs., Fig. 2a). By Chile standards poverty reaches 22 % of the human population in the region (multidimensional indicator, Observatorio Social, 2020). The area also includes the Valdivian Coastal Range, an area characterized by high precipitation level and dominated by native forest, exotic tree plantations and agricultural lands (Zamorano-Elgueta et al., 2015). The coastal range is inhabited by several species that are vulnerable to dogs, including the endangered Darwin's fox *Lycalopex fulvipes* (Silva-Rodríguez et al., 2018).

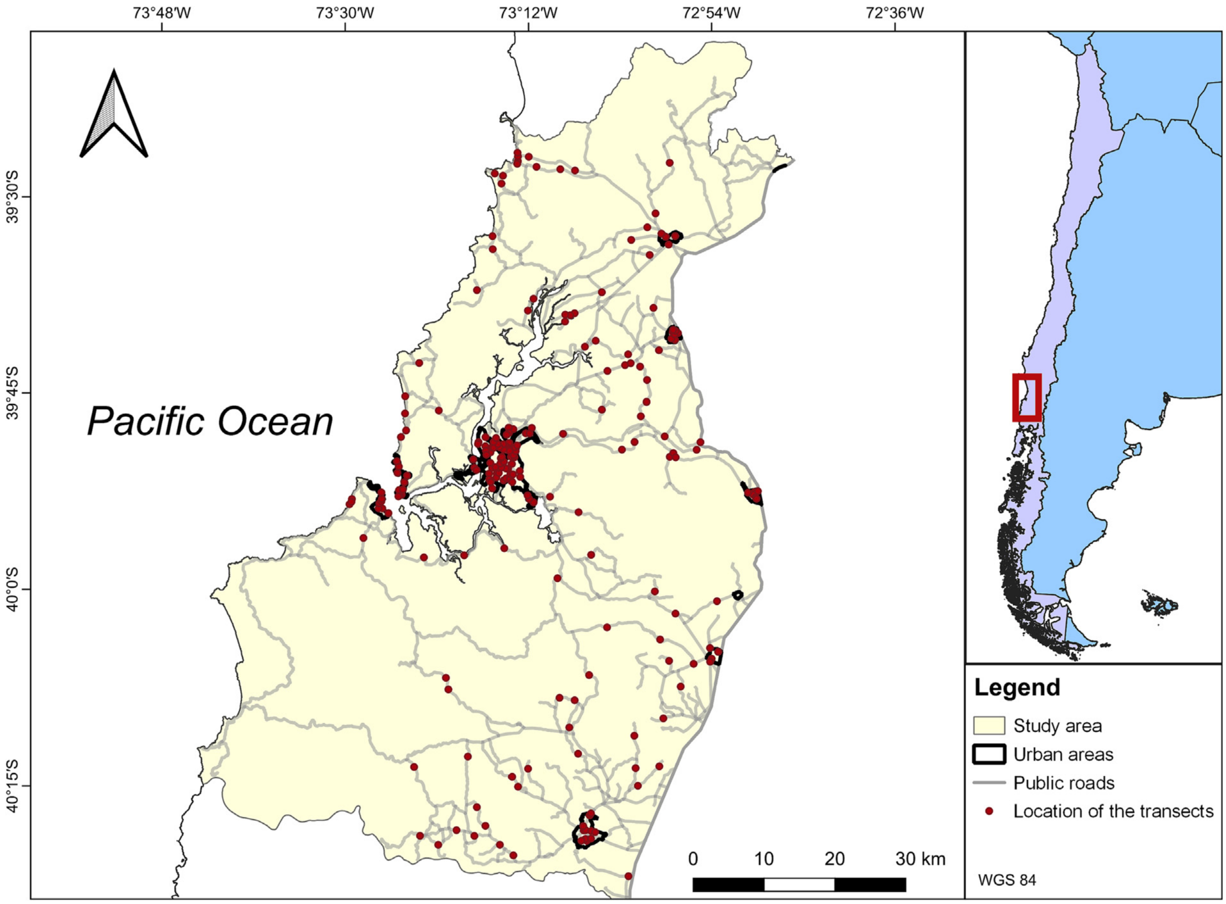

Fig. 1. Map of the study area showing the location of the transects.

2.2. General design

We used a stratified random sampling design, where approximately half of the effort was allocated to rural areas and half to urban areas. We aimed for a minimum sample size of at least 200 sites, determined through an a priori power analysis conducted for a Poisson regression in G*Power 3.1.9.2. (Faul et al., 2007). For sampling purposes, we used Chile's definition of urban area (see above, INE, 2019). This was operationalized using the pre-census cartography (INE, 2017). In urban areas, we generated 130 random points in QGIS (QGIS.org, 2022), and in Google Earth (www.google.com/intl/es/earth/) we determined the nearest street/road. In rural areas, we limited the generation of random points to public roads, to ensure sampling was feasible. Some of the points were discarded due to safety concerns (those on the major highway), logistical reasons and location inside gated communities. We maintained a minimum distance of at least 200 m between the nearest transects. In a few cases, points were relocated when urban areas were not adequately represented. At each of the selected points we set a 125-m transect. The width of the street varied, but most of them ranged between 6 and 15 m (including sidewalks). In the case of urban areas, we attempted to set one of the transect extremes to a street corner, to facilitate sampling. We sampled 109 transects defined a priori as urban and 104 as rural. During field work we corrected the classification of some transects located in the border of urban-rural areas, and after the publication of the final census cartography we noticed that some areas had been reclassified from urban to rural, leading us to update our database. Considering these reclassifications our sampling included 106 urban and 107 rural transects.

2.3. Dog counts

From July to October 2018, we conducted repeated dog counts in each of the selected transects. At each of the transects, we walked through the roads counting every dog detected in public spaces. In exceptional cases—where observer security was at risk—we drove instead of walking the transect. Transects were surveyed once per day during five consecutive days, to reduce the risk of not meeting the closure assumption (Belsare and Gompper, 2013). In a few cases (<1 % of survey occasions), transects were temporarily inaccessible due to security reasons (e.g., forestry operations, fallen trees), leaving them with a lower number of sampling occasions. Count data generated under this protocol was later used to model dog abundance accounting for uncertainty in detection using binomial N-mixture models (Royle, 2004, see modelling approaches in the corresponding section below).

In the case of rural transects, we recorded all cases where we were certain that dogs were owned. The evidence used to allocate dogs to ownership status included one or more of several sources of evidence including observing dogs repeatedly inside the same property, interactions between dogs and their owners (e.g., owners calling their dogs), observation of dogs coming out of the property when detecting the researchers, dogs performing livestock-guarding functions and in, most cases, confirmation of dog ownership status by the owners. The approach used in rural areas was logistically not feasible in urban areas.

At the beginning of the sampling, we had several cases of dogs harassing our team, thus we started recording dog harassment to the research team for the remaining transects ($n = 193$), as a proxy of harassment to pedestrians. We considered harassment to be any case where dogs approached aggressively—usually barking—towards the research team. In addition to dogs, at each of the transects we recorded the presence of food sources including evidence of intentionally provided food or water and dog-accessible garbage, and the time and whether it was raining during the sampling.

Fig. 2. Free-roaming dogs in the study area. (a) Free-roaming dogs resting near the civic center of San José de la Mariquina. (b) Pack of free-roaming dogs harassing a sea lion (*Otaria flavescens*) in Valdivia. (c) Shelter—with a dog inside—and food provided to free-roaming dogs in Valdivia. (d) Free-roaming dogs harassing the research team during surveys in Mafil. (e) Chilla fox (*Lycalopex griseus*) killed by dogs in a University campus in the city of Valdivia, March 2022.

2.4. Interviews

At each of the transects we conducted interviews to obtain information regarding ownership and management of owned dogs, as well as interactions with free-roaming dogs. Questionnaires are widely used to address dog management problems, as it provides cost-effective and reliable information (e.g., Sepúlveda et al., 2014; Craft et al., 2017; Tiwari et al., 2019; Villatoro et al., 2019; Bhalla et al., 2021). For example, previous work in the area shown concordance between dog management reported in interviews and direct observation (see Villatoro et al., 2019). The questionnaire adapted questions from previous studies (e.g., Silva-Rodríguez and Sieving, 2011, 2012; Villatoro et al., 2016), but included mostly new questions. The questionnaire had four sections. The first section sought to obtain information on current dog ownership, including number of dogs owned, dog movement restriction—only restricted during the day, only restricted during the night, always restricted, occasionally restricted, never restricted—and neutering (Villatoro et al., 2016, 2019). The second section was only answered by dog owners. This section concerned management information, such as whether the respondent's dogs visited the veterinarian, were vaccinated against rabies, or treated against parasites, and if free-roaming dogs had been adopted in the household. Here we also asked whether the respondent felt loved by their dogs, and whether their dogs had chased or attacked wild animals ("wild animals" and "birds" were asked separately and integrated later as "wildlife"), bitten people, attacked sheep, or poultry or had been attacked or killed by other dogs in the street. Most of the questions in this section were multiple choice (yes, no, do not know and do not answer) and covered the last year. The choice of one year as recall frame, is related to the fact that infrequent events are often better estimated by recalls from the previous year than by extrapolating events from the previous month (Golden et al., 2013). For a few questions there were follow up inquiries that could be open or multiple choice and that aimed to obtain further information or to prevent possible mistakes. For example, when asking about attacks on wild animals, we asked about the wild animals involved. This was important, because in some cases respondents reported that their dog harassed 'wild animals', but the animal involved was a domestic cat. The third section was directed to all respondents independent of whether they owned dogs or not. Again, most questions were presented as multiple choice (yes, no, do not know and do not answer) and covered the last year. Questions aimed at obtaining information regarding the respondent's interaction with free-roaming dogs. In this category we included questions regarding behaviors (feeding dogs) and feelings (whether free-roaming dogs had made their day, felt sad at the sight of abandoned dogs, felt threatened by free-roaming dogs, felt protected by free-roaming dogs). Furthermore, we asked for information regarding possible negative experiences (being bitten, sheep or poultry attacked by dogs, stepping on feces, garbage bags damaged by dogs and traffic accidents) or could have been observed by them (attacks on wildlife, as above). As in the previous section we obtained additional information for some of the questions and we asked respondents whether they considered free-roaming dogs ('perros callejeros') as a problem in the area. In the fourth and last section we sought socioeconomic information on the respondent, including gender, age, education, number of residents and household income.

We attempted to interview all properties in the transect. Properties were included if at least one of their entrances opened towards the transect. Accordingly, 1310 properties were visited between September 2018 and January 2019. Interviews were not conducted simultaneously with dog counts, due to logistical factors. In cases where it was not possible to conduct the interview either because no one opened the door, or because the interviewer was asked to come back later, the interviewers returned at least once more. We interviewed one person—age 18 or older—per household. Before the interview, we informed respondents about the objectives of the study, and assured then that participation was voluntary and anonymous. After signing the informed consent—approved by the Ethics Committee at Universidad Austral de Chile (Certificate#004/2017)—we conducted the interview. A total of 553 interviews met all inclusion criteria, therefore the final response rate was 42 %.

2.5. Transect characterization

Each of the transects was classified as urban or rural, according to the 2017 Census (INE, 2022). Additionally, for each of the transects (defined as the road segment and the properties that surround it), we obtained the tax valuation of properties (October 2021) using official sources (SII, 2021). Each inhabited urban transect was categorized in one out of four categories according to the median tax valuation of houses: low (less than CLP $20 million [c. USD$ 24,570 in October 2021]), medium (from CLP $20 million to $50 million), high ($50 million and above [c. USD$ 56,915]) and others (including areas that were predominantly industrial or where tax valuation was not available), whereas rural transects were classified as inhabited rural—when transects included at least one house inhabited by people—and uninhabited rural, if no inhabited properties were located in the transect. We recorded the municipality for each of the transects. A single (rural) transect was in the municipality of Rio Bueno, therefore it was grouped with those located in the neighboring municipality (La Unión).

For each transect we estimated the number of owned dogs with outdoor access. First, we used the data obtained from the interviews answered by residents to estimate the mean number of dogs with outdoor access per house (apartments and commercial properties excluded) in urban and rural areas ($n = 457$ properties included). We considered that any dog that was not reported to be fully restricted was allowed to roam at least occasionally. To model the mean number of dogs with outdoor access per household we fitted a generalized linear mixed model using zero-inflated Poisson distribution and log link (Zuur et al., 2009) and treated the transect as random effect. In addition to the constant model, we explored two alternatives to fit the count component of the model: (1) including rural areas as a fixed effect (i.e., urban versus rural), and (2) including the categories stated above (high, medium, low and others for urban areas and inhabited rural areas). In the case of the zero-inflated component, we included whether a transect was rural as a covariate for the zero-inflated component of the model. The performance of the models was assessed using the corrected Akaike Information Criterion (AICc, Burnham and Anderson, 2002). Models were fit using packages glmmTMB (Brooks et al., 2017) and bbmle (Bolker and R Development Core Team, 2022) in R (R Core Team, 2022). Finally, based on the best AICc model (Table S1, S2), we estimated the mean number of dogs with outdoor access per household in urban (0.4 dogs) and rural areas (1.5 dogs) and multiplied it by the number of inhabited households in the transect, to reach an estimate of owned dogs with outdoor access (DogsOut) per transect. This variable (DogsOut) was later used to determine if the abundance of free-roaming dogs in streets was explained by the owned dogs with outdoor access (see below).

2.6. Estimation of dog abundance and its association with transect-level covariates

We used the dog counts (see above) to model free-ranging dog abundance (dogs that were supervised when detected were excluded) using Royle's (2004) binomial N-mixture models for spatially replicated counts. Royle's models treat abundance recorded at each of the transects (N_i) as a random effect distributed according to a mixing distribution (Royle, 2004). N-mixture models allow the inclusion of covariates to model abundance as well as probability of detection (Royle, 2004) and have been previously used to estimate dog abundance (Ribeiro et al., 2019). We fitted a model that included the estimated number of owned dogs with outdoor access (DogsOut, see above), area classification (low tax valuation, medium tax valuation, high tax valuation, other, uninhabited rural, and inhabited rural) and municipality (Mariquina, Valdivia, Mafil, Los Lagos, Paillaco, Corral, La Unión) as covariates for dog abundance. The estimated number of owned dogs with outdoor access was included because we expected owned dogs to be a major source of free-roaming dogs. The socioeconomic proxy was used because we expected higher dog abundance for more vulnerable neighborhoods (e.g., Rubel and Carbajo, 2019). Finally, we included municipality because dog related rules and level of enforcement may vary between municipalities. For the detection component of the model, we included three survey-specific covariates. Time—coded as before and after 3 pm—was included because dog activity patterns could vary due to factors linked to the presence of residents at houses. The decision to use two categories was taken after initial data exploration. Weekends—compared to weekdays—were included because owners were expected to be more often at home during weekends and if true, this could affect the presence of dogs on streets. Precipitation when sampling (yes or no) was included because we had observed that during rain dogs looked for cover making it more difficult to detect them.

To adjust N-mixture models we explored three potential mixture distributions: Poisson, Zero-Inflated Poisson, and Negative Binomial. Even though AICc favored Negative Binomial models, we chose to use Zero-Inflated Poisson because the estimates based on Negative Binomial distribution were unrealistically high and did not stabilize even at high K values (>1000, i.e., "Integer upper index of integration for N-mixture", Fiske and Chandler, 2011). Similar situations are well-known in N-mixture models, and under these situations it is advisable to choose the Poisson or Zero-inflated Poisson mixtures (Kery and Royle, 2016). The choice of Zero-Inflated Poisson over Poisson was based on AICc (ΔAICc $= 47.2$ for their respective global models). Model selection was conducted using the corrected Quasi Akaike Information Criterion (QAICc, Burnham and Anderson, 2002), because there was evidence of overdispersion in the global model ($\hat{c} = 1.37$, Bootstrapped (10,000 samples) χ^2 fit statistic p-value $= 0.006$). We selected the best detection model using the global abundance model (i.e., including municipality, area classification, and estimated number of free-roaming owned dogs). Then, we conducted model selection for abundance, keeping the best detection model constant. As predictor variables for abundance, we used municipality, area classification, and estimated number of owned dogs with outdoor access (DogsOut, see above). N-mixture models were fitted in unmarked (Fiske and Chandler, 2011), model selection was conducted in AICcmodavg (Mazerolle, 2020), and figures were produced using ggplot2 (Wickham, 2016).

2.7. Statistical analyses of interview data

We modeled the effects of socioeconomic categories on six different dog managements in dog-owning households (allowing ≥1 dog to roam at least occasionally, having ≥1 dog dewormed, neutering ≥1 dog, not neutering ≥1 dog, having ≥1 dog vaccinated, and visiting the veterinarian) and five additional variables for all respondents (being aware that neighbors in the street abandoned dogs, being aware that dogs were abandoned in the street, adopting free-roaming dogs, feeding free-roaming dogs in their street, and owning a dog). Behaviors of interest were coded as "1" when reported by the respondent, and "0" otherwise. We only included information provided by residents of the property visited and excluded the "others" classification from the analyses because the number of residents interviewed in these areas was low. In cases of perfect separation (i.e., when all responses for a socioeconomic category were "0"), we excluded the socioeconomic category involved. The data was analyzed using generalized linear mixed effects models with binomial error and logit link (Zuur et al., 2009) using package lme4 (Bates et al., 2015). To model the detection of food and/or water provision in the transects, as well as in cases where a fitted mixed model was (near) singular, we fitted generalized linear models in package glm2 (Marschner, 2011). Figures were elaborated using ggplot2 (Wickham, 2016).

Finally, we modeled the odds of a resident respondent reporting 1) being bitten by dogs in the area, 2) a respondent's dogs attacked by other dogs in the street, (3) feeling harassed by dogs in their own street, (4) feeling protected by free-roaming dogs in their street, (5) stepping on dog feces in their street, (6) having garbage bags damaged by dogs, (7) opinion whether dogs were a problem in the area, (8) having hen losses to dogs (only for hen-owning households), (9) having sheep losses due to dogs (only for sheep-owning households) and (10) observing dogs harassing—chasing or attacking—wildlife in the area during the last year as a function of (1) the mean number of dogs detected in the transect (i.e., the average of the counts), and (2) the fitted abundance of dogs in the transect (based on the N-mixture models), to determine if dog-caused problems were associated with free-roaming dog abundance. We only analyzed data provided by residents of the area. The same approach was used to determine if the probability that the research team was harassed by dogs was associated to dog abundance. We used generalized linear mixed effect models (binomial error and logit link) treating the transect as a random effect. We compared three alternative models—mean number of dogs, fitted number of dogs, and intercept only—through AICc (Burnham and Anderson, 2002). As before, data was analyzed in package lme4 (Bates et al., 2015). In some cases—when models were singular or near singular, and in the case of harassment to the research team—we used generalized linear models (GLM) in package glm2 (Marschner, 2011). All statistical analyses were conducted in R (R Core Team, 2022).

3. Results

3.1. Free-roaming dog counts and abundance estimation

During counts, we observed free-roaming dogs in 46.9 % of the transects, including 70.8 % of urban and 23.4 % of rural transects. The mean number of unsupervised dogs detected per transect per visit was 0.2 in rural areas and 1.1 in urban areas. In rural areas, at least 74.1 % of the unsupervised dogs detected had an owner. In urban areas, the ownership status of free-roaming dogs was not determined.

N-mixture models for abundance estimation showed that uncertainty in the probability of detecting dogs was largely explained by rain and time ($\omega_i = 0.72$, Table 1a), whereas abundance was explained by the number of owned dogs with outdoor access in the transect (DogsOut, derived from interviews) and by the neighborhood classification ($\omega_i = 0.99$, Table 1b). Considering the best QAICc model, the probability of detecting dogs was lower when raining and after 3 pm, whereas dog abundance was higher in urban areas with low tax valuation, intermediate in urban areas with medium tax valuation and inhabited rural areas, and lower in urban areas with high tax valuation and uninhabited rural areas (Table 2, Fig. 3).

3.2. Human behaviors that favor dog presence

Most rural properties interviewed owned at least one dog (86.8 %), versus 60.6 % of urban properties (Table 3). The mean number of owned dogs per property was 2.3 for rural areas and 1.2 for urban areas, whereas human:dog ratio was 1.3 and 2.9 for rural and urban areas respectively. Human behaviors that favor the presence of free-roaming dogs were ubiquitous. Owned dogs were allowed to roam, at least occasionally, in 62.3 % of rural properties (71.7 % of dog owning rural properties) and 23.1 % of urban properties (38.2 % of dog owning urban properties). At the transect level, this implies that in at least 80.0 % of inhabited rural transects and 59.0 % of urban transects, one or more owned dogs were allowed to roam (Table 3). Dog abandonment in the neighborhood was reported to affect 75.6 % of the transects, and in 33.8 % of the transects one or more respondents reported that neighbors had abandoned dogs. Adoption of free-roaming dogs was reported in 45.9 % of the transects. Lack of veterinary care was also common. In 57.1 % of the transects there was at least one dog that did not go to the veterinarian within the last year, and in 70.3 %, 45.5 % and 87.6 % of the transects there was at least one dog that was not vaccinated against rabies, dewormed, or neutered, respectively. At the property level, 67.7 % of owners reported that at least one dog went to the veterinarian, 56.7 % at least one dog vaccinated and 78.8 % dewormed within the previous year. Also, 52.6 % of dog owning properties reported at least one dog neutered, but at the same time 72.2 % reported at least one dog that was not neutered (note that a single house can have neutered and unneutered dogs). Finally, 45.7 % of respondents reported to feed free-roaming dogs in the area where the survey was conducted, implying that free-roaming dogs were fed—at least occasionally—in 71.3 % of the transects where interviews were conducted. During dog counts, we detected evidence of food or water provision for dogs in 32.1 % of urban transects, contrasting with 1.9 % in rural transects.

Further statistical analyses were conducted using only those answers provided by residents of the interviewed property. We found that the proportion of households that owned dogs was higher in rural than in urban areas (Fig. 4a). The proportion of properties that allowed dogs to roam at least occasionally was significantly higher in rural than in urban areas but did not differ between urban neighborhoods that differed in tax valuation (Fig. 4b). Dog vaccination and visit to the veterinarian during the previous year was lower in rural than urban areas but did not differ between urban neighborhoods, whereas deworming within the last year and neutering did not differ between areas (Fig. 4b).

Dog abandonment was reported more often in rural areas and urban areas with low tax valuation than in other urban areas (Fig. 4a). Similarly, respondents reported dog abandonment by neighbors more often in areas with low than medium tax valuation (Fig. 4a), whereas this was not reported in neighborhoods with high tax valuation. Adoption of free-roaming dogs was not reported in any neighborhood with high tax

Table 1
N-mixture model selection for the number of dogs using urban and rural transects in southern Chile. Models were fit using zero-inflated Poisson mixture distributions and adjusting for overdispersion ($\hat{c} = 1.37$). Models are ranked according to QAICc and its respective ΔQAICc and QAICc weight (ω_i). (a) Selection of detection models, (b) selection of abundance models.

	K	QAICc	ΔQAICc	ω_i
(a) Selection of detection models				
p(Rain + Time) psi(.) λ(Area classification + DogsOut + Municipality)	18	1271.07	0.00	0.72
p(Rain + Time + Weekend) psi(.) λ(Area classification + DogsOut + Municipality)	19	1273.48	2.41	0.21
p(Time) psi(.) λ(Area classification + DogsOut + Municipality)	17	1276.31	5.24	0.05
p(Time + Weekend) psi(.)λ(Area classification + DogsOut + Municipality)	18	1278.63	7.56	0.02
p(Rain) psi(.)λ(Area classification + DogsOut + Municipality)	17	1284.53	13.46	0.00
p(Rain + Weekend) psi(.)λ(Area classification + DogsOut + Municipality)	18	1286.11	15.04	0.00
p(.) psi(.)λ(Area classification + DogsOut + Municipality)	16	1289.00	17.92	0.00
p(Weekend) psi(.)λ(Area classification + DogsOut + Municipality)	17	1291.01	19.93	0.00
(b) Selection of abundance models				
p(Rain + Time) psi(.) λ(Area classification + DogsOut)	12	1260.90	0.00	0.99
p(Rain + Time) psi(.) λ(Area classification + DogsOut + Municipality)	18	1271.07	10.17	0.01
p(Rain + Time) psi(.) λ(Area classification)	11	1274.94	14.03	0.00
p(Rain + Time) psi(.) λ(Area classification + Municipality)	17	1284.94	24.03	0.00
p(Rain + Time) psi(.) λ(DogsOut + Municipality)	13	1331.46	70.55	0.00
p(Rain + Time) psi(.) λ(DogsOut)	7	1332.17	71.26	0.00
p(Rain + Time) psi(.) λ(.)	6	1368.73	107.83	0.00
p(Rain + Time) psi(.) λ(Municipality)	12	1375.29	114.38	0.00

Table 2
Parameter estimates for the best QAICc model used to explain the number of dogs that use urban and rural transects in southern Chile. Standard errors (SE) and confidence intervals were adjusted using the overdispersion parameter of the global model ($\hat{c} = 1.37$).

Parameter		Estimate	SE	LCI	UCI
Lambda	Intercept	0.20	0.50	−0.78	1.18
	DogsOut	0.08	0.02	0.04	0.11
	Urban Low	1.65	0.46	0.74	2.56
	Urban Medium	1.48	0.47	0.55	2.41
	Urban Other	1.02	0.55	−0.07	2.11
	Inhabited rural	0.89	0.49	−0.06	1.85
	Uninhabited rural	−2.12	0.74	−3.58	−0.66
Psi	Intercept	−1.08	0.29	−1.65	−0.51
Detection	Intercept	−1.42	0.23	−1.88	−0.96
	Rain	−0.48	0.17	−0.82	−0.14
	Time	−0.51	0.13	−0.76	−0.26

valuation and did not vary between the remaining neighborhoods (Fig. 4a). The proportion of respondents that reported feeding free-roaming dogs in their neighborhood within the previous year was lower in rural than in urban areas (Fig. 4a). Evidence of dog feeding and/or water provision (Fig. 2c) was detected in 4.9 % of inhabited and 0.0 % of uninhabited rural transects, compared to 12.5 %, 23.1 % and 50.0 % of the transects located in urban areas of high, medium, and low tax valuation, respectively (Fig. 4a).

3.3. Association between dog caused problems and dog abundance

Problems linked to free-roaming dogs were frequently reported. Nearly two thirds of respondents (63.3 %) considered free-roaming dogs to be a problem in their area. The most frequent problems reported were stepping on dog feces (64.1 %), dogs damaging garbage bags (51.1 %), free-roaming dogs attacking the dogs of the respondents (37.9 % of dog owners), making respondents feel threatened (36.5 %), harassing wild animals (23.8 %), and attacking hen (39.7 % of hen owners) and sheep (36.4 % of sheep owners). Most problems evaluated were more frequent in urban than in rural areas, both at property and transect levels (Table 3). In addition to respondents' report, the research team members were themselves harassed by free-roaming dogs in 24.4 % of the urban and 4.7 % of rural transects (Table 3, Fig. 2d).

Respondents frequently reported their dogs harassed wild animals (Table 3), especially birds. In rural areas respondents from dog owning properties reported that their dogs harassed birds (31.8 %), invasive hares (*Lepus europaeus*, 23.8 %), foxes (*Lycalopex* sp., 9.5 %) and puma (*Puma concolor*, 2.4 %). In urban areas respondents reported their dogs harassed birds (25.3 %), and occasionally rats and mice (4.3 %), invasive lagomorphs (1.0 %) and coypu (*Myocastor coypus*, 0.3 %), a large-sized native wetland rodent. Respondents also reported that they observed other free-roaming dogs harassed wildlife. In addition to birds (reported by 22.8 % of respondents), free-roaming dogs in urban areas harassed invasive lagomorphs (1.9 %), rats and mice (0.6 %), coypu (0.4 %), foxes (0.2 %) and sea lions (*Otaria flavescens*, 0.2 %). Free-roaming dog harassment of sea lions was also frequently observed by the research team in the city of Valdivia (Fig. 2b). In rural areas, wildlife harassment by free-roaming dogs affected birds (25.5 %), hares (9.8 %) and puma (2.0 %). In summary, dog harassment of wildlife was reported more frequently in rural (53.8 %) than in urban areas (34.8 %). However, when aggregating at transect level, dog harassment to wildlife was reported in 79.0 % of urban and 62.9 % of rural transects where interviews could be conducted (Table 3).

The likelihood that a respondent perceived that free-roaming dogs were a problem was positively correlated with the mean number of dogs detected in the area, and the same pattern was found for the odds in the past year of stepping on dog feces, being bitten by dogs, having one of their own dogs attacked by free-roaming dogs, and both feeling threatened and protected by dogs (Table 4). Similar association was found for these problems with the estimated number of free-roaming dogs, except in the case of dog bites where there was no evidence of association. Free-roaming dog harassment of the research team was also associated with the mean number of dogs detected and with the estimated number of free-roaming dogs (Table 4). In most cases AICc suggests that the mean number of dogs detected in the street is a better predictor of problems than the estimated number of dogs that use the street (Table 4). The main exceptions were stepping on dog feces and attacks on hens, which were better predicted by the

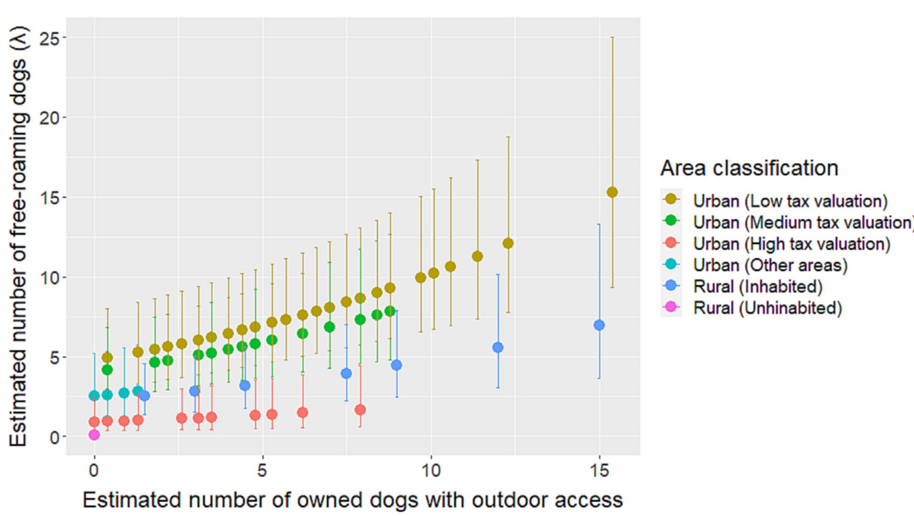

Fig. 3. Estimated number of free-roaming dogs that use streets (125-m transects) as a function of the estimated number of owned dogs allowed to roam as estimated from interviews and classification of the neighborhood. Error bars correspond to 95 % confidence intervals.

Table 3
Summary of management practices and interaction with dogs reported by respondents summarized at transect and respondent level. Time frame varies between items. Most items correspond to questions that were asked considering the last year (LY), although some of them refer to the moment when the interview was conducted (IN), or to data collected during dog surveys (SV). Differences in number of respondents are explained by the number of responses obtained for any given question (do not know and do not answer responses were excluded). Note that unlike further analyses, data was not filtered and therefore all applicable answers are included.

Item	Time frame	Proportion of transects						Proportion of respondents					
		Urban		Rural		Total		Urban		Rural		Total	
		n	%	n	%	n	%	n	%	n	%	n	%
(a) Dog management													
Owns at least one dog	IN	101	89.1	35	94.3	136	90.4	500	60.6	53	86.8	553	63.1
Owns at least one dog that roams without supervision at least occasionally	IN	100	59.0	35	80.0	135	64.4	498	23.1	53	62.3	551	26.9
Dog has been in the street without supervision	LY	89	82.0	32	75.0	121	80.2	302	56.6	45	66.7	347	57.9
Feed free-roaming dogs in their street	LY	101	82.2	35	40.0	136	71.3	499	47.5	52	28.8	551	45.7
Evidence of free-roaming dog feeding or water provision in transect	SV	106	32.1	107	1.9	213	16.9	–	–	–	–	–	–
Aware that neighbors abandoned at least one dog	LY	100	41.0	33	12.1	133	33.8	469	15.1	48	10.4	517	14.7
Dogs were abandoned in their street	LY	100	79.0	35	65.7	135	75.6	457	56.5	50	68.0	507	57.6
At least one owned dog did not go to the veterinary	LY	87	54.0	32	65.6	119	57.1	–	–	–	–	–	–
At least one of the dogs went to the veterinary	LY	–	–	–	–	–	–	296	71.6	45	42.2	341	67.7
At least one owned dog not vaccinated	LY	86	67.4	32	78.1	118	70.3	–	–	–	–	–	–
At least one of the dogs was vaccinated	LY	–	–	–	–	–	–	285	60.4	45	33.3	330	56.7
At least one owned dog not dewormed	LY	88	47.7	33	39.4	121	45.5	–	–	–	–	–	–
At least one of the dogs was dewormed	LY	–	–	–	–	–	–	294	79.9	46	71.7	340	78.8
At least one dog neutered	IN	–	–	–	–	–	–	298	52.7	44	52.3	342	52.6
At least one dog not neutered	IN	89	87.6	32	87.5	121	87.6	298	69.8	44	88.6	342	72.2
Adopted free-roaming dogs	LY	89	50.6	33	33.3	122	45.9	302	19.5	45	26.7	347	20.5
(b) Interaction with dogs													
Own dog harass wildlife	LY	88	60.2	31	54.8	119	58.8	295	28.1	42	52.4	337	31.2
Other dogs harass wildlife in the area	LY	100	61.0	34	35.3	134	54.5	479	23.4	50	28.0	529	23.8
Any dog harass wildlife	LY	100	79.0	35	62.9	135	74.8	492	34.8	52	53.8	544	36.6
Felt threatened by dogs in their street	LY	100	77.0	35	20.0	135	62.2	498	38.6	52	17.3	550	36.5
Respondent bitten by dogs in the area	LY	101	20.8	35	2.9	136	16.2	499	5.2	52	1.9	551	4.9
Felt protected by dogs in their street	LY	100	81.0	35	42.9	135	71.1	487	47.2	52	32.7	539	45.8
Felt sad at the sight of abandoned dogs	LY	101	98.0	35	97.1	136	97.8	495	87.5	52	82.7	547	87.0
A free-roaming dog made his/her day	LY	101	88.1	35	62.9	136	81.6	495	64.4	52	55.8	547	63.6
Dogs damaged garbage bags of their home	LY	100	90.0	34	50.0	134	79.9	497	51.5	51	47.1	548	51.1
Own dogs attacked by free-roaming dogs in the street	LY	89	66.3	33	39.4	122	59.0	298	38.6	45	33.3	343	37.9
Own dogs killed by free-roaming dogs	LY	89	7.9	33	3.0	122	6.6	301	2.3	45	2.2	346	2.3
Dog harassment to research team	SV	86	24.4	107	4.7	193	13.5	–	–	–	–	–	–
Sheep attacked by dogs in the property	LY	9	33.3	10	50.0	19	42.1	10	30.0	12	41.7	22	36.4
Hen attacked by dogs	LY	20	65.0	23	30.4	43	46.5	31	51.6	27	25.9	58	39.7
Considers free-roaming dogs as an important problem in the area	LY	101	87.1	35	54.3	136	78.7	488	64.5	52	51.9	540	63.3
Stepped on dog feces in their street	LY	101	83.2	35	45.7	136	73.5	497	65.8	52	48.1	549	64.1

estimated number of free-roaming dogs. The detection of dog attacks on sheep and wildlife, as well as damage to garbage bags, was not correlated to mean number of dogs nor to the fitted dog abundance (Table 4).

4. Discussion

4.1. Free-roaming dog abundance and the incidence of dog-caused problems

Free-roaming dogs are globally recognized as an important concern for public health (Dalla Villa et al., 2010), livestock production (Home et al., 2017; Montecino-Latorre and San Martín, 2019) and wildlife conservation (Doherty et al., 2017). In our study area, free-roaming dog abundance was very high, especially in lower-income neighborhoods, where the estimated number of free-roaming dogs that used the 125-m transects ranged between 5 and 15 (Fig. 3). Such abundances are extreme for carnivores and better resemble mice densities (see Cofre and Marquet, 1999). Therefore, it is not surprising that most respondents considered that dogs were a problem in their neighborhood. The incidence of dog bites was high compared to previous studies in Chile (Ibarra et al., 2003; Barrios et al., 2019, 2021) and elsewhere (e.g., Gilchrist et al., 2008; Sharma et al., 2016; Westgarth et al., 2018). These differences could be partially explained by methodological differences (e.g., interviews versus clinical records, Ibarra et al., 2003) and reporting biases. Consistent with the high bite incidence, 37 % of respondents felt threatened by dogs within the previous year, and in fact, we ourselves were harassed by dogs in nearly a quarter of the urban transects when conducting dog counts. Damage to garbage bags and stepping on dog feces was also reported by most respondents (51 and 64 % respectively, Table 3). Certainly, stepping on dog feces is not as serious as being bitten, but the fact that a high proportion of dogs were not dewormed, suggests that exposure to zoonotic parasites in public places could be an additional concern linked to high free-roaming dog abundance (e.g., Mercado et al., 2004; Alegría-Morán et al., 2021; Flores et al., 2022).

Problems associated with dogs are not limited to public health concerns. We found that 36 % of sheep owners reported dog attacks during the previous year, and damage to poultry was also common (affecting 40 % of hen owners). These numbers align with results from previous studies (e.g., Montecino-Latorre and San Martín, 2019), and therefore provide additional evidence that dogs are a serious concern for small farmers. Dog harassment on wildlife was also common and involved dogs owned by the respondents as well as other dogs. Although these dog-wildlife interactions—including lethal and non-lethal consequences—have been well documented in rural Chile (e.g., Silva-Rodríguez and Sieving, 2011, 2012; Sepúlveda et al., 2014; Cortés et al., 2021), we show that dogs also harass urban wildlife, a problem that was reported in 79 % of urban transects. Most often reported was bird harassment, although native mammals such as foxes, coypu, and sea lions were also affected, as observed during and after conducting this study (Fig. 2b, e). Recent research indicates wild carnivore species use urban green areas in Chile. In these areas spatial overlap between dogs and wild carnivores is high, although overlap in their temporal activity patterns is relatively low (Silva-Rodríguez et al., 2021). Considering that dogs can exert negative effects on wild animals in rural areas (e.g., Vanak and Gompper, 2010; Silva-Rodríguez and Sieving, 2012; Zapata-Ríos and Branch, 2018)—where dog densities are much lower than in urban areas—we hypothesize that extremely high free-roaming

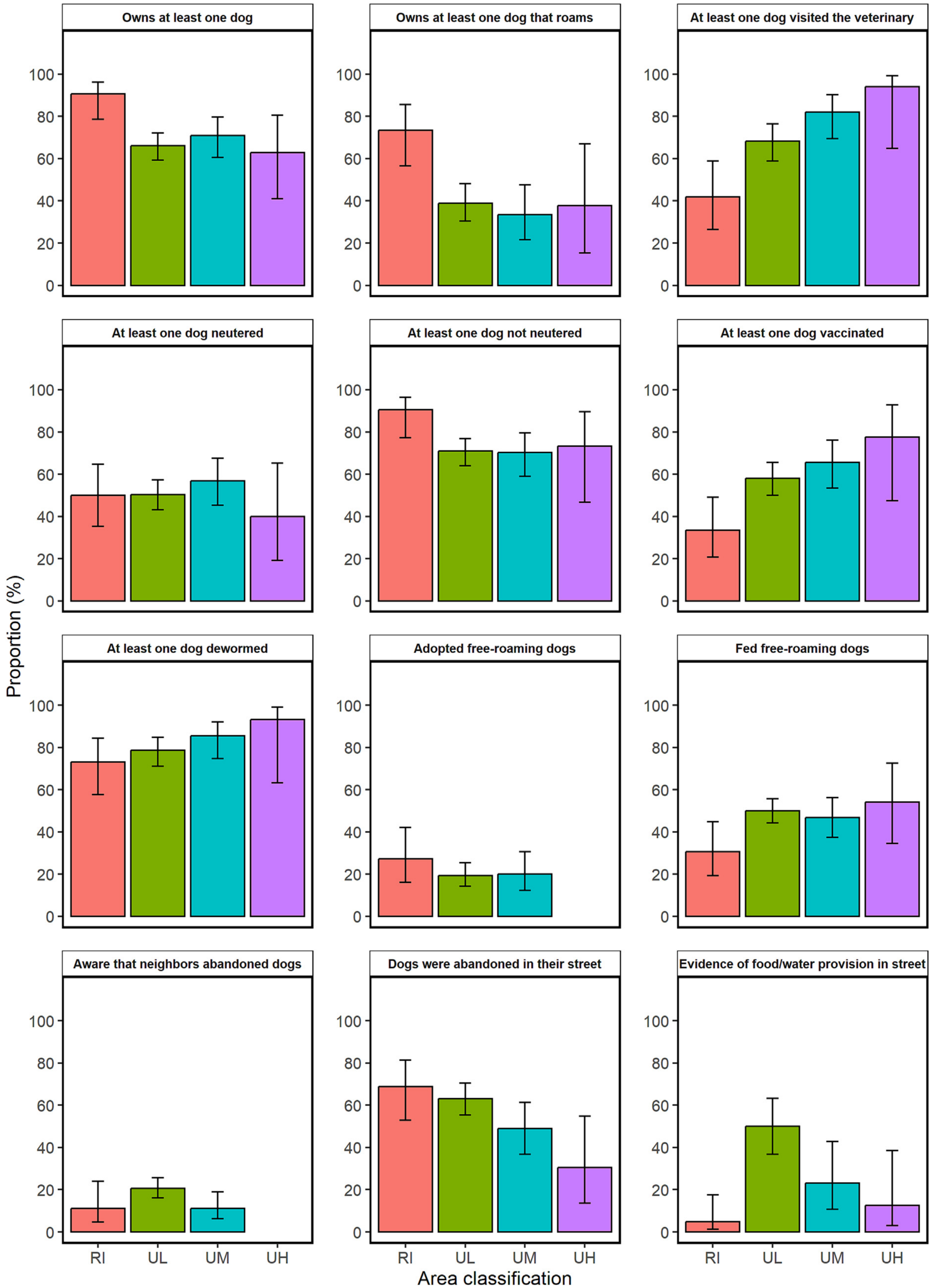

Fig. 4. Association between area classification and proportion of respondents that report different behaviors and management practices towards dogs as well as the proportion of transects where food and/or water provision was detected during dog counts. Note that the estimates are based on the results of modelling (GLMM or GLM) conducted to compare the frequency of each behavior among the different areas surveyed (Rural inhabited, RI; and urban with low, UL, medium, UM, and high tax valuation, UH; see Table S3 in supplementary material). Error bars represent 95 % confidence intervals.

Table 4
Frequency (%) with which study respondents reported the occurrence of problems associated with free-roaming dogs in the last year and its association with the mean number of dogs detected (Mean) and the fitted dog abundance (Nmix) on the street where the survey was conducted. ΔAICc and Akaike weights (ωi) values are provided to compare the alternative models. The type of model used (GLM = Generalized Linear Model, GLMM = Generalized linear mixed model), as well as the intercept (Int), effect estimates (Est), their respective standard errors (SE), and random effects variance (RE) and standard deviations (SD) are shown when applicable.

Subject assessed	n	%	Type	Model	K	ΔAICc	ωi	Int.	SE	Est.	SE	RE	SD
Bite to respondent in the area	480	5	GLM	Mean	2	0.0	0.9	−3.5	0.4	0.4	0.1	–	–
				Null	1	4.5	0.1	−2.9	0.2	–	–	–	–
				Nmix	2	5.9	0.0	−3.3	0.5	0.0	0.1	–	–
Stepped on dog feces in their street	480	66	GLMM	Nmix	3	0.0	1.0	−1.0	0.3	0.2	0.0	0.3	0.5
				Mean	3	6.4	0.0	0.0	0.2	0.5	0.1	0.4	0.6
				Null	2	28.1	0.0	0.6	0.1	–	–	0.8	0.9
Dogs damaged garbage bags of their home	479	51	GLMM	Null	2	0.0	0.5	0.0	0.1	–	–	0.1	0.3
				Mean	3	1.5	0.3	0.1	0.1	−0.1	0.1	0.1	0.3
				Nmix	3	1.9	0.2	0.0	0.2	0.0	0.0	0.1	0.3
Own dog was attacked by free-roaming dogs in their street	326	37	GLM	Mean	2	0.0	0.6	−0.9	0.2	0.2	0.1	–	–
				Nmix	2	0.7	0.4	−1.2	0.3	0.1	0.0	–	–
				Null	1	5.4	0.0	−0.5	0.1	–	–	–	–
She/he has felt threatened by free-roaming dogs in their street	481	38	GLMM	Mean	3	0.0	0.6	−0.8	0.2	0.2	0.1	0.2	0.4
				Nmix	3	1.6	0.3	−1.1	0.3	0.1	0.0	0.2	0.5
				Null	2	3.2	0.1	−0.6	0.1	–	–	0.3	0.5
She/he has felt protected by free-roaming dogs in their street	472	48	GLMM	Mean	3	0.0	1.0	−0.7	0.2	0.4	0.1	0.2	0.4
				Nmix	3	17.6	0.0	−0.6	0.3	0.1	0.0	0.3	0.5
				Null	2	19.6	0.0	−0.1	0.1	–	–	0.3	0.5
Sheep attacked by dogs in the property	22	36	GLM	Null	1	0.0	0.5	−0.6	0.4	–	–	–	–
				Nmix	2	1.2	0.3	0.4	1.0	−0.2	0.2	–	–
				Mean	2	2.4	0.2	−0.5	0.6	−0.1	0.3	–	–
Hen attacked by dogs	57	40	GLMM	Nmix	3	0.0	0.6	−1.9	1.0	0.3	0.2	0.3	0.6
				Mean	3	2.2	0.2	−0.8	0.4	0.3	0.2	0.1	0.4
				Null	2	2.7	0.2	−0.4	0.3	–	–	0.2	0.4
Free-roaming dogs harassed wildlife in the area	464	24	GLM	Null	1	0.0	0.6	−1.1	0.1	–	–	–	–
				Nmix	2	1.6	0.3	−1.0	0.3	0.0	0.0	–	–
				Mean	2	2.0	0.2	−1.1	0.2	0.0	0.1	–	–
Free-roaming dogs are an important problem in the area	473	64	GLMM	Mean	3	0.0	0.9	0.0	0.2	0.4	0.1	0.4	0.6
				Nmix	3	4.9	0.1	−0.4	0.3	0.1	0.0	0.5	0.7
				Null	2	13.4	0.0	0.6	0.1			0.7	0.8
Free-roaming dogs harassed research team[a]	80	33	GLM	Mean	2	0.0	0.9	−1.9	0.4	0.9	0.3	–	–
				Nmix	2	3.5	0.2	−2.4	0.6	0.3	0.1	–	–
				Null	1	13.1	0.0	−0.7	0.2	–	–	–	–

[a] Transects where dogs were not detected during counts were excluded from this analysis.

dog abundances—such as those we observed in some urban transects—could be an important driver of the absence of medium and large-sized wild mammals—such as mesocarnivores—in many urban neighborhoods.

We found that many of the problems caused by dogs—especially those related to public health—were more frequent in areas where the mean number of free-roaming dogs detected in the street, or the estimated free-roaming dog abundance was higher (Table 4). Paradoxically, feeling threatened and protected by dogs was positively correlated to free-roaming dog abundance. This apparent contradiction may come from the fact that although certain individual dogs may be considered dangerous, free-roaming dogs are often perceived to help to reduce the risk of burglary (Bhalla et al., 2021), or even to protect residents from aggressive dogs, as reported by some respondents. The fact that some—but not all—problems caused by dogs appear to be associated with higher dog abundances, suggests that reducing the number of free-roaming dogs could alleviate some of these problems (see also Bhalla et al., 2021; Flores et al., 2022).

Not all dog-caused problems were associated with dog abundance. For example, we did not find an association between the number of dogs detected and damage to garbage bags, predation on sheep and attacks on wildlife. In the case of damage to garbage bags, the lack of association may be related to the fact that residents take measures to prevent dog-caused damage. In the case of sheep attacks, our results resemble those of a report from India (Home et al., 2017). However, the lack of association observed could also be explained by the fact that we measured dog abundance at a small scale (the transect), so we caution that—from our data—we cannot disregard the possibility of a positive association between dog abundance and predation on livestock. Finally, we did not find an association between dog attacks on wildlife and free-roaming dog density. Previous studies have found that areas with higher probability of dog presence are less used by some native species that inhabit the region (Silva-Rodríguez and Sieving, 2012; Moreira-Arce et al., 2015). Therefore, the lack of association between dog abundance and attacks on wildlife is predictable, considering that areas with higher number of dogs could have fewer wild animals leading to lower interaction opportunities for each individual dog.

4.2. Drivers of free-roaming dog abundance

The patterns of free-roaming dog abundance show strong variation between urban and rural settings. In rural areas, dog abundance was positively correlated with the number of owned free-roaming dogs estimated through interviews (Fig. 3), and therefore, with the number of inhabited houses. In uninhabited rural transects, the number of dogs detected during surveys as well as the estimated number of free-roaming dogs was very low. The patterns observed strongly suggest that most free-roaming dogs in rural areas are owned. Supporting this statement, at least 74 % of the detections of unsupervised dogs in rural areas corresponded to owned animals. In the case of the remaining dogs, we did not determine their origin. This does not imply that they did not have owners, but rather that we did not detect them during the counts. In contrast, we did not detect a single dog—neither during sampling nor while travelling between transects (>10,000 km travelled within the study area)—that could match the definition of a feral dog (see Vanak and Gompper, 2009; OIE, 2019). The associations observed is explained by the fact that most rural households' own dogs and allow them to roam freely (Fig. 4, see also Villatoro et al., 2019). Owned dogs with outdoor access concentrate most of their activity at short distance from the owners' household (Ruiz-Izaguirre et al., 2015; Sepúlveda et al., 2015; Schüttler et al., 2022). As a result, in areas with higher number of households there is often a higher number of owned dogs roaming around. Therefore, our data provides strong evidence that the majority of free-ranging rural dogs are owned and provides a causal link that explains the frequently reported spatial association between the abundance—and presence—of rural free-roaming dogs and human settlements (see Silva-Rodríguez and Sieving, 2012; Ribeiro et al., 2019; Cortés et al., 2021).

In urban areas, the observed patterns are more complex. As in rural areas, dog abundance was positively associated to the estimated number of owned dogs allowed to roam (based on interviews), but we also found that dog abundance was higher in lower than in higher income neighborhoods. As in rural areas, the management of owned dogs provides an explanation for the patterns observed: in 59 % of urban transects—where dog owning properties were interviewed—one or more dog owners recognized that their dogs roamed, at least occasionally, and we estimated that in average 0.4 dogs per urban household could roam. Then, our data suggests that the urban areas studied may be similar to other Chilean urban areas where owned dogs are considered an important component of the free-roaming dog populations (Ibarra et al., 2006). Owned dogs with outdoor access partially explain the patterns observed in urban areas, but it does not explain by itself the higher abundance of dogs observed in lower income neighborhoods, a pattern also observed in other areas of the world (Rubel and Carbajo, 2019; Bhalla et al., 2021; Flores et al., 2022).

Our data suggests that—in addition to owned dogs—unowned dogs that are fed by part of the community ("community dogs" under the Chilean Law 21.020, Rojas et al., 2018), could be important in some urban neighborhoods. In neighborhoods with low tax valuation there were more free-roaming dogs than expected based on owned dogs allowed to roam (Fig. 3) and evidence of dog feeding on the streets was also more frequent than in other urban neighborhoods. Questionnaires did not reveal a comparable pattern, but the differences between interviews and field observations could be linked to the frequency of the behavior. Our questions inquired within a time frame of a year (i.e., feeding dogs within the previous year), whereas field observations detected recent feeding, and probably are a better representation of regular free-roaming dog feeding. Regular feeding—even by a small proportion of properties—is an important mechanism sustaining free-roaming dog populations, particularly community dogs. In fact, in India the free-roaming dog population appears to be sustained by only 10–18 % of houses (Bhalla et al., 2021). The presence of community dogs may help explain the observed variations between neighborhoods that cannot be accounted for by the number of owned dogs alone.

In addition to differences in regular feeding, differences between neighborhoods could be partially driven by dog abandonment and escapes. Residents of lower-income neighborhoods—and rural areas—reported that dogs were abandoned in their street more often than those living in higher-income neighborhoods (Fig. 4). It is likely that these reports also include dogs that were not abandoned but escaped, a distinction difficult to discriminate (unless the actual abandonment is observed). Furthermore, dog abandonment by neighbors and adoption of free-roaming dogs was reported less often in higher income neighborhoods. This would be expected if fewer dogs were abandoned in the streets they live on, leading to less opportunities to develop bonds to individual free-roaming dogs and lower chances to adopt abandoned dogs, although these patterns could also be explained by a preference for buying rather than adopting dogs. Dog abandonment is a behavior that is both infrequent and difficult to detect. For example, in Spain 1–2 dogs are abandoned per 1000 inhabitants (Fatjó et al., 2015). In Brazil a study on non-permanence of dogs at homes, found that 19.1 % were not at home after a year, mainly due to death. Abandonment was not reported in this study, but 7 % of the missing dogs had escaped, and the fate of 11 % was unknown (Menezes Penaforte et al., 2022). However, even low rates of transitions from owned to free-roaming—due to abandonment or escape—can explain large numbers of free-roaming dogs in urban areas (Makenov and Bekova, 2016). Both abandoned and lost dogs may be adopted, and return to the owned dog pool, or be fed and remain in the streets as community dogs (ICAM, 2019). A combination of higher human density—and therefore higher number of owned dogs allowed to roam—with higher levels of dog immigration through abandonment and escapes and higher food provision—leading to the establishment of community dogs—could drive the patterns observed in our study. Future studies could address the temporal variability in dog abundance patterns—which cannot be addressed with our data due to the short temporal frame of our study—and especially the population dynamics of free-roaming dogs, including the links between the owned and unowned subsets.

4.3. Management implications

The discussion on dog population management is often centered on rabies control (e.g., Morters et al., 2013; Taylor et al., 2017), but rabies is only one out of the many problems linked to free-roaming dogs (Belsare and Vanak, 2020). In fact, free-roaming dogs, whether owned or unowned, are an important environmental problem that negatively affects many fundamental human needs (sensu Max-Neef et al., 1993, modified by Costanza et al., 2007), including security (e.g., dog bites), subsistence (e.g., predation on sheep and hen), and affection (e.g., attacks on family members and pets), among others. Therefore, we consider that despite the evidence available for rabies (e.g., Morters et al., 2013), aiming at reducing the number of free-roaming dogs is important because several dog-caused problems are higher in areas where the number of free-roaming dogs is higher (Table 4).

We suggest that any strategy that aims to reduce the number of free-roaming dogs—and the associated problems—should focus primarily on owned dogs, and especially on dog owners. Specifically, the central component of any responsible dog-ownership policy should be to keep dogs inside properties, because most dogs that roam in urban and rural streets are in fact owned (this study, Ibarra et al., 2006, Sepúlveda et al., 2014). This is key in countries like Chile, where the number of owned dogs per person is extremely high compared to most countries in the world (see human: dog ratios in Gompper, 2014), and in addition containment of pets is not strictly enforced, as observed in our study. Different tools need to be used to achieve this goal, including education and especially law enforcement (see also Garde et al., 2022). Law enforcement is fundamental, because in countries like Chile the regulations that mandate keeping pets inside properties already exist (Law 21,020), but the lack of enforcement implies that there are no real consequences for those who do not comply. Also, the prevention and sanction of the abandonment of pets are essential. Currently, abandonment is a felony in Chile (Law 21,020), but these events are difficult to detect, since the regulations allow the use of non-permanent identification devices that can be easily disposed of when pets are abandoned (e.g., collars). The use of permanent identification, such as subcutaneous microchips, could facilitate the traceability of abandoned and lost dogs, helping to enforce the law, discourage abandonment, and reunite pets and owners, respectively (Fatjó et al., 2015; Zak et al., 2018).

Education is also a necessary complement (Rohlf et al., 2010; Baatz et al., 2020), to inform about the social, environmental and animal-welfare benefits of responsible pet ownership, and also about the law and consequences of not complying with it. Education of both the urban and rural populations is critical for managing the problem in rural areas, where dog immigration from urban areas (i.e., rural residents bringing dogs from cities and some urban individuals abandoning dogs in rural areas) appears to be a key driver of population dynamics. This makes single-pronged strategies, such as sterilization, ineffective (Morters et al., 2014; Villatoro et al., 2016). For management intervention purposes it is important to effectively categorize unowned dogs (e.g., lost, abandoned and community dog) and differentiate them from owned dogs that are kept in the streets. In the case of owned animals, law enforcement is critical (see above). In the case of unowned dogs, we acknowledge that the decision to feed animals is often driven by compassion (Davey et al., 2020; Tiwari et al., 2019; Haris, 2022). However, the emphasis on community dog management should be moved from feeding to adoption and containment. Finally, opportunities for dog health care, especially vaccination, appear important especially in isolated rural areas that may not have access to veterinary services. Other management alternatives that are frequently brought up in public policy discussions—such as neutering, euthanasia and dog shelters, among others—will not work if owned dogs are allowed to roam free as frequently as we detected in our study.

CRediT authorship contribution statement

Eduardo A. Silva-Rodríguez: Conceptualization, Funding acquisition, Project administration, Methodology, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Esteban I. Cortés:** Formal analysis, Data curation, Writing – review & editing, Visualization. **Brayan Zambrano:** Methodology, Investigation, Writing – review & editing. **Lisa Naughton-Treves:** Conceptualization, Methodology, Writing – review & editing. **Ariel A. Farías:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing, Visualization.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.164324.

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